THE GREENHOUSE EFFECT:

Policy Implications of a Global Warming

Edited by Dean Abrahamson and Peter Ciborowski

THE GREENHOUSE EFFECT: POLICY IMPLICATIONS OF A GLOBAL WARMING

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Edited by
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PREFACE

Due to the combustion of fossil fuels and other industrial activities, atmospheric concentrations of carbon dioxide and other greenhouse gases are increasing. Recent research suggests that mean global surface temperature will increase by one to four degrees Celsius in the early decades of the next century. Over this period, the atmospheric level of carbon dioxide should increase to about 160 percent of the preindustrial level. A significant reduction of soil moisture throughout much of the middle latitudes will accompany these increased temperatures. Significant impacts are likely in the coming decades.

Despite the potential severity of impacts, no governmental policy has been developed to slow or limit the releases of carbon dioxide or of the other gases to the atmosphere. If the atmospheric level of carbon dioxide is to be limited to 500 parts per million (ppmv), effective steps will have to be taken soon. The lack of an accepted conceptual structure through which to consider the policy implications of the greenhouse problem may be in part responsible for this inactivity.

Adaptation to climatic change, another possible policy response to anthropogenic changes in the climate, would likewise have to begin fairly soon. Many adaptive measures have long lead times. However, an integrated program for adaptation to large-scale climate change has not been layed out, and the potential limits of such a strategy have yet to be considered.

In 1983 reports of the National Academy of Sciences and the U.S. Environmental Protection Agency initiated a discussion about the relative merits of adaptive and preventive policy responses. Neither study thoroughly considered the factors which might limit the success of the different policy responses. Therefore, the Humphrey Institute of Public Affairs, the National Center for Atmospheric Research, the World Resources Institute, and the Ecosystems Center of the Marine Biological Laboratory sponsored a symposium, of which these are the proceedings, to continue the process of defining the larger policy context in which the greenhouse problem is embedded. The participants sought to redefine the problem in terms of the factors that might limit any one set of policy strategies, the criteria that might be of most use in the choice of policy options, and the time frame within which actions must be taken.

It was assumed that policies to limit the atmospheric accumulation of greenhouse gases should take into account the potential for limiting greenhouse gas concentrations to different levels, and the risk associated with different atmospheric concentrations. The potential for limiting future releases of carbon dioxide varies inversely with continued growth in the rate of fossil fuel consumption and with the time of policy action. Also, it was assumed that there is probably a set of adaptive measures which will be limited by the time of their implementation and by other factors.

The symposium addressed eight major topics:

- realizable rates at which growth in global fossil fuel consumption can be slowed and finally reversed;
- the required timing of policy initiatives to limit atmospheric carbon dioxide concentrations to various ceiling amounts;
- the extent of the risk and cost to society of different rates of fossil fuel deceleration;
- the types of adaptive measures that might help society ameliorate the impacts of global climate change on society;
- the factors that potentially limit the set of adaptive measures and the costs and risks involved in such adaptation;
- the risks of an extended period of inaction;
- short-term and long-term actions which should be taken;
- critical issues in the policy analysis of the greenhouse issue.

Unfortunately, several factors contributed to a considerable delay between the symposium and the publication of these proceedings. The editors apologize for this delay. The authors have had the opportunity to revise their papers following the symposium. In some cases, the papers were substantially revised.

There have been a number of developments since the symposium. Elements of the U.S. Congress have begun to recognize the issue, and hearings have been held. In October 1985, an expert conference of the World Meteorological Organization, the United Nations Environmental Programme, and the International Council of Scientific Unions called for a long-term policy response to the problem. Recent work has continued to refine the scientific basis for the problem.

Only one of these developments has, however, fundamentally changed the policy issues which the symposium addressed. It is now clear that the greenhouse gases other than carbon dioxide are much more important than had previously been recognized. This recognition, together with the realization that most of the other gases will be exceedingly difficult to control, may increase the urgency of efforts to limit the releases of carbon dioxide if indeed society decides to limit global warming. The warming caused by the other gases has dramatically advanced the time of the overall projected global warming. Hence, any adaptive response might also need to be implemented sooner than has been anticipated.

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This work would have not been possible without the help and encouragement provided by the Symposium Organizing Committee, which included, in addition to the editors: John Firor, National Center for Atmospheric Research; Gus Speth and Irving Mintzer, World Resources Institute; and George M. Woodwell, Ecosystems Center, Marine Biological Laboratories.

The editors also acknowledge the contributions of those symposium participants who did not write papers and of several others who assisted with the reviewing and editing of the papers. The organization of these proceedings and the introductions to each section are the sole responsibility of the editors.

INTRODUCTION

Global warming resulting from the atmospheric release of gases collectively called greenhouse gases may prove to be one of the most vexing problems facing contemporary society. The most important greenhouse gases, carbon dioxide, methane, and nitrous oxide result from the most basic of human activities--energy conversion and changing land-use.

A substantial warming is possible within the next few decades. Even conservative analyses indicate that, if vigorous efforts are not made to constrain the production and release of the greenhouse gases, well before the end of the next century we may be committed to an increase in average global temperature of over 6 degrees Celsius. A warming of 2 or 3 degrees is plausible within the next few decades. This would result in climate changes greater than any experienced since the beginning of written history. Study after study shows that a warming of several degrees and rates of warming approaching 0.5 degrees Celsius per decade are possible in the relatively near future.

At least seven federal agencies, including the Environmental Protection Agency, the Department of Energy, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, the National Science Foundation, and the Department of State, and about a dozen executive branch offices, are said to have programs related to global warming. Congress has held several informational hearings and more are scheduled. On the international scene, the World Meteorological Organization, the United Nations Environmental Programme, the International Council of Scientific Unions, and other coordinating and consulting bodies have programs. Articles are beginning to appear in the popular press and in other media. The nonprofit sector has recognized the issue but has not yet given global warming more than casual attention. In the private sector, even those interests likely to feel the heaviest impact of global warming, for example the electric utilities and the coal industry, have given no indication that they are aware of its importance.

The full implications of global warming are not yet generally appreciated. Although awareness of the problem is increasing, governmental and private sector policies are as yet largely unaffected. As was the case in 1984, when the symposium that gave rise to this volume was held, suggested policy responses are based on individual preferences. Only two responses are open to society--the preventive and the adaptive response. Some analysts assert that the preventive option simply does not exist because growth in the activities which produce the greenhouse gases are so central to human well-being. Also, it has been suggested that it has not been proven that a warmer earth is undesirable. Others are attempting to show that, given the magnitude and rates of warming that are likely, only a vigorous preventive strategy, mounted in the very near future, can prevent massive disruption of social, economic, and ecological systems.

This issue puts society between a rock and a hard place. Neither prevention nor the adaptive response is particularly attractive. Given that there are, for all practical purposes, no scrubbers to control the release of industrially-produced greenhouse gases, to implement a preventive response, it may be necessary to curtail the activities which give rise to the gases. Many of the lesser greenhouse gases are associated with activities which it would be problematic to curtail like tropical and subtropical agriculture. Hence, prevention may depend on the extent to which the use of fossil fuels, particularly coal use, can be reduced. Given the inherent unattractiveness of nuclear power and the perception that solar and other renewable energy technologies are either immature or very expensive, agreement on the need to reduce global coal use may require prolonged discussion. Preventive strategies are, therefore, intimately intertwined with energy policy.

There are several approaches to the adaptive response. Society can rely on the market; it can anticipate climate change and rely on a long-range planning response; or it can muddle through. As the editors attempt to show in their paper on the role of uncertainty, market and anticipatory planning strategies are unlikely to be successful because of considerations involving informational requirements, positive discount rates, and rates of climate change.

This volume addresses possible policy responses to global warming. The first paper represents the editors' understanding of the physical basis of global warming, and they have also prepared brief introductions to each section of the volume. The second section of the book contains a series of papers by Robert Williams et al., by John Hoffman and Stephen Seidel, by John Laurmann, and by John Firor which focus on matters directly relating to the feasibility of a preventive response. In the third section, papers by William Riebsame, by Charles Crist and Daniel Reinartz, and by James Titus address the adaptive response. The fourth section contains three quite different attempts, by Irving Mintzer and Alan Miller, by Lester Lave, and by the editors to formulate frameworks within which policies may be considered. The final section contains a single paper by Thomas Johansson and Robert Williams, outlining an energy strategy for industrialized countries, which, if followed, would substantially reduce emissions of carbon dioxide, the most important of the greenhouse gases.

The editors hope that these discussions will contribute to the evolving policy debate. Policy initiatives must be based on assessments of society's ability to respond, without unnecessary disruption, to either the consequences of the warming or to the stresses associated with actions taken to limit the emissions of carbon dioxide and the other greenhouse gases. We hope that these issues will be addressed and be given the emphasis which they deserve and will soon demand.

SECTION 1: PHYSICAL DESCRIPTION OF THE PROBLEM

THE GLOBAL GREENHOUSE PROBLEM

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INTRODUCTION

The global climate is on the verge of a major alteration. As a result of the combustion of fossil fuel and of other industrial processes, the level of carbon dioxide and other greenhouse gases in the atmosphere is increasing. These gases are radiatively active, and when increased in concentration in the atmosphere, they act to increase the resistance of the atmosphere to the loss of heat, thereby warming the surface of the planet. The average global surface temperature of the earth is expected to increase by 4 to 5 degrees Celsius over the next 100 years as a result of emission of these infrared active gases to the atmosphere. Such a warming would be unprecedented in the experience of society.

People influence climate in many ways: by releasing waste heat from urban areas; by introducing aerosols into the troposphere; and by effecting changes in surface vegetation that can change local radiation budgets. However, none of these influences have ever affected climate on a global scale. In the future, human effects on climate will be global in nature, and may result in the most pervasive set of environmental changes ever experienced by humanity.

THE ENERGY BALANCE AND CLIMATE CHANGE

Climate is the long-term set of atmospheric conditions pertaining to surface warmth; available moisture; the movements of air, humidity, storminess, and so on. It results from the energy balance of the planet. The surface heat, or energy, balance in turn results from the interplay of a number of factors: the amount of radiant energy that strikes the earth- atmosphere system; the amount of energy reflected back to space; the rate at which energy is lost to space by the atmosphere-surface system; and any resistance encountered by the surface in the loss of heat to space. The first of these is a well known quantity. Averaged over an entire year, the earth intercepts about 343 watts per square meter (w/m^2) at the top of the atmosphere. The albedo, or reflectivity of the planet, is likewise a well known quantity. Of all radiant energy incident at the top of the atmosphere, about 100 w/m^2, or 30 percent, is reflected back to space, 25 percent by the earth's cloud cover and 5 percent by snow and ice cover.[1]

The rate at which energy is lost by the atmosphere-surface system is fairly well known. In order to maintain a constant temperature, the earth's atmosphere-surface system must radiate an amount of energy equal to that absorbed. Hence, the net emission to space is 240 w/m^2.

By contrast, the resistance of the surface-atmosphere system to the loss of heat is more complex. Like any body of its size, the earth loses energy through the emission of heat, or long-wave (thermal) radiation, to space. As a result, the surface radiates energy to space in the long-wave spectral region (4 to 50 microns). However, at these wavelengths, the earth's atmosphere is quite resistant to the loss of heat. The atmosphere contains gases that absorb in the infrared, particularly near the peak of surface emission, near 10 microns. The atmosphere intercepts a part of this long-wave surface emission, and, absorbing it, reemits it in all directions. Some is emitted downward. Rather than escaping to space, this heat is trapped in the lower atmosphere, whose temperature must rise as a result. Given a rise in temperature in the lower atmosphere, downward atmospheric emission to the surface must increase, leading to increased surface temperatures.[2]

By thus retarding the planet's radiative cooling processes, the presence of these infrared active gases in the atmosphere warms the planet. The surface of the planet is roughly 33 degrees Celsius warmer than it would be were the atmosphere transparent to escaping long-wave radiation.[3] Water vapor, carbon dioxide, and ozone are the most important of these infrared active gases.[4]

Climates change when the planetary energy balance is noticeably altered. At the regional level, climate change can, up to some limiting condition, be broadly related to a change in mean global surface temperature. Caught between tropical and subtropical climates at the equator and glacial climates in the high latitudes, climate tends to move toward either a more glacial or a warmer, more tropical state upon a change in planetary temperature. With increased surface heating, the climate will warm. Ice cover will increasingly recede. Glacial climates associated with ice cover will likewise recede, to be replaced by more moderate climates. By contrast, given a global cooling, the climate will move toward a broad expansion of glacial climates and toward a colder overall climate.[5]

Of the many causes of naturally occurring climatic change, few are of interest on time-scales of less than hundreds of thousands to millions of years. The two types of change that might be of interest are the change experienced on time-scales of several hundred years and the oscillation between glacial and interglacial conditions.

At present, the climate of the planet is fixed in a cool glacial-interglacial mode. Due to glaciation at both poles, the planet is quite reflective of incoming solar radiation and, receiving less radiation, is rather cool. At relatively low planetary temperatures, the climate oscillates between a glacial and an interglacial state. Responding to slight changes in the amount of solar radiation received in the high latitudes, continental ice sheets advance and retreat in response to changes in orbital parameters. Downward variation in the amount of incident summer insolation in the high latitudes acts to reduce the rate of summer snow melt, leading to the accumulation of snow and ice cover. Over long periods of time, the earth's orbit and tilt change fairly systematically. The amount of summer solar radiation received in high latitudes is quite sensitive to these changes. The increased expanse of the ice sheets acts to depress surface temperatures. In its interglacial state, mean global temperature is depressed as much as 4 to 5 degrees

Celsius by the permanent ice fields and pack ice.[6] The effect of snow and ice accumulation during the ice ages of the last million years has been to depress the mean global surface temperature an additional 4 degrees Celsius.

It has been concluded that the climate's periodic oscillation between glacial and interglacial conditions has resulted from such a sequence of events.[7] The onset of the next glaciation can be expected within several thousand years, and as such, movement back into a glacial age can be understood to constitute the very long-term climatic future of the planet.

By contrast, over periods of anywhere from decades to hundreds of years, the climate is remarkably stable. Some typical rates of change in surface temperature are shown in Table 1. Since very pronounced changes in climate occur only over long periods, typically thousands to hundreds of thousands of years, such changes are unnoticeable on the time-scales typical of a human life.

Table 1
NATURAL CLIMATIC FLUCTUATION REPRESENTED AS THE SUM OF CYCLICAL CHANGES

Characteristic Period (in yrs.)	Fluctuation in Surface Temperature (in degrees C.)	Maximum Rate of Temperature Change (in degrees C./yr.)
100,000	6	± 0.00025
20,000	3	± 0.00045
2,500	2	± 0.00075
200	0.5	± 0.0075
100	0.5	± 0.015

Source: Interdepartmental Committee for Atmospheric Sciences, *Report of the Ad Hoc Panel on the Present Interglacial*, ICAS 18b-FY75 (Washington, D.C.: National Science Foundation, Federal Council for Science and Technology, 1974).

The last five significant changes in mean global temperature are noted in Table 2. None of these involved a departure of more than 1.5 degrees Celsius from the present value. The time period was reasonably short, from hundreds to a few thousand years. The warming in the Altithermal was probably related to orbital influences. Longer-term solar influences may have been involved in the others.* But most of these climate effects have not been satisfactorily

*Over long periods, the flux of radiation at the top of the atmosphere varies.[8] It has been suggested that such a solar influence operates on time-scales of about 180 years and, on those time-scales, might translate to a climate influence of as much as 0.7 degrees Celsius.[9]

explained. At most, one can say that, over periods of hundred of years, one finds a natural variation in mean global surface temperature of 1 to 1.5 degrees Celsius around the present value. This change is not insignificant.

At the regional level, warming or cooling can be expressed in the form of changes in the boundaries separating different climates. Roughly speaking, the scale of this displacement is on the order of hundreds of kilometers (km) per degree Celsius change in temperature.[10]

Table 2
CLIMATE CHANGE, 8,000 YBP TO PRESENT

Period	Change from Present (in degrees Celsius)
Pre-Boreal, 7,500 YBP	-0.5
Altithermal, 5,000 YBP[a]	+1
Roman, 2,000 YBP	+0.5
Early Medieval, 800 YBP[b]	+?
Little Ice Age, 500 to 200 YBP[c]	-0.5 to 1

Note: YBP = years before present.

(a) See T. Webb III and T. Wigley, "What Past Climates Can Indicate About a Warmer World," in *Projecting the Climatic Consequences of Increasing Carbon Dioxide*, M. MacCracken and F. Luther, eds., DOE/ER-0237 (Washington, D.C.: U.S. Department of Energy, 1985).

(b) See L. Williams and T. Wigley, "A Comparison of Evidence for Late Holocene Summer Temperature Variations in the Northern Hemisphere," *Quaternary Research* 20 (1983): 286.

(c) See I. Smith and W. Budd, "The Derivation of Past Climate Changes From Observed Changes of Glaciers," in *Sea Level, Ice and Climatic Change*, I. Allison, ed., publication 131 (Wallingford, U.K.: International Association of Hydrological Sciences, 1981)

FUTURE CLIMATE CHANGE

Among the influences on climate that are important on time-scales of decades to a few hundred years, only one, an increasing greenhouse effect, is likely to significantly affect future climate. Orbital factors are unlikely to affect global climate on these time-scales. As noted above, the modeling suggests that, although it is inevitable on time-scales of many thousands of years, the onset of a cooler period due to a change in the eccentricity of the planet's orbit is at least a millennium into the future.[11] On time-scales of

10 to 100 years, the solar influence is limited to a few tenths to half a degree Celsius.[12]

The same is in large part true of volcanic aerosols. Once injected as sulfate aerosols into the stratosphere, such aerosols act to increase the opacity of the atmosphere to incoming solar radiation, cooling the planet. A particularly explosive event can reduce the mean global temperature by as much as 2 degrees Celsius.[13] But, in fact, due to their short residence times (two to four years), the effect of volcanic aerosols is usually more limited. The full response depends on other parts of the climate system (e.g., the oceans) with much longer response or relaxation times. As a result, the full response is rarely experienced. An extended period of intense, concentrated explosive volcanism could be climatically important, but extended periods of explosive volcanism are rare, occurring once every 1,000 to 100,000 years over periods as long as a decade, and once every 10,000 to 1 million years for periods as long as one hundred years.[14] Overall, the record suggests a background influence from explosive volcanism of perhaps -0.2 to -0.5 degrees Celsius,[15] which a future influence would need to exceed to result in a noticeable cooling from the present.

Other possible non-greenhouse influences are shown in Table 3. By and large, they are minor. Energy production releases heat to the atmosphere. Deforestation changes surface reflectivity and favors a cooling. Generally, industrially-produced tropospheric aerosols absorb short-wave radiation reflected by the planetary surface and radiate long-wave radiation to the surface, warming it. Were they to increase, which is the usual scenario, they would slightly warm the planet.[16]

By contrast, changed atmospheric concentrations of carbon dioxide are expected to raise the mean global surface temperature by 2 to 8 degrees Celsius. Through combustion activities, the economies of the world release carbon dioxide to the atmosphere. Over long periods, combustion can result in the accumulation of significant amounts of carbon dioxide in the atmosphere. The fossil fuels are the principal culprits in release of carbon dioxide to the atmosphere. Carbon dioxide is released to the atmosphere through the combustion of any of the fossil fuels. The fossil fuels, however, form one of the fundamental bases for industrial civilization. The global energy system is at least 90 percent dependent on the fossil fuels and is wedded to them for at least the next three or four decades. As a result, significant amounts of carbon dioxide could accumulate in the atmosphere as a result of industrial activities.

Based on what we know about industrialization and economic growth in the modern world, we think that long-term releases of carbon dioxide can be predicted. Estimates for these go as high as 1,000 parts per million (ppmv),[17] or an amount sufficient to raise mean global surface temperature by 4 to 8 degrees Celsius. The most believable estimates of the future atmospheric accumulation of carbon dioxide suggest a rise on the order of 2.5 to 4 degrees Celsius.*

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*For an annual rate of increase in fossil fuel use of 1.5 percent per year sustained over the next century, an airborne fraction of 0.6 to 0.65, a non-fossil carbon release of 50 to 150 ppmv, and a delay in the response of the atmosphere of fifteen to forty-five years.

Table 3
POTENTIAL INFLUENCES ON CLIMATE, 1985-2100

Climate Influences	Effect (in degrees Celsius)
Volcanic aerosols[a]	--
Surface heat emission[b]	(+) 0.1 - 0.2
Deforestation[c]	(-) 0.1 - 0.2
Tropospheric aerosols[d]	slight warming
Stratospheric ozone depletion[e]	(±) 0.1 - 0.2

(a) No increase in the introduction of volcanic aerosols should be expected.

(b) See W. Kellogg, *Effects of Human Activities on Global Climate*, WMO 486 (Geneva: World Meteorological Organization, 1977).

(c) See R. Dickinson, "Effects of Deforestation on Climate," in *Blowing in the Wind: Deforestation and Long-Range Implications*, V. Sutlive, N. Altshuler, and M. Zamora, eds., Studies in Third World Societies (Williamsburg, Vir.: College of William and Mary, Department of Anthropology, 1981).

(d) See W. Kellogg, "Aerosols and Climate," in *Interactions of Energy and Climate*, W. Bach, J. Pankrath, and J. Williams, eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1980).

(e) See V. Ramanathan et al., "Climate-Chemical Interactions and Effects of Changing Atmospheric Trace Gases," *Reviews of Geophysics* 25 (1987): 1,441.

In addition, atmospheric levels of other infrared active gases are also expected to increase as a result of human activities. The most important of these include methane, nitrous oxide, and the chlorofluorocarbons (CFCs). It is believed that increased atmospheric levels of these gases will add an additional 2 to 3 degrees Celsius to the surface warming. With this additional increase, the possible average global surface warming is in excess of 4 to 7 degrees Celsius, or roughly three to five times the typical one-hundred year variation in surface temperature (see Table 3).

An Intensified Greenhouse Effect

The mechanism of an intensified greenhouse effect is exactly the same as that which gives us the present background greenhouse effect. As an infrared active gas, carbon dioxide absorbs in many of the same wavelengths that the surface of the earth emits heat to space. Absorbing this heat, it warms the surrounding atmosphere and increases the atmosphere's emission of heat to the surface, thereby warming it. Any increase in the number of molecules of atmospheric carbon dioxide will increase the amount of atmospheric absorption and, through a further increased downward emission of heat from the atmosphere to the surface, further warm the surface.

The greenhouse effect results from the particular ways in which the carbon dioxide molecule and other molecules interact with radiation in the atmosphere. Upon absorbing energy, the molecules become excited and begin to vibrate, spin, and bend in a waggling motion. This vibrational energy is radiated both upward and downward. The downward component contributes to net surface warming.

The intensity of a surface warming from an increased concentration of any infrared active gas depends on the strength of its absorption bands. Important absorbers have absorption bands near the spectral region of peak emission of long-wave radiation from the surface, about 10 microns. The wavelength of carbon dioxide's absortion bands is near the spectral region of peak emission of long-wave radiation from the surface, making it a powerful absorber. Its strongest absorption bands (fundamental, isotopic, and hot bands) are found in the 15 micron spectral region, with weaker (hot) bands centering at 10 microns, two bands centering at 7.6 microns, and other weak bands in the 12 to 18 micron spectral region.[18]

A number of absorption bands are located in the spectral region from 8.5 to 12.5 microns, known as the "atmospheric window." The atmosphere contains almost no important absorbers in this region, making it largely transparent in this spectral region. Once added to the atmosphere, infrared active gases absorbing at these wavelengths are often very powerful absorbers and, even in very small concentrations, can influence the heat balance of the planet. In this spectral region, temperature increases almost linearly with concentration.[19]

By contrast, the main absorption bands at 15 microns are in an optically thick spectral region. Due to the level of carbon dioxide in the atmosphere, the center of the band is saturated. As a result, absorption in this region occurs largely in the wings of the 15 micron band. Temperature is related logarithmically, rather than linearly, to concentration in this band. Temperature increases with increasing concentration, but at a decreasing rate. Of absorption in the many carbon dioxide bands, absorption in the bands centering at 15 microns is by far the most important. It accounts for roughly 80 percent of the increased absorption and surface warming associated with a doubling to a quadrupling of the present atmospheric level of carbon dioxide, dominating long-wave absorption.[20] Given this fact, the surface temperature response to increased atmospheric levels of carbon dioxide as a whole is logarithmic, each successive doubling of concentration yielding the same increase in surface temperature.

No limiting temperature is foreseen in the case of increased atmospheric levels of carbon dioxide, since, over the types of increase in concentration that might be realized over the next few centuries, the absorption bands located in the spectral region from 8.5 to 12.5 microns will probably not saturate.[21] These will contribute to the surface warming even at very high atmospheric levels of carbon dioxide.

Other Gases

The other gases are assumed to act on the climate in essentially the same way as carbon dioxide. For the most part, they have residence times longer than a year and are well mixed in the atmosphere. All have infrared absorption bands in the 4 to 15 micron region (see Table 4). Some of the more important of these include: methane (CH_4), nitrous oxide (N_2O), and the principal chlorofluorocarbons (CFC-11, CFC-12). Others include: carbon tetrafluoride (CF_4), carbon tetrachloride (CCl_4), acetylene (C_2H_2), methyl chloroform (CH_3CCl_3), methylene chloride (CH_2Cl_2), tropospheric ozone (O_3), and the chlorofluorocarbons of lesser importance, CFC-113, CFC-22, and CFC-116.[22]

The effect of the other gases is most often treated as an amplification of the projected carbon dioxide-induced warming, and the future aggregate effect of these gases is described in terms of a sensitivity parameter that amplifies the carbon dioxide warming by some constant factor. This is necessary for several reasons, not the least of which is the fact that, although future rates of increase in the atmospheric levels of these gases are poorly known, their number is sufficiently large that a constant factor increase can be assumed to capture the general magnitude of their effect on surface temperatures. In addition, the use of a sensitivity parameter can capture somewhat the effect of an increasing number of gases being added to the list of potential important future infrared absorbers.[23] Given a very long time horizon, a significant expansion is possible.

Climate Sensitivity

The radiative effects of increasing atmospheric levels of the infrared active greenhouse gases are related to a change in surface temperature through a climate sensitivity estimate. The sensitivity of surface temperature to increased concentrations of carbon dioxide is estimated for a doubling of concentration. The response of surface temperatures is made up of two distinct processes: the direct radiative effects of an increased atmospheric level of carbon dioxide and the subsequent response of water vapor, ice sheets, and other aspects of climate to this radiative forcing. Given a surface warming due to the effects of an increased atmospheric level of carbon dioxide, additional water vapor will be introduced into the atmosphere and, since water vapor is a greenhouse gas, it will, in increased concentrations (for a doubling, a 15 to 30 percent increase[24]), increase the resistance of the atmosphere to the loss of heat and warm the troposphere and surface.[25] Seasonal snow and ice cover will decline with an intensifying greenhouse effect, leading to a reduction in the planet's reflectivity and an increase in the amount of short-wave radiation received at the surface.[26] This will warm the surface. Cloud cover changes may add to or subtract from the warming. An increase of dense, low-lying clouds will tend to damp out some of the surface warming, whereas an increase in high, thin clouds will amplify it.

Table 4
GREENHOUSE GASES: ABSORPTION BANDS, CONCENTRATIONS, AND RATES OF INCREASE

Compound	Band Center (microns)	Present Concentration[a]	Present Rate of Increase (%/yr)	Approx. Period of Rise[b]	Approx. 1850 Concentration
CO_2	15	345 ppmv	0.4[c]	1880-1985	270 ppmv
O_3	9.6	20-100 ppmv	1[d]	1850-1985	(-) 25%
N_2O	7.8,17,4.5	306 ppbv	0.2-0.4[e]	1870-1985	285 ppbv
CH_4	7.7	1.70 ppmv	1[f]	1600-1985	850 ppbv
CFC-11	9.2,11.8	220 pptv	5[g]	1950-1985	--
CFC-12	9.1,8.7,10.9	375 pptv	5[g]	1940-1985	--
CCl_4	13	130 pptv	1[g]	1915-1985	--
CF_4	7.8	70 pptv	3[h]	1880-1985	--
CFC-22	12.4,7.6,9	90 pptv	10-14[i]	1960-1985	--
CFC-113	8.5,11,12	45 pptv	12-15[j]	1965-1985	--
CH_3CCl_3	14.2,9.2	130 pptv	6[g]	1955-1985	--
CH_2Cl_2	7.9,13.4	30 pptv	5[k]	1945-1985	--
CO	--	120 ppbv	1-2[l]	1850-1985	(-) 15-55%[m]
NO_x	--[n]	30-100 pptv	?	?	?

(a) Values for nitrous oxide, CFC-11, CFC-12, CFC-113, CFC-22, methane, methyl chloroform, and carbon tetrachloride are 1985 values; see the data from R. Prinn et al., presented in L. Ember et al., "Tending the Global Commons," *Chemical and Engineering News* 64 (1986): 16, and World Meteorological Organization, *Atmospheric Ozone 1985. Assessment of Our Understanding of the Processes Controlling its Present Distribution and Change*, WMO Global Ozone Research and Monitoring Project Report no. 16 (Geneva: WMO, 1986). The rest are 1980 values taken from V. Ramanathan et al., "Trace Gas Trends and Their Potential Role in Climate Change," *Journal of Geophysical Research* 90 (1985): 5,547.

(b) See D. Wuebbles, M. MacCracken, and F. Luther, *A Proposed Reference Set of Scenarios For Radiatively Active Atmospheric Constituents*, DOE/NBB-0066 (Washington, D.C.: U.S. Department of Energy, 1984).

(c) See R. Gammon, E. Sundquist, and P. Fraser, "History of Carbon Dioxide in the Atmosphere," in *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, J. Trabalka ed., DOE/ER-0239 (Washington, D.C.: U.S. Department of Energy, 1985).

(d) See J. Logan, "Tropospheric Ozone: Seasonal Behavior, Trends, and Anthropogenic Influence," *Journal of Geophysical Research* 90 (1985): 10,463; and G. Tiao et al., "A Statistical Trend Analysis of Ozonesonde Data," *Journal of Geophysical Research* 91 (1986): 13,121.

(e) See M. Khalil and R. Rasmussen, "Increase and Seasonal Cycles of Nitrous Oxide in the Earth's Atmosphere," *Tellus* 35B (1983): 161.

(f) See D. Blake and F. Rowland, "World-wide Increase in Tropospheric Methane, *Journal of Atmospheric Chemistry* 4 (1986): 43.

(g) See Ember et al. in note (a) above.

(h) See P. Fabian et al., "CF_4 and C_2F_6 in the Atmosphere," *Journal of Geophysical Research* 92 (1987): 9,831.

(i) See R.A. Rasmussen and M.A. Khalil, "Atmospheric Fluorocarbons and Methyl Chloroform at the South Pole," *Antarctic Journal of the United States: 1982 Review* (1982): 203.

(j) See D.R. Blake, Testimony Before the U.S. Senate Committee on Energy and Natural Resources, November 9, 1987.

(k) See E. Bauer, "A Catalogue of Changing Influences on Stratospheric Ozone," *Journal of Geophysical Research* 84 (1979): 6,929.

(l) See M. Khalil and R. Rasmussen, "Global Trends of Carbon Monoxide," *Eos* 68 (1987): 1,213 (abstract).

(m) See A.M. Thompson and R.J. Cicerone, "Possible Perturbations to Atmospheric CO, CH_4, and OH," *Journal of Geophysical Research* 91 (1986): 10,853.

(n) NO_2 has absorption bands at 8.7 and 7.4 microns.

The direct radiative effects of a doubling are one of the better-known parameters in the carbon dioxide-climate problem.[27] They are estimated at about 4 watts per square meter in increased downward radiation from the atmosphere. This translates roughly to an increase in mean global temperature of about 1.2 degrees Celsius.

By contrast, the feedback responses of the climate system are only approximately known. Hence, there is a good deal of divergent opinion as to the specific contribution of these responses to climate sensitivity. The most advanced climate models generate sensitivities to doubled atmospheric levels of carbon dioxide that fall into a range of 2 to 4.2 degrees Celsius.[28] Since the direct radiative effect is estimated at about 1 degree Celsius, the feedback response from water vapor, ice cover changes, and changes in cloud cover contributes 1 to 3 degrees Celsius to the warming. The most advanced of this class of climate models calculates sensitivities at the high end of that range, 3.5 to 4.2 degrees Celsius.[29] In the case of the higher sensitivity, the water vapor feedback dominates the calculation, accounting for more than half of the net warming. The direct radiative effects of carbon dioxide account for about one-fourth of the surface warming (see Table 5). Of the remainder, the ice-albedo effect accounts for about 10 percent. A change in cloud distribution and height adds about one-fifth.

Table 5
COMPONENTS OF WARMING FROM DOUBLING OF
CARBON DIOXIDE, GISS MODEL

Components	Degrees Celsius
Direct radiative effect	1.2
Positive feedbacks	
Water vapor feedback	2.7
Ice-albedo feedback	0.4
Cloud feedback	0.9
Negative feedbacks	
Lapse rate adjustment	(-) 1.2

Source: J. Hansen et al., "Climate Sensitivity: Analysis of Feedback Mechanisms," in *Climate Processes and Climate Sensitivity*, J. Hansen and T. Takahashi, eds. (Washington, D.C.: American Geophysical Union, 1984).

The strength of these advanced three dimensional models lies in the fact that, unlike earlier climate models, they generate sensitivities based on the sum of the calculated regional responses of water vapor, snow and ice cover, and other aspects of the climate to the direct radiative effects of increased levels of carbon dioxide, and do not depend on externally prescribed values. This is evident, for instance, in the case of the lapse rate response, one of the most important feedback responses of the climate system. The lapse rate is the rate at which temperature changes with altitude, and it is important in determining the partitioning of heating within the surface-atmosphere system. Given a fixed amount of total heating in the atmosphere-surface system, if the atmosphere warms more than the surface, the surface must cool.[30] This is a negative lapse rate feedback. A negative response is expected to prevail globally (see Table 5), but since the response in higher latitudes is expected to be positive, it is tempered by some responses at the regional level. These must be individually calculated.

As a result of the increasing sophistication of climate modeling, the range of possible values for climate sensitivity can be assumed to lie within the 2 to 4.2 degree Celsius range, and more likely than not toward the higher end of that range. The effects of warming on cloud cover constitute the one major caveat. Average global surface temperature is sensitive to changes in cloud cover. For instance, in order to halve the sensitivity of the climate at 35 degrees north latitude to a doubling of the atmospheric level of carbon dioxide, low lying clouds need to increase by only 1.5 percent or the abundance of high clouds to decline by 2.5 percent.[31] It is possible that the net effect of changes in cloud cover could enhance, limit, or have no effect on climate sensitivity.

A 50 percent reduction in climate sensitivity as a result of the play of the cloud parameter is taken as the upper limit to a potential negative cloud feedback. Working from the climate model results of the latest generation of general circulation models (GCMs), this results in a lower limit to the warming of 1.8 to 2.1 degrees Celsius from a doubling of the atmospheric level of carbon dioxide.[32]

Compared to the sensitivities that result from simpler models (see Table 6), the estimates suggested by the GCM results are quite sensitive to an increase in the atmospheric level of carbon dioxide. The simpler models, however, cannot be taken as particularly good indicators of climate sensitivity. At best, these models can be taken to indicate the broad magnitude of the climate response. The model results depend on a large number of externally prescribed values, and this opens the way for many different estimates of what globally averaged values might look like for any one climate response.[33] Given this situation, and the fact that, since they employ many simplifying assumptions, the models cannot account for non-radiative convective climate processes (e.g., dynamic and thermodynamic processes), the models are not sufficiently developed to help one narrowly ascertain climate sensitivity. For such purposes, the results of the GCMs are to be preferred.

Table 6
ESTIMATED CLIMATE SENSITIVITY FOR DIFFERENT MODEL TYPES

Model Type	Sensitivity (in degrees Celsius)
Radiative convective models	1.2 - 3.2
Energy balance models	0.8 - 3.5
General circulation models	2.0 - 4.2
Latest GCMs	3.5 - 4.2

Note: for a doubling of carbon dioxide.

Sources: M. Schlesinger and J. Mitchell, "Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide," in *Projecting the Climatic Effects of Increasing Carbon Dioxide*, M. MacCracken and F. Luther, eds., DOE/ER-0237 (Washington, D.C.: U.S. Department of Energy, 1985); M. Schlesinger, "Climate Model Simulations of CO_2-Induced Climatic Change," *Advances in Geophysics* 26 (1984): 141; M. Budyko, K. Ya Vinnikov, and N. Yefimova, "The Dependence of the Air Temperature and Precipitation on Carbon Dioxide Concentration in the Atmosphere," *Meteorology and Hydrology* 4 (1982): 5; and W. Clark et al., "The Carbon Dioxide Question: A Perspective for 1982," in *Carbon Dioxide Review: 1982*, W. Clark, ed. (New York: Oxford University Press, 1982).

Sensitivity Parameter for the Other Greenhouse Gases

A first order estimate of the change in mean global surface temperature resulting from the other gases is often estimated against a doubling of methane and tropospheric ozone concentrations, a 25 percent increase in the atmospheric level of nitrous oxide, and an increase in levels of the chlorofluorocarbons and chlorocarbons each to 1 part per billion (ppbv).* Based on the results of one-dimensional energy balance or radiative-convective models, such a pattern of increase would yield an increase in mean global surface temperature of about 1.5 degrees Celsius. Incorporating the effects of other gases increases this. The estimates are based on a model with a sensitivity (1.8 degrees Celsius) at the lower end of the accepted range. If adjusted, this estimate would be on the order of 1.8 to 3 degrees Celsius. However, given the uncertainties in the projected rate of build-up of the other gases, these estimates are more properly given as a sensitivity parameter, as discussed earlier. Much recent work suggests that this sensitivity parameter would double the estimated carbon dioxide-induce baseline warming expected in the next century.[39] If the present rates of increase were to be utilized to define this sensitivity parameter, the baseline warming would be increased by an additional 50 percent.[40]

Past Greenhouse Additions to the Atmosphere

About 140 to 170 billion metric tons (gigatons, or GT) of carbon were added to the atmosphere between 1850 and 1985. Because only a part of the annually emitted carbon dioxide remains in the atmosphere, the total amount of carbon that was emitted to the atmosphere over this period was much larger. About 173 GT were released as a result of fossil fuel combustion.[41] Anywhere from 90 to 360 GT were released as a result of forest clearing and other land-use changes in the middle latitudes and the tropics.[42] As a result of human activities, the size of the biosphere has been reduced by about 40 percent, although this happened over a period of many centuries.[43] The atmospheric concentration of carbon dioxide has increased about 25 percent since 1850, rising from the preindustrial level of 265 to 280 to the present 345 ppmv.

The atmospheric level of methane has been increasing since the sixteenth century.[44] The present level is approximately double the preindustrial level

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*Given the expected usages of the chlorofluorocarbons, constant production rates might constitute a lower limit on future emissions rates for CFC-11 and CFC-12. At constant 1977 production rates, concentrations will increase to 2 ppbv.[34] Based on the projected rates of increase in fossil fuel usage (or possibly on rates of agricultural fertilizer application), nitrous oxide is expected to increase in concentration by 25 to 50 percent.[35] The atmospheric level of methane scales largely with population increase.[36] Based on the expected rate of population growth, this might be expected to increase 40 to 100 percent over the next forty-five years. Other temperature-sensitive releases of methane would double the present atmospheric level.[37] Concentrations of the chlorocarbons are increasing at annual rates of 3 to 6 percent. The tropospheric level of ozone is thought likely to increase by 50 percent within forty years.[38]

of 825 ppbv and has increased about 135 to 145 percent since the beginning of the global agricultural expansion in the early seventeenth century. The rate of increase in the level of methane in the atmosphere has progressively increased, from around 0.1 percent per year in 1800 to about 0.2 percent per year in 1886 to 0.6 percent per year in 1900.[45] Modeling exercises indicate that the tropospheric ozone level may have increased about 10 percent since 1945.[46] If so, the preindustrial level would have been about 20 to 60 ppbv.

There were no preindustrial levels of most of the rest of the infrared active gases. The preindustrial level of nitrous oxide was probably about 295 ppbv, suggesting a cumulative input of 13 million tons of nitrous oxide to the atmosphere. With no preindustrial levels (and long lifetimes), the input of the other gases would about equal their atmosphere mass, or 3.8 and 5.7 million metric tons of CFC-11 and CFC-12, respectively, and 0.7, 0.09, and 3.7 million metric tons of CFC-22, carbon tetrafluoride, and carbon tetrachloride, respectively.[47] At present, about 785 thousand metric tons total of CFC-11 and CFC-12 are produced annually. Annual global production of carbon tetrafluoride and methyl chloroform is estimated at 1,030 and 545 thousand metric tons, respectively.[48]

Present Rates of Increase

The atmospheric concentration of carbon dioxide is increasing at a annual rate of about 0.4 percent. The present annual net addition of carbon to the atmosphere is about 3.5 GT, resulting in an annual increase in the atmospheric level of carbon dioxide of about 1.5 ppmv per year. The atmospheric concentration of methane is increasing by about 1 percent per year[49] and at that rate would double in seventy years. Concentrations of CFC-11 and CFC-12 are increasing about 5 percent per year, although the rate of increase is declining. With the exception of nitrous oxide, the atmospheric concentrations of the remainder of the gases are increasing at rates of anywhere from 1 to 15 percent per year (see Table 4).. The atmospheric concentration of nitrous oxide is increasing about 0.2 to 0.4 percent per year.[50]

Carbon Dioxide Signal?

The climate has grown about 0.5 degrees Celsius warmer from 1850 to 1985.[51] This is often taken as evidence of the onset of an intensifying greenhouse effect. Other evidence assembled thus far includes: a sustained middle latitude warming evident in patterns of glacier retreat;[52] a rising sea level;[53] evidence that temperatures in recent years have been among the warmest in the last thousand years; changes in diurnial temperatures similar to those that might be expected with an intensifying greenhouse effect;[54] and indications of a long-term Arctic warming taken from temperature profiles of Alaskan soils.[55] Evidence of a stratospheric cooling, a consequence of an intensifying greenhouse effect, is also available.[56]

In a narrow technical sense, the relationship between past releases of carbon dioxide and the historic rise in mean global surface temperature has not been confirmed by an unambiguous signal from nature.[57] The warming trend has yet to emerge outside the range of natural temperature variability, and until it does it will not be possible to say for certain that it is not the product of random climatic fluctuation.

This situation is not unexpected. The response of the climate system to an external perturbation, like a change in the atmospheric carbon dioxide concentration, is not immediate. In some cases, years are required for the system to fully respond to a change. The most important brake on the climate system is found in the mass of the earth's oceans, which have a large heat capacity and can delay the effects of a change in the atmospheric level of carbon dioxide from two to five decades or longer.[58] As a result, whereas the mean global temperature would have been perhaps 0.8 to 1.5 degrees Celsius higher than in 1985 had the response of the climate system been immediate, in fact, it has warmed only about 0.5 degrees Celsius. (This effect will continue to act in the future and will delay any future change for like periods of time.) In any case, the full equilibrium warming from past greenhouse emissions is in some cases simply not large enough to constitute an unambiguous signal, even were its full effects not to be delayed by the heat capacity of the oceans. A 0.8 degree Celsius warming remains within or close to the range of natural variability, making detection difficult.

As a result of these factors, most scientists suggest that firm confirmation of the signal is at least a decade or a decade and a half in the future. If non-greenhouse factors that influence climate over the short-term can be satisfactorily accounted for, it might be possible to separate out the effect of increased ambient carbon dioxide and maneuver around these problems.[59]

Future Levels of Climatic Change

Given some knowledge of the basic parameters involved in climate change, estimates of the magnitude and rate of future climate change can be offered. Values for the most important parameters used to estimate change at the global level are given in Table 7. Based on these values, it is evident that, as a result of human activities, global climate will soon warm.

Table 7
PARAMETERS GOVERNING ANTHROPOGENIC CLIMATIC CHANGE, PRESENT-2070

Parameter	Likely Value	Possible Value
CO_2 level[a]	670 ppmv	530-830 ppmv
Other greenhouse gases	150% of CO_2	50-300% of CO_2
Climate sensitivity to a doubling of CO_2	3.5-4.2 degrees C	2-4.5 degrees C
Ocean thermal delay	40 years	20-60 years
Global warming, 2070[b]	4-5 degrees C	2-6 degrees C

Note: assumes that no preventive action is taken.

(a) Based on the apparent airborne fraction (0.58), adjusted upward to account for decreasing oceanic uptake of carbon dioxide. Estimates are solely for the fossil fuel source.

(b) Calculated to account for the carbon dioxide released from the biosphere and other sources (50 ppmv).

CLIMATIC CHANGE: THE GEOGRAPHICAL COMPONENT

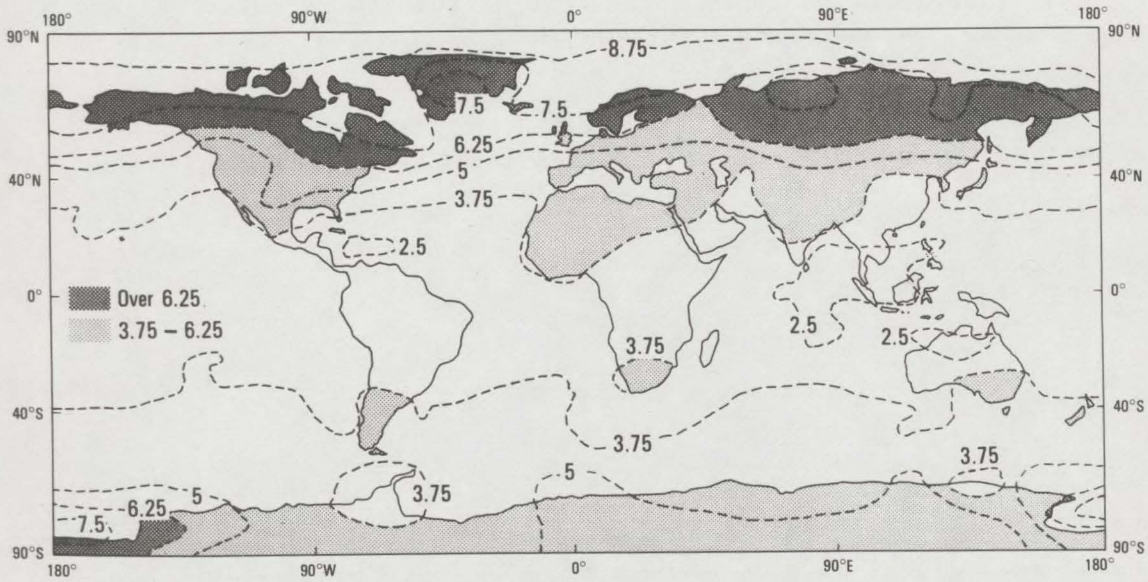
Temperature

Global warming will be disproportionately experienced in the high polar regions, mostly due to interactions of increased temperatures on the one hand and the water vapor content of polar atmospheres and snow and ice cover on the other.[60] Polar temperatures are expected to rise about three times more than the temperature of the globe as a whole (see Figure 1).

Abundant empirical evidence exists to substantiate this polar response to a global warming. For instance, the response to the slight (0.5 degree Celsius) warming experienced between 1880 and 1940 was most pronounced in sub-Arctic regions, where temperatures rose as much as 5 degrees Celsius.[61] Evidence is also available from warmer periods of the more distant past.[62]

A polar warming will affect the cryosphere. There are large ice sheets on the island of Greenland and on Antarctica and in the Arctic basin there is a floating sheet of pack ice. Most of the northernmost lands are frozen. In middle latitudes there exist cirque and small mountain glaciers. The latter would melt upon a small warming.[63] Glacier termini retreat on the order of 1 km per degree Celsius increase in temperature.[64]

Figure 1
ANNUAL SURFACE TEMPERATURE CHANGE FOR INCREASED CARBON DIOXIDE
(in degrees Celsius)



Adapted from S. Manabe and R. Stouffer, "Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration in the Atmosphere," *Journal of Geophysical Research* 85, CIO (1980): 5,529.

A polar warming resulting from a 4 or 5 degree Celsius increase in mean global surface temperature will probably melt the Arctic ice pack[65] and initiate long-term thawing of the continental permafrost. The modeling efforts disagree about the nature of the Arctic pack ice's disappearance. Some suggest summer melting and winter reappearance and others a year-round absence of ice cover. The temperature rise required to melt the Arctic pack ice is also disputed. One needs to go back to the late Tertiary, 3 to 15 million years before present, to find a period in which the Arctic basin was clear of ice. The mean surface temperature of the planet was probably 4 or 5 degrees Celsius higher than now.[66] Some modelers have been able to clear the basin of ice with a global warming of 2.5 degrees Celsius.[67] A 5 degree Celsius polar warming is estimated to result in a 500 km retreat of summer ice margins, leaving the diameter of the ice sheet a mere 1,500 km.[68] The geographical extent of the ice pack appears to have declined about 10 percent during the 1880 to 1940 warming.[69]

A good deal of discussion has focused on the West Antarctic Ice sheet, which is grounded on rock lying below sea level. This ice sheet is expected to remain in place throughout the next 200 years, although it is likely to eventually collapse in response to a warming.[70] Global sea levels would rise 5 to 8 meters were this to occur.

More likely is melting at the ice sheet's margins. This would raise sea levels. Thermal expansion of the upper layers of the ocean would also raise sea levels. Sea level would rise about 60 centimeters (cm) with a 1 degree warming of the entire ocean.[71] In the next century, sea level is expected to rise 1.5 to 2 meters (see Table 8).[72] From 1880 to 1940, it rose at a rate of about 15 cm per century.[73]

Finally, the warming experienced in the equatorial regions is expected to be about half the global average, while that of the middle latitudes would be about the same as the average global change.[74]

Table 8
CONTRIBUTION TO RISING SEA LEVEL, 1985-2100
(In meters)

Mountain glaciers and small Arctic ice caps[a]	0.25
Permafrost[b]	0.02
Greenland[c]	0.25-0.61
Antarctica[d]	0.24-0.5
Thermal expansion[e]	0.72
Total	1.48-2.1

Note: assumes a global surface warming of 4 to 7 degrees Celsius.

(a) See M. Meier, "Contribution of Small Glaciers to Global Sea Level," *Science* 226 (1984): 1,418.

(b) See R. Barry, "Snow Cover, Sea Ice and Permafrost," in *Glaciers, Ice Sheets, and Sea Level: Effects of a CO_2-Induced Climatic Change*, Committee on Glaciology, National Research Council, ed., DOE/ER/60235-1 (Washington, D.C.: Department of Energy, 1985).

(c) See R. Bindschadler, "Contribution of the Greenland Ice Cap to Changing Sea Level: Present and Future," in Committee on Glaciology, National Research Council, note (b) above.

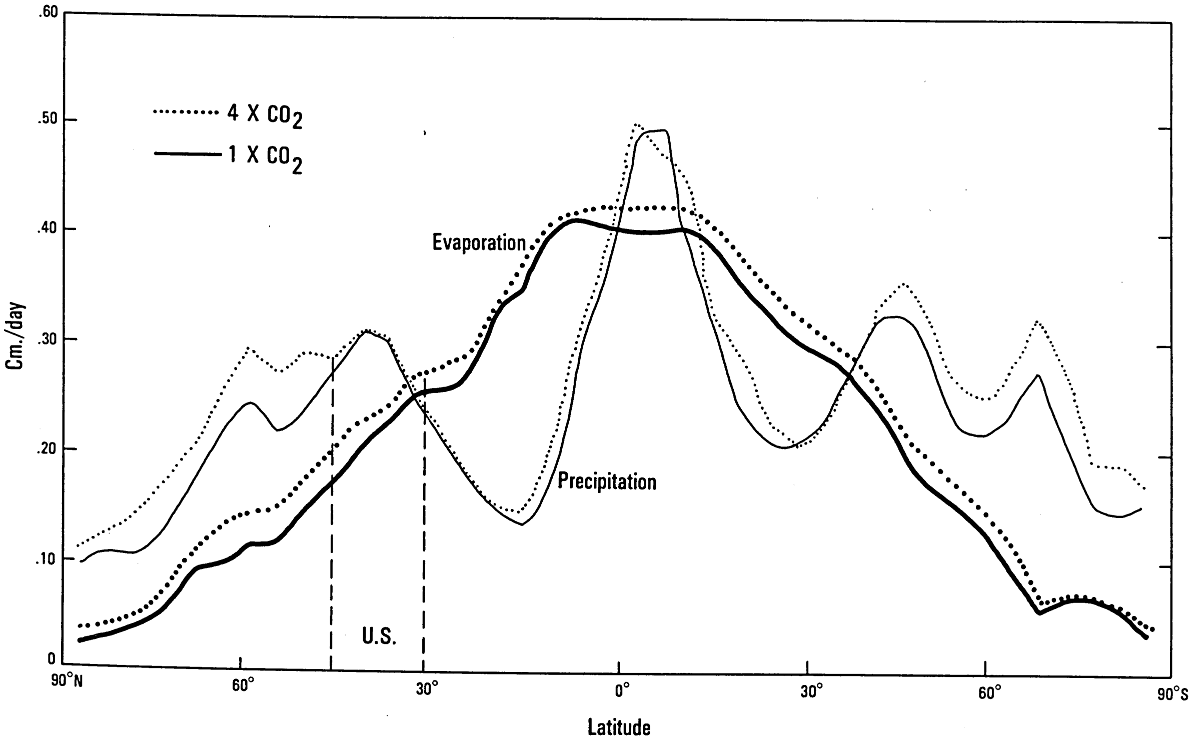
(d) See R. Thomas, "Responses of the Polar Ice Sheets to Climatic Warming," in Committee on Glaciology, National Research Council, note (b) above; and C. Lingle, "A Model of a Polar Ice Stream and Future Sea-Level Rise Due to a Possible Drastic Retreat of the West Antarctic Ice Sheet," in Committee on Glaciology, National Research Council, in note (b) above.

(e) See J. Hoffman, D. Keyes, and J. Titus, *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100 and Research Needs*, EPA 230-09-007 (Washington, D.C.: U.S. Environmental Protection Agency, 1983).

Moisture

General patterns of precipitation change are suggested by the global climate models.[75] The global hydrological cycle should become more active. Increased surface heating should lead to a rise in the rate of evaporation, and to a concomitant rise in the rate of precipitation (see Figure 2). The models suggest about a 7 to 12 percent increase in global hydrological activity.

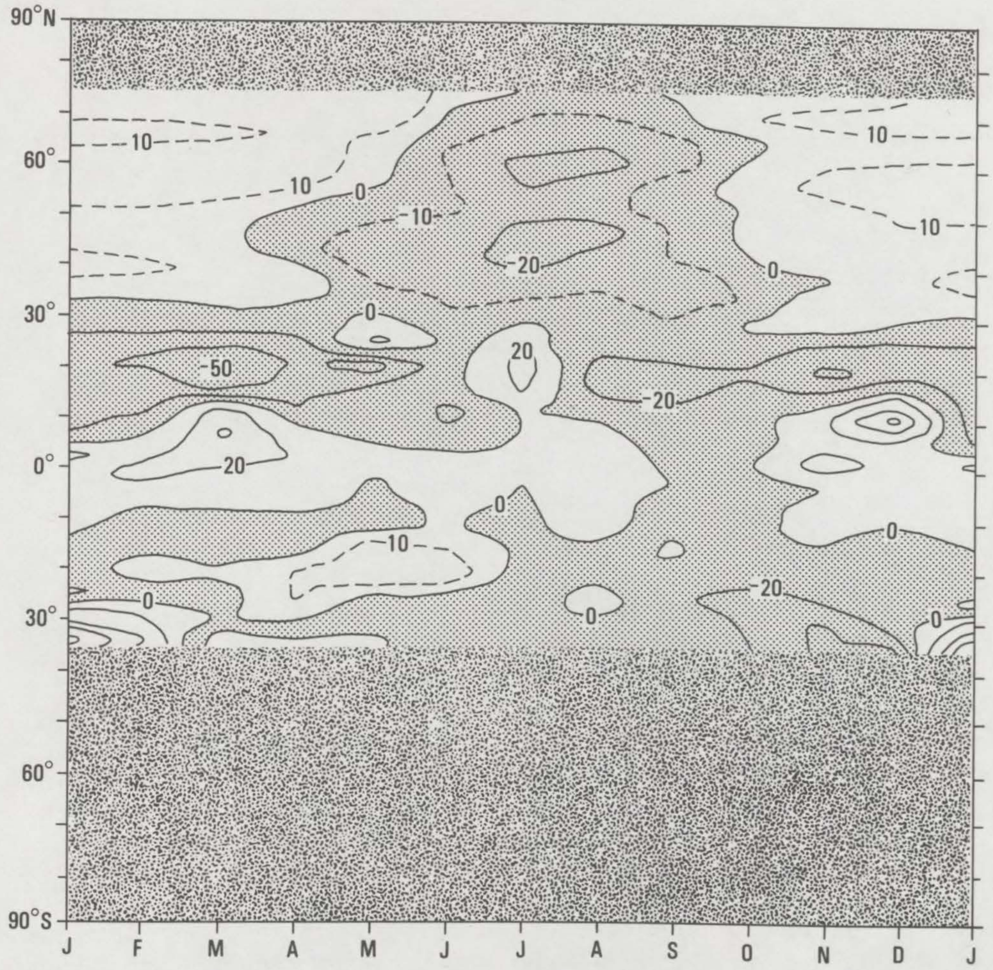
Figure 2
GLOBAL WATER BALANCE CHANGE FOR INCREASED CARBON DIOXIDE



Adapted from S. Manabe and R. Stouffer, "Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration in the Atmosphere," *Journal of Geophysical Research* 85, CIO (1980): 5,549.

However, whereas the net increase in evaporation is spread evenly through the year and across latitudes, the net increase in precipitation has a marked latitudinal and seasonal character. Precipitation increases substantially in the high latitudes. Precipitation, however, remains about the same or changes only slightly in the middle latitudes. As a result, spring and summer soil moisture declines markedly in the middle latitudes (see Figure 3). Since seasonal precipitation in continental interiors is often dependent upon the availability of surface moisture, summer precipitation often declines in the model results.[76] Significant drying is often evident in the model results for the subtropical region of the northern hemisphere (10 to 30 degrees north latitude).[77]

Figure 3
SOIL MOISTURE CHANGE FOR INCREASED CARBON DIOXIDE



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In addition, changes in the general circulation of the atmosphere are possible. The meteorological equator separates the atmospheric circulations of the northern and southern hemispheres. It varies with the respective intensities of these hemispheric circulations. The intensity of each hemispheric circulation varies with the size of the temperature gradient or difference between the poles and the equator. This gradient should, on average, decline in the northern hemisphere with a melting of the Arctic basin ice. This might result in a displacement of the meteorological equator about five degrees north from its present location at about five degrees north latitude.[78]

The positioning of different climatic regimes is broadly controlled by the structure of the circulation of the atmosphere, i.e., by the arrangement of different atmospheric circulations and circulation cells from the equator to the poles. A displacement of the northern hemispheric circulation five degrees in latitude would result in a concomitant displacement of these circulations, perhaps as much as 550 km.[79] If correct, this would bring intensely dry anticyclonic influence into the middle latitudes, deflecting northward the present circulatory features of middle latitude climates and leading to an intense drying.*

Changes in surface moisture depend on changes in precipitation, and at the regional level these cannot often be predicted with any confidence at present. Hence, despite the plausibility of the above reasoning, there are at best a few continental areas and broad latitudinal regions where we can confidently characterize future trends. The continental interior of North America constitutes one area of confidence. Drying is likely here.[81] Drying is also likely in the continental areas in the middle latitudes. Although, with the exception of the situation in the North American sector, one cannot confidently offer moisture projections at the regional level, the evidence nonetheless indicates a general drying in a broad latitude band, either in the lower middle latitudes or in the middle latitudes from thirty to thirty-eight degrees north latitude.[82] The drying shows a clear poleward progression with further warming,[83] and so would eventually come to dominate most parts of the middle latitudes.

Elsewhere the situation is more ambiguous. The Mediterranean region of the European sector may be an exception. Here the evidence suggests a drying analogous to that of the North American interior. In most other regions, the evidence is contradictory.** One can say, however, that there is little reason to be optimistic about the situation in the most populous region of the world, the subtropics and tropics from ten to thirty degrees north latitude, where a generalized drying is suggested.

Ecological Impacts

Global warming would have a significant effect on natural ecosystems. The region of Arctic permafrost and tundra can be expected to retreat poleward about 100 to 200 km per degree Celsius increase in mean global temperature.[84]

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*A displacement of the main circulatory features would also be expected to result from the projected changes in seasonal and permanent ice cover. The dominant feature of the middle latitude circulation is the main depression track. It typically lies at the edge of seasonal snow and ice cover, or the region of greatest surface temperature contrast. It moves north and south with the seasonal progression of snow and ice. As snow and ice cover are premanently melted back toward the poles, this depression or storm track will follow, perhaps 500 km or more, or, as the modeling suggests, five degrees in latitude.[80] Precipitation in the middle latitudes is dependent on the main storm track. Were this storm track to be displaced toward the poles, precipitation in the middle latitudes--at least in summer--would decline.

**For instance, in a belt from zero to twenty degrees south latitude, one finds wetter climates, much wetter climates, drier climates, and intensely arid climates, depending on the model or analogue that one uses.

The same is true of sub-Arctic and temperate tree lines.[85] During past climate changes, tree lines migrated at maximum rates of a few km per decade.[86] The rate of migration is constrained by the dispersal rates of seeds and tree life. From Table 7, the rate at which tree lines would have to migrate would be something on the order of 50 to 200 km per decade, or well beyond the rates that forest systems can maintain. This suggests the possibility of a generalized impoverishment of these ecosystems throughout the middle latitudes.

Animals would also be affected. Many animals can migrate at rates substantially in excess of the rates of forest migration. But to the degree that due to a rapidly changing climate the stability of ecosystems is substantially lessened, the animals that depend on a diverse ecology would undergo considerable stress. Human influences would compound this. The migration of species would be possible only if it were to go unhindered by the obstructions that humankind, since industrialization, has built to the movements of species. The ranges of many species are confined to narrow regions surrounded by intense human uses. Species confined to such reserves would probably be unable to migrate.[87]

In the high Arctic, the survival of animals that now inhabit the tundra would be questionable. During past warm periods, animals have tended to migrate northward.[88] If the warming was to be so intense as to lead not simply to the displacement of tree lines but to the complete or near complete disappearance of the present vegetation of the high latitudes, many polar species would simply disappear. Any global warming that was to return the planet to conditions like those that prevailed during the late or middle Tertiary (e.g., an average global warming of 4 to 6 degrees Celsius) would almost certainly result in such a change.

Implications for Climates of the United States

With a global warming of 4 to 5 degrees Celsius, the climate of the United States would probably be warmer and drier. Surface temperatures that now prevail in El Paso would shift to Missouri, while those of Kansas City would prevail in southern Minnesota.[89] Soil moisture would be reduced. Evidence taken from a wide variety of models, analogues, and other approaches is presented in Table 9. It is strongly suggestive of a trend to a much drier climate.

Prospective changes in surface winds are not well understood. The Arctic Basin has been modeled to act as a summer heat sink upon the complete summer disappearance of the floating ice, leading to increased fluxes of sensible heat from about forty degrees north latitude toward the pole,[90] and probably increased zonal circulation and increased surface wind. High zonal index historically has been related to drought episodes,[91] and could increase the frequency of drought throughout much of the central and western United States, although this could have been predicted simply on the basis of a change to a generally drier climate.[92]

The water balance would be affected by a global warming. Due to changes in the timing of seasons, snow melt would take place about a month sooner than at present. Evaporation would also be higher, and precipitation might be reduced in summer. Streamflow would also decline[93] (see Table 10).

Table 9
MOISTURE CHANGES IN THE MIDDLE OF THE CONTINENTAL UNITED STATES

Type of Evidence	Summer Soil Moisture	Temperature Rise as a Percent of the Mean Global Rise
Climate Models		
GDFL 1986	Drier	150-200
GDFL 1981	Drier	120-150
NCAR 1984	Largely drier	below 60
NCAR 1983	Largely drier[a]	--
GISS 1984	Drier	100
BMO 1987	Drier	100-200
BMO 1984	Wetter[b]	50-100
Reconstructions		
Butzer 1980[c]	Drier	--
Flohn 1980[d]	Drier	--
Suggested by Warm Decades and Years		
Jaeger 1983	Drier	--
Wigley 1979	Drier	--
Rind 1985	Largely drier	--
Paulutikoff 1984		
Case A, B	Drier	100-250
Case C	Mixed	160-333

(a) No change in the southern Great Plains.
(b) Drier in the northern Great Plains.
(c) Altithermal reconstruction.
(d) Late Tertiary reconstruction.

Sources:

GDFL 1986: S. Manabe and R. Wetherald, "Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide," *Science* 232 (1986): 626.

GDFL 1981: S. Manabe, R. Wetherald, and R. Stouffer, "Summer Dryness Due to an Increase of Atmospheric CO_2 Concentration," *Climatic Change* 3 (1981): 347.

NCAR 1984: W. Washington and G. Kiehl, "Seasonal Cycle Experiment on the Climate Sensitivity Due to a Doubling of CO_2 With an Atmospheric General Circulation Model Coupled to a Simple Mixed-Layed Ocean Model," *Journal of Geophysical Research* 89 (1984): 9,475.

NCAR 1983: W. Washington and G. Meehl, "General Circulation Model Experiments on the Climatic Effects Due to a Doubling and Quadrupling of Carbon Dioxide Concentration," *Journal of Geophysical Research* 88 (1983): 6,600.

BMO 1987: C. Wilson and J. Mitchell, "A Doubled Co_2 Climate Sensivitity Experiment with a Global Climate Model Including a Simple Ocean Model," *Journal of Geophysical Research* 92 (1987): 13,315.

BMO 1984: J. Mitchell and G. Lupton, "A 4 x CO_2 Integration with Prescribed Changes in Sea Surface Temperature," *Progress in Biometeorology* 3 (1984): 353.

GISS 1984: J. Hansen, et al., "Climate Sensitivity: Analysis of Feedback Mechanisms," in J. Hansen and T. Takahashi eds., *Climate Processes and Climate Sensitivity* (Washington, D.C.: American Geophysical Union, 1984).

D. Rind and S. Lebedeff, *Potential Climatic Impacts of Increasing Atmospheric* CO_2 *With Emphasis on Water Availability and Hydrology in the United States*, EPA 230-04-84-006 (Washington, D.C.: U.S. Environmental Protection Agency, 1984).

K. Butzer, "Adaptation to Global Environmental Change," *Professional Geographer* 32 (1980): 269.

H. Flohn, *Possible Climatic Consequences of a Man-Made Global Warming*, RR-80-30 (Laxenburg, Austria: International Institute for Applied Analysis, 1980).

J. Jaeger and W. Kellogg, "Anomalies in Temperature and Rainfall During Warm Arctic Seasons," *Climatic Change* 5 (1983): 39.

T. Wigley, P. Jones, and P. Kelly, "Scenarios for a Warm, High-CO_2 World," *Nature* 283 (1979): 17.

J. Palutikoff, T. Wigley, and J. Lough, *Seasonal Climate Scenarios for Europe and North America in a High-*CO_2 *Warmer World*, DOE/EV/10098-5 (Washington, D.C.: U.S. Department of Energy, 1984).

Table 10
COMPARISON OF WATER REQUIREMENTS AND SUPPLIES
IN SEVEN RIVER BASINS

	Present Climate	Warmer and Drier Climate[a]	
Water Region	Ratio of Requirement to Supply	Percent Change in Supply	Ratio of Requirement to Supply
Missouri	0.43	-63.9	1.18
Arkansas/White/Red	0.18	-53.8	0.39
Texas Gulf	0.35	-49.8	0.70
Rio Grande	0.91	-75.7	3.72
Upper Colorado	0.99	-39.6	1.65
Lower Colorado	1.19	-56.5	2.68
California	0.41	-43.9	0.74
Seven regions together	0.43	-53	0.90

(a) With a regional warming of 2 degrees Celsius and a 10 percent decline in precipitation.

Source: R. Revelle and P. Waggoner, "Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States," in *Changing Climate*, Carbon Dioxide Assessment Board, National Research Council (Washington, D.C.: National Academy Press, 1983).

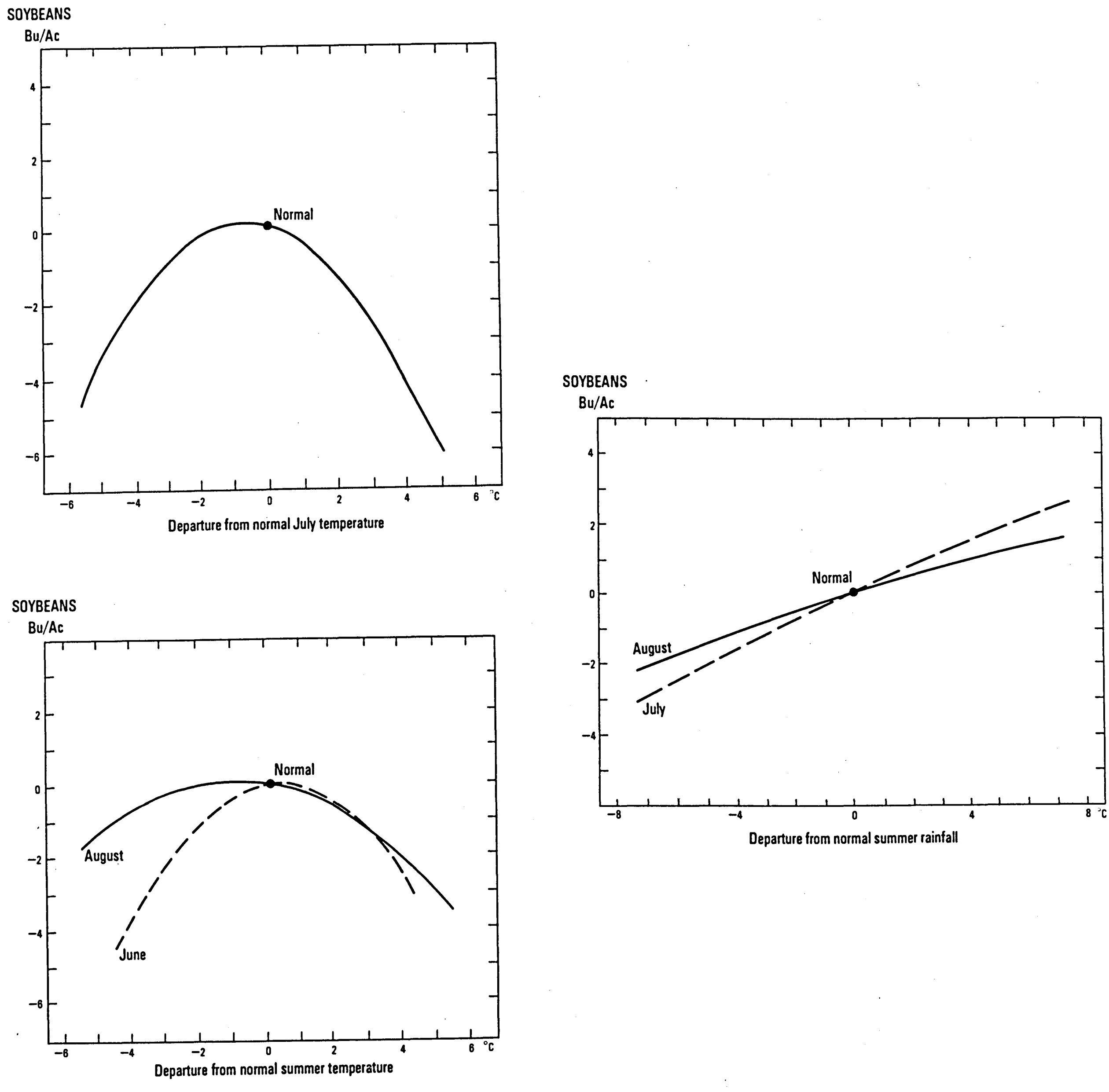
Finally, the number of storms along the southern and eastern coasts might increase. More hurricanes would develop as tropical oceans warm and the surface area of waters about 77 Fahrenheit--the temperature needed for the formation of storms--expands northward. Their intensity would also increase.[94]

EXAMPLE IMPACTS IN THE UNITED STATES

Agriculture

The sensitivity of American agriculture to climate is apparent through: the distribution of yields across climate regions;[95] the limiting climatic conditions at the boundaries of crop regions;[96] production in climatically marginal producing areas;[97] the geographical pattern of interannual yield variability;[98] and the use of fallowing systems.[99] The grain-producing region of the U.S. is already too warm and slightly too dry during the critical periods of the growing season.[100] For instance, for soybeans, the present conditions are too warm in July and August and precipitation is too low in July for optimal production (see Figure 4).

Figure 4
INFLUENCE OF CLIMATE FACTORS ON SOYBEAN YIELDS

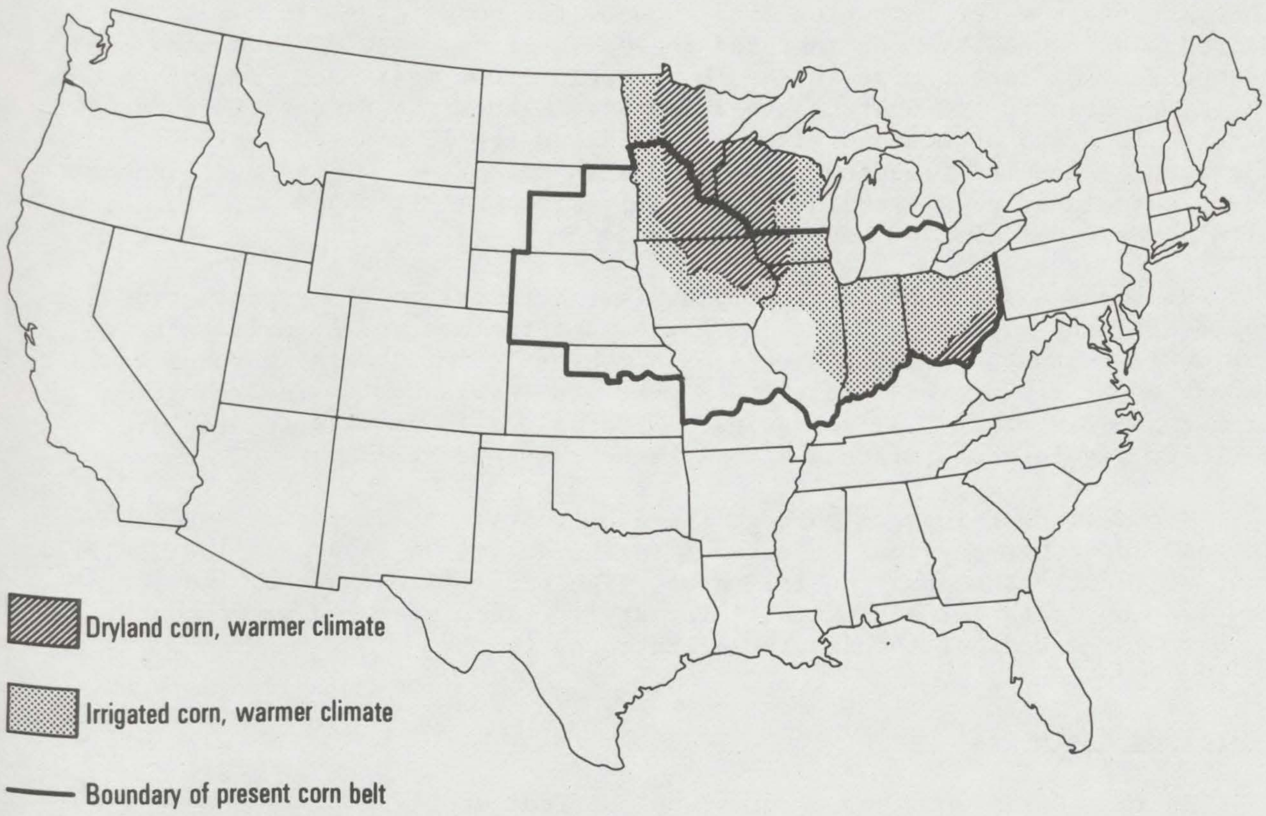


Reprinted from L. Thompson, "Weather and Technology in the Production of Soybeans in the Central United States," *Agronomy Journal* 62 (1970): 232, by permission of American Society of Agronomy, Inc.

Regression analyses and plant physiological models suggest that with a global warming yields of the major agricultural crops would decline about 5 percent per degree Celsius increase in temperature.[101] The response to precipitation decline tends to be on the order of about -2 to -10 percent.[102]

Farmers will respond to these effects and attempt to limit the worst effects through the application of technology. This will be most problematic at the western and southern margins of the present agricultural belts. Short of a major revolution in crop breeding, these marginal areas must go out of production or revert to less valuable crops: corn to wheat at the western margin of the corn belt (see Figure 5); wheat to sorghum at the western and southern margin of the wheat belt.[103] Adaptation of American agriculture to a warming will also be limited by: the present and future demands on western surface waters (see Table 10); ground water depletion; the costs of new irrigation ($400 to 600 per acre[104]); the effects of increased wind erosion of soils (wind erosion varies inversely with soil moisture, and should increase as it warms[105]); increased losses to insects;[106] and the absence of suitable soils and topography in the more northerly states.

Figure 5
SHIFT IN THE CORN BELT FOR A 3 DEGREE CELSIUS WARMING AND A 10 PERCENT REDUCTION IN SUMMER RAINFALL



Adapted from T. Blasing and A. Solomon, *Response of the North American Corn Belt to Climate Warming*, TR006, Washington, D.C.: United States Department of Energy, Office of Energy Research, August 1983.

It is impossible to know whether the farmer will be able to limit impacts. It depends on the effect of a warming and drying on the economics of the farm. Surface water transfers, if financed by the farmer, would affect the economics of production and life on the farm. The relocation of agricultural regions would involve heavy capital costs, particularly if production is relocated into regions lacking the required infrastructure: schools, roads, soils, and so on.[107] If the farmer was to be forced to absorb these costs, he would be significantly affected. Higher production costs would affect the ability of the farmer to respond. So, while the system may "adapt," we do not really know what that means in any practical sense. It is likely that adaptation will be costly and difficult.

Coastal Impacts

A sea level rise of 1.5 to 2 meters would inundate many areas along the Atlantic and Gulf coasts.[108] Some cities like Charleston, South Carolina would lose up to one-quarter of their present land area.[109] Impacts that are likely to result include the destruction of buildings, roads, and other structures and the increased costs to localities of maintaining present infrastructures. Increased salt water intrusion into groundwater supplies would result and degrade water quality. An increase in sea level also would flood many coastal beaches. A 0.3 meter rise in sea level would erode most sandy beaches along the U.S. Atlantic and Gulf coasts 30 meters inland.[110] Barrier islands would migrate landward or would break-up. Increased sea levels would also increase storm surge and the flooding associated with storms.[111] The annual economic costs associated with storm damage in Galveston are estimated to quintuple with a sea level rise of several meters.[112]

Rising sea level would destroy habitat critical to the reproductive cycles of many migratory birds and marine and fur-bearing animals. It is estimated that about 50 to 80 percent of the existing coastal marches would be inundated by rising sea level.[113] Higher sea levels would also result in higher salinities in U.S. estuaries. With only a 13 cm rise in sea level, salinity levels would migrate 2 to 4 km up the Delaware River.[114]

Mitigation of impacts through the construction of dikes, sea walls, levees, and other physical structures is thought to be economically justified only at locations of substantial value, like population centers, industrial centers, and sites of historical interest.[115] Such measures are thought to involve large and heretofore unprecedented costs.[116]

Increased Electrical Demand

Increased ambient temperatures would affect energy utilization in the United States. Heating degree days would decline. Heating degree days decline about 10 percent for each 1 degree Celsius increase in temperature,[117] or, for a 5 degree Celsius warming, as much as 50 percent. Heating accounts for about 15 percent of total U.S. energy use. So total U.S. energy use might decline 8 to 10 percent.

The number of cooling degree days would also rise, thereby increasing peak summer electrical demand. Based on historical evidence taken from the

Upper Midwest, peak demand rises about 10 percent for each 2.5 degree Celsius rise in temperature.[118] The expanded demand for electricity would arise only during the warmest months, so that the net increase in energy consumption would be limited. However, given the prevailing trends in the capital costs associated with the construction of large thermal power plants, a 20 percent increase in electrical generating capacity would represent a formidable expansion in capacity.

SOURCES, SINKS AND POLICY RESPONSES

Carbon dioxide and the other greenhouse gases are released to the atmosphere as a result of human activities. Fossil fuel combustion is by far the biggest culprit, but population pressure and land-use changes are factors. Any form of intervention would need to target fossil fuel combustion and these other influences.

Carbon Dioxide

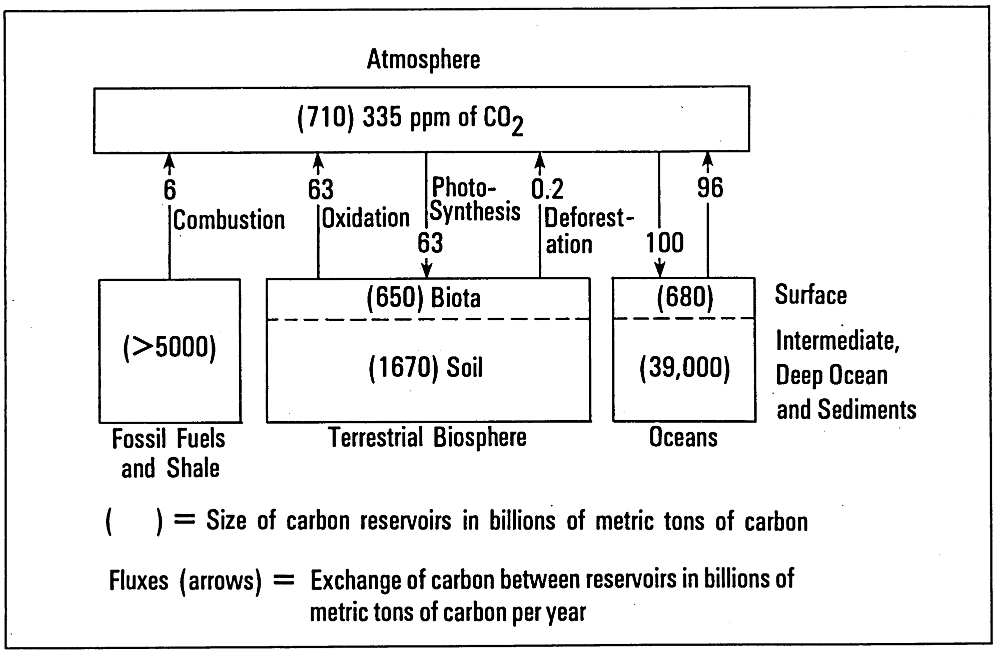
Carbon dioxide results from the oxidation of carbon from the biosphere and fossil fuels. Once emitted, 40 to 70 percent is retained in the atmosphere and the remainder is absorbed into the oceans. Annually about 5.5 GT of carbon are emitted as carbon dioxide as a result of the combustion of fossil fuels.[119] Between 0.6 and 2.6 GT per year are released as a result of deforestation.[120] The conversion of limestone to lime in cement-making may emit another 0.1 GT of carbon to the atmosphere.

Each 3.5 GT of carbon dioxide added to the atmosphere increases the reservoir of atmospheric carbon by about 0.5 percent. The atmosphere contains about 700 GT of carbon (see Figure 6). About 550 to 650 GT and 1,500 to 2,000 GT of carbon are held in the terrestrial biota and in soils, respectively. The oceans contain about 39,000 GT of carbon. Greater than 10 million GT are held as carbonates in limestone and dolomites. Fossil fuel deposits contain 5,000 to 10,000 GT of recoverable carbon.

Long-term releases of carbon dioxide from tropical deforestation are limited by the size of the remaining tropical forests. The total amount of carbon that might be added to the atmosphere from this source is limited to a maximum 125 GT of carbon, or equivalent to a net addition of about 70 ppmv of carbon dioxide to the atmosphere. Revelle and Munk suggest a likely future input of about 40 ppmv.[121] Other estimates range from about 30 ppmv upward.[122] A 40 ppmv increase would raise the mean global surface temperature by 0.3 to 0.6 degrees Celsius.

Some of this warming will be countered by the effect of changes in the reflectivity of the planet as whole tropical areas are denuded of vegetative cover. A cooling of about 0.1 degrees Celsius or so is likely to result from deforestation.[123] But, presumably, increased vegetative growth in higher latitudes will compensate for this. Increased growth in higher latitudes would result in the net removal of carbon dioxide from the atmosphere. This removal might amount to some 50 to 100 GT of carbon, or the equivalent of 15 to 25 ppmv.[124] On the other hand, plant respiration would release carbon dioxide to the atmosphere. The respiration rate controls the rate of decay of plant organic matter. It increases with increasing temperature. Soils respire about 20 to 30 percent more per degree Celsius increase in temperature. Soils might release something like 100 GT of carbon in the next century, or the equivalent of 25 ppmv of carbon dioxide.[125] Other minor sources of carbon dioxide emissions like ocean outgassing, the decay of methane, and cement-making would add to this. (Over the next ninety years, these might add 30 to 60 ppmv of carbon dioxide to the atmosphere.[126]) With the net contribution from deforestation and forest growth, this suggests a biospheric/other source contribution of about 50 to 100 ppmv.

Figure 6
EXCHANGEABLE CARBON RESERVOIRS AND FLUXES

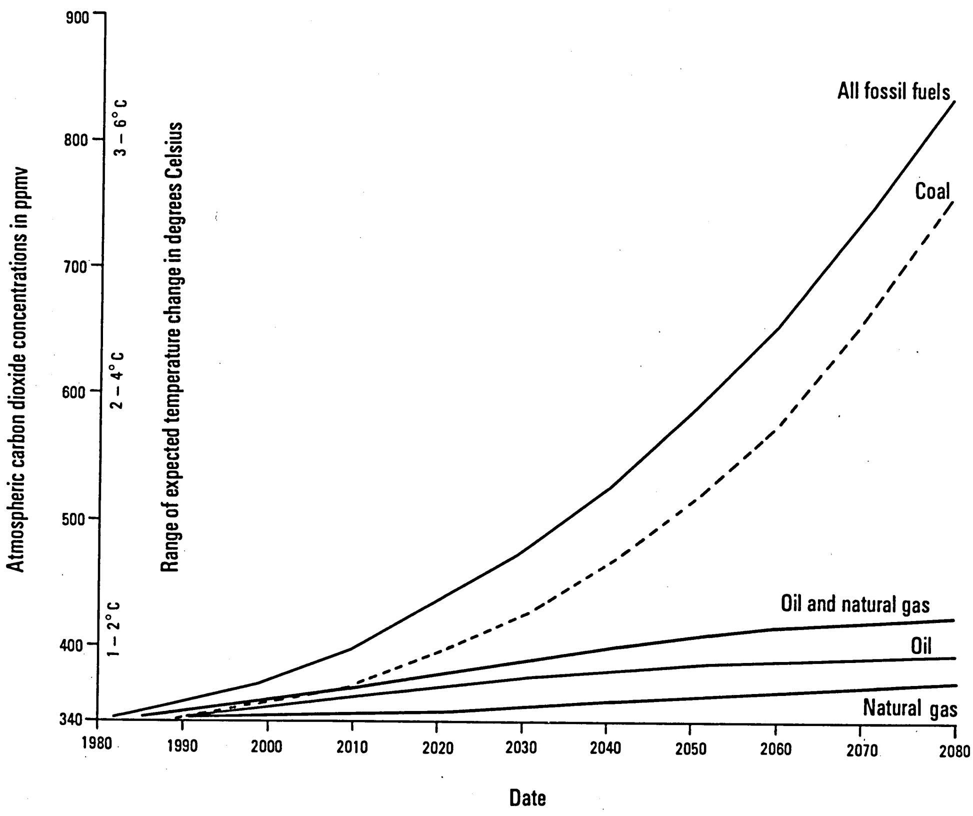


Source: Carbon Dioxide Effects Research and Assessment Program, U.S. Department of Energy, *Summary of the Carbon Dioxide Effects Research and Assessment Program*, 002/1 (Washington, D.C.: U.S. Department of Energy, 1980).

Future increases in atmospheric carbon dioxide resulting from fossil fuel combustion are difficult to estimate. The resource base is essentially unlimited in the time horizon of interest. Recoverable resources of fossil carbon are large enough to increase atmospheric levels of carbon dioxide to four to five times the present level, with an upper limit of five to eight times the present level.[127] To date, only about 150 GT, or 3 percent or less of the total reserve of recoverable carbon, has been consumed. Most of what remains is in the form of coal, oil shale, and tar sands.

About 370 to 520 GT of carbon are buried beneath the ground as oil and natural gas.[128] Most of this is likely to be combusted within the next seventy-five years. This would increase the atmospheric concentration of carbon dioxide to about 420 ppmv, or about 150 percent of the preindustrial level and, in conjunction with coal consumption at constant 1980 levels, raise the level of carbon dioxide to 460 ppmv by 2060. There are about 3,500 to 4,000 GT of carbon in global coal resources.[129] Assuming the complete combustion of all oil and natural gas, a vigorous coal policy (initial growth rates of 4.5 percent per year, declining to 2 percent per year) would raise the atmospheric level of carbon dioxide to about 800 ppmv by the year 2075 (see Figure 7).[130]

Figure 7
ATMOSPHERIC CARBON DIOXIDE CONCENTRATION FOR A VIGOROUS GLOBAL COAL USE EXPANSION



Source: H. Perry and H. Landsberg, "Projected World Energy Consumption," in *Energy and Climate*, Geophysical Research Board, National Academy of Sciences (Washington, D.C.: National Academy of Sciences, 1977).

Fossil fuel consumption grew about 4.5 percent per year in the period from 1945 to 1972. Global fossil fuel combustion has increased about 1.86 percent per year since 1973,[131] a rate of increase which if continued would double the preindustrial level of carbon dioxide by 2055. Most analysts project that consumption will increase between 1.5 and 2 percent per year.[132]

Future rates of increase in combustion depend on economic factors that relate energy use to material production in society. They also depend on the scale of production in society (and therefore on population), and on the type and the efficiency of production. Given a large population engaged in low efficiency, energy-intensive industrial activities, large inputs of carbon to the atmosphere are inevitable.

Not a great deal can be said about releases of carbon to the atmosphere as a result of the long-term play of economic forces and the presence of large global populations. The energy-economy models are ambiguous. Although nearly all accede to the proposition that high rates of population and industrial growth may make high carbon dioxide levels inevitable, there is a good deal of disagreement as to the exact level of carbon dioxide accumulation that would in fact result. This level is variously estimated as high as 1,000 ppmv and as low as 500 ppmv. Population growth and industrialization are processes that, without much argument, can be considered largely beyond the influence of policy intervention. The minimum carbon dioxide accumulation consequent to the play of these factors constitutes a lower bound on what policy intervention can achieve.

Coal is the critical fuel. Depending on how it is combusted, per British Thermal Unit (BTU), coal releases about two or three times as much carbon dioxide as natural gas.[133] Large future releases of carbon dioxide can result only from coal and oil shale consumption. An ambitious coal exploitation policy at rates of increase in combustion analogous to those of oil this last 100 years (4.5 percent per year) would, even in absence of carbon emission from any other source, double the amount of carbon dioxide presently in the atmosphere by about 2060.

Future Levels of Carbon Dioxide

An exact accounting of the total increase in the atmospheric level of carbon dioxide that is likely over the next 100 years, assuming that something can be said about trends in emissions, depends on the particular response of the oceans. The oceans constitute the principal sink for emitted carbon dioxide that does not remain in the atmosphere. Most carbon dioxide is taken up by the oceans chemically as a result of a set of reactions with carbonate ion. Carbon dioxide is absorbed into the oceans as a result of changes in the partial pressure, or concentration, of atmospheric carbon dioxide. Like any large body of water, the oceans tend toward equilibrium with atmospheric carbon dioxide. As the atmospheric concentration of carbon dioxide increases, the partial pressures of carbon dioxide in the ocean and atmosphere diverge, and carbon moves to the oceans, where it is dissolved. Once dissolved, carbon dioxide and sea water react to form carbonic acid, which then reacts with the most basic form of carbon dioxide in the ocean, carbonate ion, to form bicarbonate ion, which is incorporated into the shells of calcareous animals and removed downward to the deep oceans.

By itself, the first of these two processes can remove little excess carbon dioxide from the atmosphere. The amount of dissolved oceanic carbon dioxide in direct exchange with the atmosphere is small: less than 0.6 percent of the inorganic carbon of the surface layer. To be effective, dissolved carbon dioxide must be continuously removed from the surface layer. The availability of carbonate ion controls the rate at which dissolved carbon dioxide is removed from the surface layer. But, although the presence of carbonate ion makes it possible for the ocean's surface layer to absorb roughly eight times the carbon it would otherwise absorb, carbonate ion is sufficiently scarce to facilitate the removal of only a part of the carbon dioxide added to the atmosphere annually. Only 30 to 40 percent of this annual increment is removed to the oceans each year.*

In the future, this rate of uptake must decline.[136] Carbonate ion is consumed in the reactions leading to the formation of bicarbonate. Once consumed, carbonate ion is removed from the surface layer for decades. As the atmospheric level of carbon dioxide increases, and as bicarbonate increases in the surface layer, the reservoir of carbonate ions declines, and with it the rate of oceanic uptake of carbon dioxide. Based on the ocean models, it is suggested that by 2070 carbonate depletion will depress the amount of annually emitted carbon that is withdrawn into the oceans by perhaps 7 to 15 percent.[137]

Ocean circulation is driven by wintertime formation of cold, dense waters in the high latitudes, and its intensity may decline as the area of cold, high salinity water contracts. Parcels of water moving between the deep oceans and the surface layer bear carbonate ions, the product of calcium carbonate dissolution at depths below 5 km. It has been suggested that water in the high latitudes will warm and, being less dense, will increasingly work against the sinking action that presently sets this circulation into motion. Of particular concern is the recession of seasonal sea ice cover, which is the effective driving force for the formation of deep ocean waters.

This change may affect the rate of oceanic absorption of emitted carbon dioxide. Although this climatic effect is not well understood, the change will certainly be in the direction of decreased absorption. The consequences are suggested to be on the same order as the effects of the depletion of carbonate ion (e.g., a 5 to 9 percent decline in oceanic absorption).[138]

In Table 11, estimated future atmospheric levels of carbon dioxide are presented for different rates of increase in emissions. Given about a doubling of the present atmospheric concentration, an equilibrium level will, after hundreds of years, be established at about 450 ppmv.[139]

*This is the upper limit of the amount of carbon that the current ocean models can accommodate.[134] Given different estimates of the total emission of carbon to the atmosphere (5 to 7.5 GT per year) and of the observed annual increase (3.5 GT) in the atmosphere, up to 60 percent of emitted carbon might need to be taken up by the oceans. The missing sink (0 to 20 percent) is usually assumed to go back into the biosphere through increased biospheric growth stimulated by increased ambient carbon dioxide levels. Such enhanced growth is uncertain.[135] It is possible that presently unknown ocean processes or substantial errors in the calculation of the amount of emitted carbon dioxide can account for this residual.

Table 11
ATMOSPHERIC CARBON DIOXIDE CONCENTRATIONS FOR DIFFERENT RATES OF INCREASE OF EMISSIONS, 2030 and 2070

Rates of Increase in Emissions (in percent per year)	Atmospheric Carbon Dioxide Level (in ppmv)	
	2030	2070
2.5	425-484	664-872
2.0	415-467	587-745
1.5	408-454	527-648
1.0	401-441	480-575

Note: assuming a range of oceanic uptake of 30 to 60 percent.

Methane, Tropospheric Ozone, and Carbon Monoxide

The anthropogenic sources of the other greenhouse gases are not as well understood. These gases result from two sources: direct release into the atmosphere and the photochemical production of these gases in the atmosphere as a result of the release to and interaction in the atmosphere of other photochemically active gases. In terms of sheer numbers, most of the other gases are released directly from the surface. The chemistry of the others is complex.

A case in point is methane. Methane is directly released into the atmosphere upon the anaerobic decomposition of organic matter in waterlogged soils, swamps, landfills, marshes, and freshwater and marine sediments, and upon biomass burning and activities relating to the transport of natural gas and the mining of coal.[140] Once released to the atmosphere, it acts like carbon dioxide to warm the planet. After a five- to ten-year residence in the atmosphere, it is oxidized to carbon monoxide. The oxidation process, however, results in various chemical by-products that are important to the chemistry of the troposphere. Tropospheric ozone is formed photochemically as a result of the oxidation of methane.[141] So is carbon monoxide, which, although not radiatively active, is, like methane, quite photochemically active. Once present in the atmosphere, carbon monoxide interacts with the hydroxyl radical (OH) in the presence of nitric oxide (NO_x) to photochemically produce ozone in situ in the troposphere.[142]

The chain of reactions leading to the formation of ozone in the troposphere from the oxidation of methane is complex. Even more complex is the relationship of methane to carbon monoxide. Methane is oxidized to carbon monoxide through a set of reactions involving OH.[143] Its rather long lifetime in the atmosphere results from the limited pool of OH available for the process. If the pool were a good deal larger, the lifetime of methane might be half its present value. Conversely, were the pool much smaller, the lifetime of methane would be longer and, given a constant source at the surface, the atmospheric concentration of methane would increase. Carbon monoxide emissions tend to make this pool smaller. Like methane, carbon monoxide is highly reactive with OH. Once present in the atmosphere, it is oxidized to carbon dioxide through a set of reactions similar to those that reduce methane to carbon monoxide. Increasing emissions of carbon monoxide tend, therefore, to shrink the pool of OH available for the removal of methane and to result in its increase in the atmosphere.[144]

Only about one-third of carbon monoxide emissions result from the oxidation of methane.[145] Surface emissions resulting from combustion processes and biomass burning account for the majority of carbon monoxide emissions. Roughly, a doubling of carbon monoxide emissions from fossil fuel combustion would result in a 25 percent increase in the level of methane in the atmosphere; a four-fold increase in carbon monoxide emissions would result in a 75 percent increase.[146]

In addition to methane, other greenhouse gases also are removed from the atmosphere through reaction with OH. Some of these include: methyl chloroform, methylene chloride, and methyl chloride.[147] Were surface methane or carbon monoxide emissions to significantly increase, the abundance of these might increase in the atmosphere. Ozone is removed from the troposphere through reactions with OH. So, in addition to affecting tropospheric ozone's photochemical rate of production, rising surface emissions of carbon monoxide or methane would also slow its rate of removal, leading to an increasing tropospheric level of ozone. Given the size of the OH pool, a four-fold increase in emissions of carbon monoxide, nitric oxide, and methane from fossil fuel combustion would result in about a 50 percent increase in tropospheric ozone abundances.[148]

Rates of increase of tropospheric ozone abundances, as well as the abundances of methane and other gases, are dependent on the rate of surface release of carbon monoxide, nitric oxide, and methane.

Carbon Monoxide: Carbon monoxide is produced through incomplete combustion of organic matter or through the oxidation of methane. The primary biogenic sources of carbon monoxide appear to be the oceans, forest fires, photochemical oxidation of terpenes and isoprenes from plant sources, open burning of agricultural wastes, biomass burning, and the oxidation of methane.[149] Observations of the atmospheric distribution of carbon monoxide suggest an annual production of about 2.3 GT per year from these sources, and that oxidation of methane produces perhaps 30 percent of this.[150] About 0.5 GT of carbon monoxide may be produced annually through the incomplete combustion of fossil fuel. As a whole, emissions from combustion activities (20 percent), wood burning (2 percent), and land clearing (21 percent) account for about 40 percent of all carbon monoxide surface emissions. About half of all surface methane emissions are controlled by human activities. Thus about half of carbon monoxide emissions are anthropogenic in origin.

Of the combustion-related source, about one-half is associated with incomplete combustion in internal combustion engines.[151] Other industrial processes account for about one-third of the total. The remainder results from incomplete combustion in central station generating facilities (14 percent) and waste disposal (4 percent).

The background carbon monoxide level is about 0.11 ppmv. It appears to be increasing about 1 percent per year.[152] Assuming that surface emissions of carbon monoxide have been increasing since industrialization, OH concentrations should have declined and tropospheric ozone levels increased from 1880 to 1985. Assuming a 50 percent increase in carbon monoxide emissions, OH should have decreased by about 12 percent.[153] A 10 to 50 percent increase in tropospheric ozone has been suggested.[154] The tropospheric concentration of ozone appears to be increasing about 1 percent per year. It is roughly 20 percent higher in the northern hemisphere than in the southern, consistent with larger northern hemispheric carbon monoxide emissions sources.[155] OH levels might be 20 percent lower.[156] A doubling of the tropospheric concentration of ozone is possible.[157]

<u>Nitric Oxide</u>: The rate of ozone and methane accumulation in the atmosphere is dependent on emissions of nitric oxide. Nitric oxide acts to catalyze the reactions leading to the in situ production of ozone.[158] Increasing nitric oxide emissions also increase OH in the atmosphere and reduce methane abundances.* Fossil fuel combustion and biomass burning constitute the main anthropogenic sources of nitric oxide.

<u>Methane</u>: About 80 to 85 percent of all atmospheric methane is of biogenic origin, whereas only about 15 to 20 percent is released during the production or combustion of fossil fuel.[160] About 50 to 80 percent of the surface sources of methane are controlled by human activities. Cattle account for about one-sixth to one-third of the emissions. With biomass burning, rice paddies account for about 25 to 40 percent of emissions.[161] Thus, rice paddy agriculture, biomass burning, and enteric fermentation account for 40 to 70 percent of terrestrial methane production. These sources scale with population increase. Since 1940, the area employed in the cultivation of rice increased about 80 percent, about 1.6 percent per year.[162] About 90 percent of emitted methane is oxidized to carbon monoxide. The remainder is transported to the stratosphere.

Present calculations suggest that roughly 30 percent of the observed increase has resulted from surface emissions of carbon monoxide and 70 percent from agricultural activities.[163] Assuming that this will continue to be true, methane concentrations will continue to increase due to an expanding global population--about 25 percent by 2000.

The surface methane release is temperature dependent. Anaerobic respiration increases with increasing temperature. This rate controls the rate of methane production from the decay of plant organic matter. With warmer temperatures, it should rise.[164]** Upon a warming, methane will also be

*For a four-fold increase in nitric oxide emissions, methane abundances decline 15 to 20 percent. But ozone abundances increase by about 25 percent and, since tropospheric ozone is a more efficient infrared absorber than methane, the net effect is toward a warming.[159]
**The resulting emission would partially offset the effects of higher temperatures on OH abundances. OH increases in concentration with temperature. Increased OH abundances would shorten the residence time of methane in the atmosphere and would reduce methane levels, but the temperature effect should still be positive, yielding a net increase in methane of about 1 ppmv, or an amount equal to about two-thirds of the present level.

released from coastal sediments. The amount of the release is thought to be large. The release could increase the present atmospheric level of methane by perhaps 66 to 133 percent.[165] These releases, in conjunction with a continuation of the present rate of increase in surface emissions, imply something like a tripling of the present level of methane in the next century.

Chlorocarbons, Fluorocarbons and Chlorofluorocarbons

Compared to methane and ozone, the cycles of many of the chlorocarbons, fluorocarbons and CFCs are much less involved. Most are released through industrial activities. Once released to the atmosphere, some of these gases are removed from the troposphere through photochemical interactions with OH; these include methylene chloride, methyl chloroform, methyl chloride, CFC-22, and a few others. Others are transported to the stratosphere, where, after many decades, or in some cases millenia, they are destroyed through photolysis.[166]* During transport to the high stratosphere, the chlorofluorocarbons warm the top of the troposphere, or tropopause. It has been suggested that this would increase the amount of water vapor in the stratosphere, which is exceedingly dry, and further enhance the greenhouse effect.[169] Methane is thought to act similarly.[170]

CFC-11 and CFC-12 are used predominantly in spray cans (60 percent) and refrigeration (5 percent). They are also used as foam-blowing agents (35 percent) and as solvents.[171] Other CFCs (22, 502, and 114) have been developed as substitutes for CFC-11 and CFC-12. Carbon tetrachloride is released in the production of the CFCs. Carbon tetrafluoride and CFC-116 are released during aluminum refining. Methylene chloride and methyl chloroform are used as solvents.[172] Spray can uses of the chlorofluorocarbons were banned in the 1970s in the United States, Canada and Sweden.

Although together they may be important, with the exception of CFC-11 and CFC-12, the climatic effect of each individual gas will be quite small, typically 0.1 degrees Celsius or less.[173] Hence, it will be difficult to control the releases of most of them.

Nitrous Oxide

Nitrous oxide is released from animal and human wastes, inland bodies of water, and directly from the soil by denitrifying bacteria. It is also directly released into the atmosphere as a result of fossil fuel combustion.[174] A large amount of nitrogen is annually fixed in agricultural soils as nitrites. But the rate at which nitrous oxide is released from soils subsequent to anthropogenic fixation is uncertain; some suggest a 50 percent

*Free chlorine released through photolysis of the CFCs interacts photochemically with stratospheric ozone, depleting it. A global cooling or a global warming of 0.1 to 0.2 degrees Celsius could result from a 20 to 30 percent stratospheric ozone reduction.[167] The residence times for CFC-11 and CFC-12 are 65 and 120 years, respectively,[168] and so this depletion would not be realized for 50 to 100 years.

release within ten years[175] and others suggest that full denitrification will occur only over hundreds of years.[176] Studies suggest that about 2 percent of nitrogen is released from the soils one year after application. With a much delayed release, nitrous oxide levels would double only after many hundreds of years.

At present, the data on the historic build-up of nitrous oxide in the atmosphere are consistent with either a pure fossil fuel source increasing 4 percent per year or a pure fertilizer source increasing 6 percent per year. Based on those rates of increase, by 2025 the atmospheric concentration of nitrous oxide should increase by 16 to 32 percent to 353 to 403 ppbv.[177] The primary sink for nitrous oxide appears to be photodissociation and chemical interaction with molecular oxygen in the stratosphere. The residence time for nitrous oxide is estimated to be about 120 years.

It has been suggested that nitrous oxide releases may increase with a warming.[178] Little work has been directed to this issue.

The Other Gas Effect

Table 12 shows a typical estimate for the projected changes in the atmospheric levels of the other greenhouse gases. Annual rates of increase in concentrations range from a few tenths of a percent to 3 percent. Estimates from other sources are roughly comparable.[179] Despite uncertainties in the photochemical models, and in future technological and economic trends, there is general agreement that rates of increase like these (though not necessarily these specific rates) will prevail. The estimates given in Table 12 would result by 2030 in a warming of 1.8 to 2.2 degrees Celsius.

Table 12
CHANGES IN CONCENTRATIONS OF GREENHOUSE GASES, 1980-2030

Chemical Compound	Percent Increase	Rate of Increase (%/year)
CO_2	30	0.6
CH_4	50-80	0.8-1.2
N_2O	15-50	0.3-0.8
CFC-11	170-450	2-3.4
CFC-12	115-330	1.5-2.9
CO	10-120	0.2-1.6
NO, NO_2	0-100	0-1.4
O_3, tropospheric	45-50	0.7-0.8

Source: G. MacDonald, *Climate Change and Acid Rain*, MP86W00010 (McLean, Vir.: The Mitre Corporation, 1986).

Policy Responses

The greenhouse problem is essentially an energy and environmental policy problem requiring that society either make alterations in energy and industrial policies to limit the impending warming or adapt to it.

Of the other gases, it is probably possible to limit somewhat the tropospheric build-up of ozone through emissions controls on carbon monoxide and nitric oxide released from the energy sector. Controls can also be imposed on releases of CFC-11 and CFC-12. The degree of control that might be realized is probably on the order of 0.5 to 2 degrees Celsius.[180]

A gradual transition to a non-carbon energy system appears to be the only feasible means by which to limit the atmospheric buildup of carbon dioxide. A transition to a new energy source implies few large economic costs as long as it is conducted over a sufficiently long period and change in the use of fuels and the construction of facilities fits the typical turnover time of capital. Some non-carbon replacement fuels already are cost competitive or nearly cost competitive with fossil sources. This is also true in the case of energy conservation resulting from improvements in energy efficiency.[181] It might also be feasible to replace the energy produced through the combustion of fossil fuels through an expansion of the existing civilian nuclear energy programs.

The transition from one dominant energy system to another probably requires about fifty to seventy-five years.[182] This results from the very long lifetimes of many fossil fuel facilities and from constraints arising from the material and economic requirements of large-scale, rapid expansion of non-fossil energy supplies. As a result, it will probably be difficult to limit atmospheric levels of carbon dioxide to less than 500 ppmv, or 1.85 times the preindustrial level, even in the event that a long-term transition to a non-fossil energy system was to be initiated immediately.[183]

An increase in the atmospheric level of carbon dioxide to 500 ppmv would result in an average global warming of 2 to 3.5 degrees Celsius. Assuming a fifty to seventy-five year market penetration time for new energy sources, we can calculate the effect of delays in the implementation of policies designed to effect a transition to a non-fossil energy system. A 2 to 5 degrees Celsius warming would result were action to be delayed to the year 2020, and a 2.5 to 6 degrees Celsus warming would result from a delay of fifty years.[184] To this one would have to add the effect of the other greenhouse gases.

The potential for preventive action through reforestation, or through the removal of carbon dioxide from power plant stacks and deposition in the oceans, is limited. Reforestation on a scale that might result in a significant withdrawal of carbon from the atmosphere (and incorporation in the biosphere) would involve enormous expanses of land.* The future demand for land to grow food to feed a growing global population renders such a response infeasible.[185] Stack removal of carbon dioxide and its subsequent sequestration in the deep ocean, although theoretically possible, is limited by cost considerations, the effects of scrubbing on the efficiency of electricity production, and the limited pool of emissions that might be controlled through stack scrubbing.[186] Only about 25 percent of all global carbon dioxide emissions are emitted from power plant stacks and therefore are subject to control. These considerations render such a response infeasible over the long-term.

A number of adaptive postures are also evident. Enhanced irrigation capacity would be an important adaptive mechanism for U.S. agriculture. Water management would be important. Efforts to reduce the present rates of ground water depletion, soil erosion, and desertification would help conserve valuable resources for future use.

Other frequently cited adaptive mechanisms include: the development of more drought- and heat-resistant cultivars and more effective pesticides; changes in the inland water transport system to accommodate streamflow reductions; improved coastal planning; continued improvements in the efficiency of cooling devices to offset increased summer peak electrical demand; and the diversification of national economic activity in situations where present activities are found to be climate sensitive. In addition, one might consider: improved mechanisms of drought assistance; an enlarged global food reserve; and international mechanisms through which to equally allocate the burden and benefits of a warming.

Some potential adaptive mechanisms could be delayed until impacts are actually experienced. However, a number of adaptive mechanisms require a substantial lead time for planning and construction. This is true for any

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*For instance, to remove about 125 ppmv of carbon dioxide from the atmosphere, it would be necessary to reforest a land area the size of the remaining forested area in the tropics.

system of large-scale inter-basin water transfer. The initial steps toward such systems would have to be taken fairly soon if they are to be of timely use. Any technological interventions that have lengthly lead times would be constrainted.

No rigorous analysis of the adaptive response has yet been conducted. With a few exceptions,[187] its nature and preconditions have not been investigated, nor has its feasibility undergone close scrutiny. Typically, it is assumed that, due to constraints on the ability of society to limit fossil fuel use, the preventive response is unworkable and that society's only recourse is to an adaptive posture. This is premature. Due to the lack of rigorous attention paid to the adaptive response, it is possible that the reasoning could run in the opposite direction: that, due to physical constraints on the ability of society to adapt to a global warming, a much slower rate of warming than is projected is a prerequisite of any attempt by society to adapt to a changing climate. To slow the rate, a preventive response would be needed.

In absence of a rigorous analysis of the adaptive response, it will not be possible to say which of the two principal responses open to society--prevention or adaptation--is the more desirable. This requires that more attention be paid to the adaptive response than has heretofore been the case. In absence of a renewed commitment of society to its preservationist values, its decisions depend on this analysis.

CONCLUSION

As a result of the combustion of fossil fuels, carbon dioxide is being released to the atmosphere. Other gases like nitrous oxide, methane, and the chlorofluorocarbons are being released as a result of changes in land use and industrial practices. At projected rates of expansion in the activities leading to the release of the greenhouse gases, by 2070, mean global surface temperature will rise 4 to 5 degrees Celsius. A wide variety of impacts, many of them negative, can be expected.

Climate has undegone changes in the past. However, most past changes have been slow and gradual, and have allowed natural and human systems to adapt. The projected changes will be unprecedented in their rapidity.

There are no technical fixes, no easy answers to the greenhouse-climate change problem. Any serious effort to limit emissions would entail a thoroughgoing transformation of the global economy.

The effects of climate change will be most pronounced on unmanaged natural systems. Entire plant and animal species will be lost as the climate changes. It is our responsibility, having set into motion the processes leading to climate change, to limit these losses to the absolute minimum.

NOTES

1. S. Schneider and W. Kellogg, "The Chemical Basis for Climate Change," in *Chemistry of the Lower Atmosphere*, S. Rasool, ed., (New York: Plenum Press, 1973).

2. F. Luther, and R. Ellingson, "Carbon Dioxide and the Radiation Budget," in *Projecting the Climatic Effects of Increasing Carbon Dioxide*, M. MacCracken and F. Luther, eds., DOE/ER-0237 (Washington, D.C.: U.S. Department of Energy, 1985).

3. J. Hansen et al., "Climate Sensitivity to Increasing Greenhouse Gases," in *The Greenhouse Effect and Sea Level Rise: A Challenge for This Generation*, M. Barth and J. Titus, eds. (New York: Van Nostrand, 1984.)

4. R. Dickinson, "Modeling Climate Changes Due to Carbon Dioxide Increases," in *Carbon Dioxide Review: 1982*, W. Clark, ed., (New York: Oxford University Press, 1982).

5. H. Lamb, "The Role of Atmosphere and Oceans in Relation to Climatic Changes and the Growth of Ice-Sheets on Land," in *Problems in Paleoclimatology*, A. Nairn, ed. (London: Interscience Publishers, 1963); S. Manabe and D. Hahn, "Simulation of the Tropical Climate of an Ice Age," *Journal of Geophysical Research* 82 (1977): 3,889. For another ice age simulation see S. Manabe and A. Broccoli, "The Influence of Continental Ice Sheets on the Climate of an Ice Age," *Journal of Geophysical Research* 90 (1985): 2,167.

6. E. Barron and W. Washington, "The Role of Geographical Variables in Explaining Paleoclimates: Results From Cretaceous Climate Model Sensitivity Studies," *Journal of Geophysical Research* 89 (1984): 1,267; and W. Sellers, "A Global Climatic Model Based on the Energy Balance of the Earth-Atmosphere System," *Journal of Applied Meteorology* 8 (1969): 392.

7. J. Hays, J. Imbrie, and N. Shackleton, "Variations in the Earth's Orbit: Pacemaker of the Ice Ages," *Science* 194 (1976): 1,121.

8. J. Eddy, R. Gilliland, and D. Hoyt, "Changes in the Solar Constant and Climatic Effects," *Nature* 300 (1982): 689.

9. W. Broecker, "Climatic Change: Are We on the Brink of a Pronounced Global Warming?", *Science* 188 (1975): 460.

10. E. Dorf, "Climatic Changes of the Past and Present," *American Scientist* 48 (1960): 341; and J.C. Bernabo and T. Webb III, "Changing Patterns in the Holocene Pollen Record of Northeastern North America: A Mapped Summary," *Quaternary Research* 8 (1977): 64; see particularly the spruce and hemlock declines. See also the corn belt movement with temperature in J. Newman, "Climate Change Impacts on the Growing Season of the North American Corn Belt," *International Journal of Biometeorology* 7 (1980): 128. For the change in the positioning of middle latitude forests between the late Eocene and early Miocene (a cooling of 4 to 8 degrees

Celsius), see J. Olson, "Cenozoic Fluctuations in Biotic Parts of the Global Carbon Cycle," in *The Carbon Cycle and Atmospheric CO_2*: Natural Variations Archaen to Present, E. Sundquist and W. Broecker, eds. (Washington, D.C.: American Geophysical Union, 1985), and W. Emanuel, H. Shugart, and M. Stevenson, "Climatic Change and the Broad-scale Distribution of Terrestrial Ecosystem Complexes," *Climatic Change* 7 (1985): 29.

11. W. Kellogg, *Effects of Human Activities on Global Climate*, WMO 486 (Geneva: World Meteorological Organization, 1977).

12. R. Gilliland, "Solar, Volcanic, and CO_2 Forcing of Recent Climatic Changes," *Climatic Change* 4 (1982): 111. It is believed that over long periods, the flux of radiation at the top of the atmosphere can vary as much as 0.5 percent. Roughly, an increase of 0.1 percent in this flux would increase mean global surface temperature about 0.1 degrees Celsius. See Eddy, Gilliland, and Hoyt, note 8 above. For the solar influence over the past one-hundred years, see J. Hansen et al., "Climate Impact of Increasing Atmospheric Carbon Dioxide," *Science* 213 (1981): 957.

13. See Hansen et al. in note 12 above.

14. J. Pollack et al., "Volcanic Explosions and Climatic Change: A Theoretical Assessment," *Journal of Geophysical Research* 81 (1976): 1,071.

15. See Gilliland in note 12 above; and J. Hansen et al. in note 12 above; Hansen et al. gives an estimate of about 0.1 degree Celsius. Also, see B. Taylor et al., "Volcanic Eruptions and Long-Term Temperature Records: An Empirical Search For Cause and Effect," *Quarterly Journal of the Royal Meteorological Society* 106 (1980): 175; C.-D. Schonwiese, "Climatic Variability Within the Modern Instrumentally-based Period," in *Carbon Dioxide: Current Views and Developments in Energy/Climate Research*, W. Bach et al., eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1983); and A. Robock, "The 'Little Ice Age': Northern Hemisphere Average Observations and Model Calculations," *Science* 206 (1979): 1,402; the estimate of 0.5 degrees Celsius for the volcanic influence excludes the climatic influence of the Tambora explosion, which was unprecedented in recent millennia in the amount of aerosol matter introduced into the atmosphere, and in climatic influence.

16. W. Kellogg, "Aerosols and Climate," in *Interactions of Energy and Climate*, W. Bach, J. Pankrath and J. Williams, eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1980).

17. For instance, see S. Seidel and D. Keyes, *Can We Delay a Greenhouse Warming?* (Washington, D.C.: U.S. Environmental Protection Agency, 1983).

18. See note 2 above.

19. T. Augustsson and V. Ramanathan, "A Radiative-Convective Model Study of the CO_2-Climate Problem," *Journal of the Atmospheric Sciences* 34 (1977): 448.

20. Ibid.

21. Ibid.

22. V. Ramanathan et al., "Trace Gas Trends and Their Potential Role in Climate Change," *Journal of Geophysical Research* 90 (1985): 5,547.

23. For instance, see the list of possible infrared active gases not yet accounted for in the other gas sensitivity calculation in Ramanathan et al., note 22 above; J. Chamberlain et al., "Climate Effects of Minor Atmospheric Constituents," in Clark, note 4 above; World Meteorological Organization Global Ozone Research and Monitoring Program, *Report of the Meeting of Experts on Potential Climatic Effects of Ozone and Other Minor Trace Gases*, report 14 (Geneva: World Meteorological Organization, 1982); and in R. Dickinson and R. Cicerone, "The Future Global Warming from Atmospheric Trace Gases," *Nature* 319 (1986): 109. Some of these include: CFC-13, CFC-21, CFC-113, CFC-114, CFC-115, CFC 116, CFC-123, CFC-134a, CFC-132b, CFC-142b, Halon-1301, Halon-1211, acetylene, ethylene, ethane, propane, pentane, benzene, peroxyacetyl nitrate, hydrogen cyanide, dinitrogen pentoxide, nitrogen dioxide, nitric oxide, ammonia, nitric acid, methyl bromide, methyl fluoride, methyl iodide, sulfur dioxide, carbonyl sulfide, carbon disulfide, sulfur hexafluoride, formaldehyde, methanol, cynagen, formic acid, methyl pentanes, and hydrogen chloride. If each of these gases, and others not listed, were in the future to contribute as little as 0.02 degrees Celsius to the warming, the total could amount to as much as 0.5 degrees Celsius.

24. J. Hansen et al., "Climate Sensitivity: Analysis of Feedback Mechanisms," in *Climate Processes and Climate Sensitivity*, J. Hansen and T. Takahashi, eds. (Washington, D.C.: American Geophysical Union, 1984).

25. S. Manabe and R. Wetherald, "On the Distribution of Climate Change Resulting from an Increase in CO_2 Content of the Atmosphere," *Journal of the Atmospheric Sciences* 37 (1980): 99.

26. W.-C. Wang and P. Stone, "Effect of Ice-Albedo Feedback on Global Sensitivity in a One-Dimensional Radiative-Convective Climate Model," *Journal of the Atmospheric Sciences* 37 (1980): 545.

27. See note 4 above.

28. S. Manabe and R. Stouffer, "Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration," *Journal of Geophysical Research* 85 (1980): 5,529; J. Mitchell and G. Lupton, "A 4 X CO_2 Integration With Prescribed Changes in Sea Surface Temperatures," *Progress in Biometeorology* 3 (1984): 353; W. Washington and G. Meehl, "Seasonal Cycle Experiment on the Climate Sensitivity Due to a Doubling of CO_2 With an Atmospheric General Circulation Model Coupled to a Simple Mixed-Layer Ocean Model," *Journal of Geophysical Research* 89 (1984): 9,475; R. Wetherald and S. Manabe, "Influence of Seasonal Variability Upon the Sensitivity of a Model Climate," *Journal of Geophysical Research* 86 (1981): 1,194; and S. Manabe and R. Wetherald, "Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide," *Science* 232 (1986): 626.

29. M. Schlesinger and J. Mitchell, "Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide," in MacCracken and Luther, note 2 above.

30. M. Schlesinger, "Analysis of Results from Energy Balance and Radiative-Convection Models," note 2 above, appendix A.

31. R. Reck, "Carbon Dioxide and Climate: Comparison of One-Dimensional and Three-Dimensional Models," in *Environmental and Climatic Impact of Coal Utilization*, J. Singh and A. Deepak, eds. (New York: Academic Press, 1980).

32. See note 29 above. A 50 percent reduction in climate sensitivity is taken from R. Somerville and L. Remer, "Cloud Optical Thickness Feedbacks in the CO_2 Climate Problem," *Journal of Geophysical Research* 89 (1984): 9,668.

33. As an example of this, due to their structure, the models rely upon what are acknowledged to be simplistic and potentially unrealistic descriptions of some climate feedbacks (e.g., water vapor, lapse rate). See Schlesinger, note 30 above.

34. D. Ehhalt, "The Effects of Chlorofluoromethanes on Climate," in Bach, Pankrath, and Williams, note 16 above.

35. R. Weiss, "The Temporal and Spatial Distribution of Tropospheric Nitrous Oxide," *Journal of Geophysical Research* 86 (1981): 7,185.

36. M. Khalil and R. Rasmussen, "Causes of Increasing Atmospheric Methane: Depletion of Hydroxyl Radicals and the Rise of Emissions," *Atmospheric Environment* 19 (1985): 397.

37. S. Hameed and R. Cess, "Impact of a Global Warming on Biospheric Sources of Methane and Its Climatic Consequences," *Tellus* 35 (1983): 1.

38. S. Liu et al., "On the Origin of Tropospheric Ozone," *Journal of Geophysical Research* 85 (1980): 7;546. For present rate of increase, see J. Logan, "Tropospheric Ozone: Seasonal Behavior, Trends, and Anthropogenic Influence," *Journal of Geophysical Research* 90 (1985): 10,463; J. Angell and J. Korshover, "Global Variation in Total Ozone and Layer Mean Ozone: An Update Through 1981," *Journal of Climate and Applied Meteorology* 22 (1983): 1,611; and G. Tiao, et al., "A Statistical Trend Analysis of Ozonesonde Data," *Journal of Geophysical Research* 91 (1986): 13,121.

39. See Chamberlain et al. in note 23 above, and note 22 above.

40. See P. Ciborowski and D. Abrahamson, "The Greenhouse Problem: The Role of Uncertainty," this volume.

41. R. Rotty and C. Masters, "Carbon Dioxide from Fossil Fuel Combustion: Trends, Resources, and Technological Implications," in *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, J. Trabalka, ed., DOE/ER-0239 (Washington, D.C.: U.S. Department of Energy, 1985).

42. R. Houghton et al., "Carbon Dioxide Exchange Between the Atmosphere and Terrestrial Ecosystems," in Trabalka, note 41 above.

43. J. Olson, H. Pfuderer, and Y. Chan, *Changes in the Global Carbon Cycle and the Biosphere*, ORNL/EIS-109 (Oak Ridge, Tenn.: Oak Ridge National Laboratory, 1978).

44. Concentrations about doubled over this period. See R. Rasmussen and M. Khalil, "Atmospheric Methane in the Recent and Ancient Atmospheres: Concentrations, Trends, and Interhemispheric Gradient," *Journal of Geophysical Research* 89 (1984): 11,559; H. Craig and C. Chou, "Methane: The Record in Polar Ice Cores," *Geophysical Research Letters* 9 (1982): 1,221; and G. Pearman et al., "Evidence of Changing Concentrations of Atmospheric CO_2, N_2O and CH_4 From Air Bubbles in Antarctic Ice," *Nature* 320 (1986): 248.

45. See Rasmussen and Khalil in note 44 above; and Craig and Chou in note 44 above.

46. See Liu et al. in note 38 above.

47. Chamberlain et al. in note 23 above.

48. A. Miller and I. Mintzer, *The Sky is the Limit: Strategies for Protecting the Ozone Layer*, research report 3 (Washington, D.C.: World Resources Institute, 1986).

49. D. Blake and F. Rowland, "World-wide Increase in Tropospheric Methane," *Journal of Atmospheric Chemistry* 4 (1986): 43. For a long-term 1.7 percent per year increase, see B. Stauffer et al., "Increase of Atmospheric Methane Recorded in Antarctic Ice Core," *Science* 229 (1985): 1,386. For a 1 percent per year increase from 1950 to 1980, and an average 0.5 percent per year increase from 1900 to 1980, see Craig and Chou in note 44 above, p. 477. For an increase that fits to an average 0.7 percent per year increase from 1900 to 1980, see Pearman et al. in note 44 above.

50. See note 35 above.

51. P. Jones, T. Wigley, and P. Kelly, "Variations in Surface Air Temperatures: Part 1. Northern Hemisphere, 1881-1980," *Monthly Weather Review* 110 (1982): 59.

52. J. Oerlemans, "Glaciers as Indicators of a Carbon Dioxide Warming," *Nature* 320 (1986): 607.

53. T. Barnett, "The Estimation of 'Global' Sea Level Change: A Problem of Uniqueness," *Journal of Geophysical Research* 89 (1984): 7,980.

54. T. Karl, G. Kukla, and J. Gavin, "Decreasing Diurnial Temperature Range in the United States and Canada from 1941 Through 1980," *Journal of Climate and Applied Meteorology* 23 (1984): 1,489.

55. A. Lachenbruch and B.V. Marshall, "Changing Climate: Geothermal Evidence from Permafrost in the Alaskan Arctic," *Science* 234 (1986): 689.

56. G. Oehlert, "Trends in Atmospheric Temperature Profiles," *Journal of Geophysical Research* 91 (1986): 11,845; and K. Labitzke et al., "Long-Term Temperature Trends in the Stratosphere: Possible Influence of Anthropogenic Gases," *Geophysical Research Letters* 13 (1986): 52.

57. See Carbon Dioxide Assessment Committee, National Research Council, *Changing Climate* (Washington, D.C.: National Academy Press, 1983). For the detection of a marginally significant signal, see T. Barnett, "Detection of Changes in the Global Troposphere Temperature Field Induced by Greenhouse Gases," *Journal of Geophysical Research* 91 (1986): 6,659.

58. See note 24 above.

59. W. Kellogg and R. Bojkov, eds., *Report of the JSC/CAS Meeting of Experts on Detection of Possible Climate Change* (Geneva: World Meteorological Organization, 1982).

60. S. Manabe, "Carbon Dioxide and Climatic Change," in *Advances in Geophysics*, vol. 25, *Theory of Climate*, B. Saltzman, ed. (New York: Academic Press, 1983).

61. P. Kelly et al., "Variations in Surface Air Temperatures: Part 2: Arctic Regions, 1881-1980," *Monthly Weather Review* 110 (1982): 71.

62. Disproportionate polar warming also has been noted in the temperature records of two warmer epochs, the Altithermal and the early medieval. Average sub-Arctic temperatures are known to have been at least 5 degrees Celsius warmer than now about 5,500 years before the present, although the mean global temperature was 1 degree Celsius above the present value. See J. Ritchie and F. K. Hare, "Late-Quaternary Vegetation and Climate Near the Arctic Tree Line of Northwestern North America," *Quaternary Research* 1 (1971): 331. The Arctic front, defined by the southernmost extension of the Arctic air mass, appears to have been displaced at least 350 km northward during the Altithermal. See H. Lamb, *Climate: Present, Past and Future*, vol. 2, (London: Methuen and Co., 1977). For evidence of a generalized latitudinal dependence of temperature in reconstructions of the Eem Interglacial, see B. Frenzel, "The Pleistocene Vegetation of Northern Eurasia," *Science* 161 (1968): 637.

63. World Climate Programme, *An Assessment of the Role of CO_2 on Climate Variations and Their Impact* (Geneva: World Meteorological Organization, 1981); and R. Barry, "The Cryosphere and Climatic Change," in *Detecting the Climatic Effects of Increasing Carbon Dioxide*, M. MacCracken and F. Luther, eds., DOE/ER-0235 (Washington, D.C.: U.S. Department of Energy, 1985).

64. Estimates for a 4.5 degree Celsius mean global warming suggest a melting of mountain glaciers and small Arctic island ice caps equivalent to 26 cm of sea level rise, or about 50 to 100 percent of all the ice in these systems. See M. Meier, "Contribution of Small Glaciers to Global Sea Level," *Science* 226 (1984): 1,418.

65. H. Flohn, *Major Climatic Events Associated With A Prolonged CO_2-Induced Warming* ORAU/IEA-81-8 (M) (Oak Ridge, Tenn.: Oak Ridge Associated Universities, Institute for Energy Analysis, 1981). For the last time the Arctic was ice-free, the late Tertiary, with mean global temperature perhaps 4 degrees Celsius above the present, see N. Shackleton et al., "Oxygen Isotope Calibration of the Onset of Ice-Rafting and History of Glaciation in the North Atlantic Region," *Nature* 307 (1984): 620. For a divergent opinion on an ice-free Arctic, see A. Semtner, "On Modelling the Seasonal Thermodynamic Cycle of Sea Ice in Studies of Climatic Change," *Climatic Change* 6 (1984): 27.

66. See Shackleton et al. in note 65 above.

67. C. Parkinson and W. Kellogg, "Arctic Sea Ice Decay Simulated for a CO_2-Induced Temperature Rise," *Climatic Change* 2 (1980): 149.

68. See Barry in note 63 above.

69. H. Lamb, *Climate: Present, Past and Future*, vol 1. (London: Methuen and Co., 1972).

70. C. Bentley, "The West Antarctic Ice Sheet: Diagnosis and Prognosis," in *Carbon Dioxide, Science and Consensus*, CONF-820970 (Washington, D.C.: U.S. Department of Energy, 1983).

71. J. Hollin and R. Barry, "Empirical and Theoretical Evidence Concerning the Response of the Earth's Ice and Snow Cover to a Global Temperature Increase," *Environment International* 2 (1979): 437.

72. For a similar estimate, see J. Hoffmann, D. Keyes, and J. Titus, *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs*, EPA 230-09-007 (Washington, D.C.: U.S. Environmental Protection Agency, 1983); also R. Thomas, "Future Sea Level Rise and Its Early Detection by Satellite Remote Sensing," in *Effects of Changes in Stratospheric Ozone and Global Climate*, vol. 4, *Sea Level Rise*, J. Titus, ed. (Washington, D.C.: U.S. Environmental Protection Agency, 1986).

73. See note 71 above.

74. See note 24 above; Manabe and Stouffer in note 28 above; and Manabe and Wetherald in note 28 above.

75. See, for instance, S. Manabe, R. Wetherald, and R. Stouffer, "Summer Dryness Due to an Increase of Atmospheric Carbon Dioxide Concentration," *Climatic Change* 3 (1981): 347.

76. For instance, see the seasonal response in the European sector in C. Wilson and J. Mitchell, "Simulated Climate and CO_2-Induced Climate Change Over Western Europe," *Climatic Change* 10 (1987): 11; and D. Rind and S. Lebedeff, *Potential Climatic Impacts of Increasing Atmospheric CO_2 with Emphasis on Water Availability and Hydrology in the United States*, EPA 230-04-84-006 (Washington, D.C.: U.S. Environmental Protection Agency, 1984).

77. See Geophysical Fluid Dynamics Laboratory (GDFL) 1986, Goddard Institute for Space Studies (GISS) 1984, and National Center for Atmospheric Research (NCAR) 1984 latitude distribution of soil moisture change in Schlesinger and Mitchell in note 29 above; and see Mitchell and Lupton in note 28 above.

78. H. Flohn, "Climate Change and an Ice-Free Arctic Ocean," in Clark, note 4 above.

79. Ibid.

80. See note 75 above.

81. W. Kellogg, "Precipitation Trends on a Warmer Earth," *Interpretation of Climate and Photochemical Models, Ozone and Temperature Measurements*, R. Reck and J. Hummel, eds. (New York: American Institute of Physics, 1982).

82. For the former and the latter cases, respectively, see NCAR 1984, and GDFL (and GISS) latitudinally averaged soil moisture simulations in Schlesinger and Mitchell, note 29 above.

83. D. Rind, "The Dynamics of Warm and Cold Climates," *Journal of the Atmospheric Sciences* 43 (1986): 3; and S. Manabe and K. Bryan Jr., "CO_2-Induced Change in a Coupled Ocean-Atmosphere Model and Its Paleoclimatic Implications," *Journal of Geophysical Research* 90 (1985): 11,689.

84. See World Climate Programme in note 63 above. This region appears to have been displaced several hundred km northward during the Altithermal and the previous interglacial during which mean global temperature was about 1 degree Celsius warmer than now. See Lamb in note 62 above.

85. See note 10 above. The tree line advanced about 300 km into Keewatin during the Altithermal, and in Siberia was located on the Arctic shore. See Frenzel in note 62 above. Based on the slight warming from 900 to 1200 A.D., the tree line response appears to be about 100 km per degree Celsius warming. See C. Sorenson et al., "Paleosols and the Forest Border in Keewatin, N.W.T.," *Quaternary Research* 1 (1971): 468.

86. P. Moore, "Tree Boundaries on the Move," *Nature* 326 (1987): 545.

87. R. Peters and J. Darling, "The Greenhouse Effect and Nature Reserves," *Bioscience* 35 (1985): 707.

88. Ibid.

89. Present average annual temperatures at El Paso, Kansas City and Minneapolis, respectively, are 63, 54, and 44 degrees Fahrenheit. A 4 degree Celsius mean global warming would result in average annual increases in the United States of about 4 to 6 degrees Celsius or 7 to 11 degrees Fahrenheit.

90. See Manabe and Stouffer in note 28 above.

91. R. Bryson and W. Wendland, "Tentative Climatic Patterns for Some Late Glacial and Post-glacial Episodes in Central North America," in *Life, Land and Water*, J. Mayer-Oakes, ed. (Winnipeg: University of Manitoba, 1967).

92. See Rind and Lebedeff in note 76 above. Year to year, precipitation statistics are fairly noisy, but they do, nonetheless, tend to settle down into patterns around some central tendency. As the climate changes, it will affect not only the central tendency, but also the distribution of values around the central tendency. Lower the central tendency and you lower the value for the average minimum and increase the frequency of drought.

93. W. Langbein, et al., *Annual Run-off in the United States*, U.S. Geological Survey circular 52 (Washington, D.C.: U.S. Department of the Interior, 1949). For possible mitigating effects, see T. Wigley and P. Jones, "Influences of Precipitation Changes and Direct CO_2 Effects on Streamflow," *Nature* 314 (1985): 149.

94. K. Emanuel, "The Dependence of Hurricane Intensity on Climate," *Nature* 326 (1987): 483.

95. State-wide averaged corn yields decline about 20 percent as one progresses westward from Illinois into the Great Plains, and about 30 to 50 percent as one moves south into Appalachia and the southeastern states. Wheat yields decline about 50 percent from Illinois to Montana. See U.S. Department of Agriculture, *Agricultural Statistics* (Washington, D.C.: U.S. Government Printing Office, 1975-84).

96. The western boundary of the corn belt is defined by the requirement of a minimum of 20 inches of annual rainfall. See R. Neild and N. Richman, "Agroclimates Normal for Maize," *Agricultural Meteorology* 24 (1981): 83. The southern boundary is defined by maximum daily temperatures; the southern states are too warm for optimal cultivation. See R. Neild, "Temperature and Rainfall Influences on the Phenology and Yield of Grain Sorghum and Maize: A Comparison," *Agricultural Meteorology* 27 (1982): 79. Great Plains wheat production is generally limited by moisture conditions at its western boundary and at its southern boundary by high growing season temperatures.

97. For instance, for corn, yields in Columbia, Missouri; Lincoln, Nebraska; and Manhattan, Kansas are about 90, 70, and 75 percent of the corn belt average, respectively. See J. Benci et al., "Effects of Hypothetical Climatic Changes on Production and Yield of Corn," in *Impacts of Climatic Change on the Biosphere*, Climatic Impact Assessment Program, monograph 5 (Washington, D.C.: U.S. Department of Transportation, 1975).

98. For corn, annual average yield variability increases east to west and north to south. For instance, Missouri corn production has an 88 percent probability of yield reductions of 20 percent at least 10 percent of the time; the same value for eastern production (Ohio and Illinois) and more northerly production (Iowa) is 30 and 59 percent, respectively. See F. Huff and J. Neill, "Effects of Natural Climatic Fluctuations on the

Temporal and Spatial Variation in Crop Yields," *Journal of Applied Meteorology* 21 (1982): 540. For wheat, annual yield variability increases in climatically marginal areas. The percentage of acreage not harvested increases from 10 percent in eastern Nebraska and Kansas to 30 and 40 percent, respectively, in western Kansas and eastern Colorado. See P. Michaels, "Price, Weather, and 'Acreage Abandonment' in Western Great Plains Wheat Culture," *Journal of Climate and Applied Meteorology* 22 (1983): 1,296.

99. Annual production of wheat and other small grains declines east to west as soil moisture conditions demand increasing use of fallowing systems.

100. See L. Thompson, "Weather and Technology in the Production of Corn in the U.S. Corn Belt," *Agronomy Journal* 61 (1969): 453; L. Thompson, "Weather and Technology in the Production of Soybeans in the Central United States," *Agronomy Journal* 62 (1970): 232; and L. Thompson, "Weather and Technology in the Production of Wheat in the United States," *Journal of Soil and Water Conservation* 24 (1969): 219. Wheat and other small grains are sensitive to above average temperatures in May and June and to reduced rainfall after seeding.

101. R. Warrick, R. Gifford, with M. Parry, "CO_2, Climatic Change and Agriculture," in *The Greenhouse Effect, Climatic Changes and Ecosystems*, B. Bolin et al., eds. (Chichester, U.K.: John Wiley and Sons, 1986). Other studies suggest that yields would decline on the order of 10 to 20 percent for each 2 degrees Celsius warming. See R. Shaw, "Climate Change and the Future of American Agriculture," in *The Future of American Agriculture as a Strategic Resource*, S. Batie and R. Healy, eds. (Washington, D.C.: Conservation Foundation, 1980); W. Terjung et al., "Yield Responses of Crops to Changes in Environment and Management Practices: Model Sensitivity Analysis. I. Maize," *International Journal of Biometeorology* 28 (1984): 261; the Benci, Thompson, and Leeper models in Benci et al. in note 97 above; and S. Ramirez, C. Sakamoto and R. Jensen, "Wheat," in Climatic Impact Assessment Program in note 97 above (see both the Ramirez, Sakamoto, and Jensen, and the North Dakota State University models).

102. See Shaw in note 101 above; Terjung et al. in note 101 above; the Thompson and Leeper models in Benci et al. in note 97 above; and Ramirez et al. in note 101 above.

103. W. Decker, V. Jones, and R. Achutuni, "The Impact of CO_2-Induced Climate Change on U.S. Agriculture," in *Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health*, M. White, ed., DOE/ER-0236 (Washington, D.C.: U.S. Department of Energy, 1985).

104. W.B. Sundquist, K. Menz, and C. Neumeyer, *A Technology Assessment of Commercial Corn Production in the United States*, Agricultural Experiment Station bulletin 546-1982 (Minneapolis: University of Minnesota, 1982).

105. E. Skidmore, "The Wind Erosion Problem," in *CRS Handbook of Soils, Climate and Agriculture*, V. Kilmer, ed. (Boca Raton, Fla.: CRS Press, 1982).

106. D. Pimentel, "Increased CO_2 Effects on the Environment and in Turn on Agriculture and Forestry," in *Workshop on Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change*, Carbon Dioxide Effects Research and Assessment Program, CONF-7904143 (Washington, D.C.: U.S. Department of Energy, 1980).

107. J. Niedercorn, "The Capital Costs of Climatically Induced Shifts in Agricultural Production: The Example of the American Corn Belt," in *The Urban Costs of Climatic Modification*, T. Ferrar, ed. (New York: John Wiley and Sons, 1976).

108. J. Titus, et al., *Sea Level Rise Overview Paper* (Washington, D.C.: U.S. Environmental Protection Agency, 1983).

109. S. Leatherman, "Coastal Geomorphic Responses to Sea Level Rise: Galveston Bay, Texas," in Barth and Titus, note 3 above.

110. See Hoffmann, Seidel, and Keyes in note 72 above.

111. R. Sorensen, R. Weisman, and G. Lennon, "Methods for Controlling the Increased Shore Erosion/Inundation, Storm Surge, and Salinity Intrusion Caused by a Postulated Sea Level Rise," paper prepared for ICF Inc. and the U.S. Environmental Protection Agency, Bethlehem, Penn., 1983.

112. M. Gibbs, "Economic Analysis of Sea Level Rise: Methods and Results," in Barth and Titus, note 3 above.

113. J. Titus, "Rising Sea Levels: The Impact They Pose," *EPA Journal* 12 (1986): 17.

114. C. Hull and R. Tortoriello, "Sea Level Trend and Salinity in the Delaware Estuary," staff paper for the Delaware Basin Commission, West Trenton, N.J., 1979.

115. Ibid.

116. See note 111 above.

117. G. McKay and T. Allsopp, "The Role of Climate in Affecting Energy Demand/Supply," in Bach, Pankrath and Williams, note 16 above.

118. E. Larson, D. Abrahamson, and P. Ciborowski, "Effects of Atmospheric Carbon Dioxide on U.S. Peak Electrical Generating Capacity," *IEEE Technology and Society Magazine*, December 1984.

119. R. Rotty and G. Marland, "Fossil Fuel Combustion: Recent Amounts, Patterns, and Trends of CO_2," in *The Changing Carbon Cycle: A Global Analysis*, J. Trabalka and D. Reichle, eds. (New York: Springer-Verlag, 1986).

120. See note 42 above.

121. R. Revelle and W. Munk, "The Carbon Dioxide Cycle and the Biosphere," in *Energy and Climate*, Geophysics Research Board, National Research Council (Washington, D.C.: National Academy of Sciences, 1977).

122. J. Trabalka et al., "Human Alterations of the Global Carbon Cycle and the Projected Future," in Trabalka, note 41 above; and G. Woodwell, "Biotic Effects on the Concentration of Atmospheric Carbon Dioxide: A Review and Projection," in Carbon Dioxide Assessment Committee, National Research Council, note 57 above. The net carbon input to the atmosphere is calculated for an airborne fraction of 0.56.

123. R. Dickinson, "Effects of Deforestation on Climate," in *Blowing in the Wind: Deforestation and Long Range Implications*, V. Sutlive, N. Altshuler and M. Zamora, eds., Studies in Third World Societies (Williamsburg, Vir.: College of William and Mary, Department of Anthropology, 1981).

124. G. Kohlmaier et al., "The Role of the Biosphere in the Carbon Cycle and Biota Models," in Bach et al. in note 15 above. For an estimate of about 15 to 18 ppmv for a 4 degree Celsius warming stretched over eighty years, see P. Miller, "Carbon Balance in Northern Ecosystems and the Potential Effect of Carbon Dioxide-Induced Climate Change," in *Global Dynamics of Biospheric Carbon*, S. Brown, ed., CONF-8108131 (Washington, D.C.: U.S. Department of Energy, 1982).

125. See Kohlmaier et al, note 124 above.

126. See Ciborowski and Abrahamson, note 40 above, Table 9.

127. R. Rotty and G. Marland, "Constraints on Fossil Fuel Use," in Bach, Pankrath and Williams, note 16 above.

128. Ibid.

129. See note 41 above.

130. Ideal depletion curves for oil and natural gas are taken from H. Perry and H. Landsberg, "Projected World Energy Consumption," in Geophysics Research Board, National Research Council, note 121 above. 2 GT is assumed as the initial carbon input into the atmosphere from coal combustion.

131. See note 119 above.

132. For a range of estimates, see A. Perry, "Carbon Dioxide Production Scenarios," in Clark, note 4 above. Also see the estimates cited in: H.-H. Rogner, "Long-Term Energy Projections and Novel Energy Systems," in Trabalka and Reichle, note 119, above.

133. A. Albanese and M. Steinberg, *Environmental Control Technology for Atmospheric Carbon Dioxide*, DOE/EV-0079 (Washington, D.C.: U.S. Department of Energy, 1980).

134. See Trabalka et al. in note 122 above.

135. Ibid.

136. C.F. Baes, Jr., "The Role of the Oceans in the Carbon Cycle," in Bach et al. in note 15 above.

137. See the model results presented in Trabalka et al. in note 122 above, Table 10.6; and Seidel and Keyes in note 17 above.

138. This assumes a 50 percent reduction in the area of cold surface waters. For the relation of the airborne fraction to the area of cold surface water, see T. Takahashi and A. Azevedo, "The Oceans as a CO_2 Reservoir," in Reck and Hummel, note 81 above.

139. C.F. Baes, Jr. and G. Killough, "Chemical and Biological Processes in CO_2-Ocean Models," in Trabalka and Reichle, note 119 above.

140. D. Ehhalt, "On the Rise: Methane in the Global Atmosphere," *Environment* 27 (1985): 6.

141. See Liu et al. in note 38 above.

142. J. Fishman, S. Solomon, and P. Crutzen, "Observational and Theoretical Evidence in Support of a Significant In-situ Photochemical Source of Tropospheric Ozone," *Tellus* 31 (1979): 432.

143. S. Wofsy, "Interactions of CH_4 and CO in the Earth's Atmosphere," *Annual Reviews of Earth and Planetary Science* 4 (1976): 441.

144. W. Chameides, S. Liu, and R. Cicerone, "Possible Variations in Atmospheric Methane," *Journal of Geophysical Research* 82 (1977): 1,795.

145. J. Logan et al., "Tropospheric Chemistry: A Global Perspective," *Journal of Geophysical Research* 86 (1981): 7,210.

146. See note 144 above.

147. See note 22 above.

148. S. Hameed, R. Cess and J. Hogan, "Response of the Global Climate to Changes in Atmospheric Chemical Composition Due to Fossil Fuel Burning," *Journal of Geophysical Research* 85 (1980): 7,537.

149. See note 145 above.

150. Ibid.

151. Ibid.

152. M. Khalil and R. Rasmussen, "Global Trends of Carbon Monoxide," *Eos* 68, no. 44 (1987): 1,213.

153. See note 22 above.

154. N. Sze, "Anthropogenic CO Emissions: Implications for the Atmospheric CO- OH-CH_4 Cycle," *Science* 195 (1977): 673; J. Logan et al., "Atmospheric Chemistry: Response to Human Influence," *Philosophical Transactions of the Royal Society of London* 290 (1978): 187; and S. Hameed, J. Pinto, and R. Stewart, "Sensitivity of the Predicted CO-OH-CH_4 Perturbation to Tropospheric NO_x Concentrations," *Journal of Geophysical Research* 84 (1979): 763.

155. See note 142 above.

156. See note 36 above.

157. See Logan et al. in note 154 above.

158. See Hameed, Pinto, and Stewart in note 154 above.

159. See note 148 above.

160. P. Crutzen, "The Role of the Tropics in Atmospheric Chemistry," in *Geophysiology of Amazonia*, R. Dickinson, ed. (New York: John Wiley and Sons, 1986); and see note 140 above.

161. M. Khalil and R. Rasmussen, "Sources, Sinks, and Seasonal Cycles of Atmospheric Methane," *Journal of Geophysical Research* 88 (1983): 5,131; and W. Seiler, "Contribution of Biological Processes to the Global Budget of CH_4 in the Atmosphere," in *Current Perspectives in Microbial Ecology*, M. Klug and C. Reddy, eds. (Washington, D.C.: American Society for Microbiology, 1984).

162. A. Holzapfel-Pschorn and W. Seiler, "Methane Emission During a Cultivation Period From an Italian Rice Paddy," *Journal of Geophysical Research* 91 (1986): 11,803.

163. See note 36 above.

164. See note 37 above.

165. R. Revelle, "Methane Hydrates in Continental Slope Sediments and Increasing Atmospheric Carbon Dioxide," in Carbon Dioxide Assessment Committee, National Research Council, note 57 above.

166. See note 22 above.

167. V. Ramanathan and R. Dickinson, "The Role of Stratospheric Ozone in the Zonal and Seasonal Radiative Energy Balance of the Earth-Troposphere System," *Journal of the Atmospheric Sciences* 36 (1979): 1,084; and note 22 above.

168. See note 22 above; and note 35 above.

169. R. Dickinson, S. Liu, and T. Donahue, "Effect of Chlorofluoromethane Infrared Radiation on Zonal Atmospheric Temperatures," *Journal of the Atmospheric Sciences* 35 (1978): 2,142.

170. W.-C. Wang, D. Wuebbles, and W. Washington, "Potential Climatic Effects of Perturbations Other Than Carbon Dioxide," in MacCracken and Luther, note 2 above.

171. See note 48 above.

172. See note 22 above.

173. Ibid.

174. See note 35 above.

175. M. McElroy, S. Wofsy and Y. Yung, "The Nitrogen Cycle: Perturbations Due to Man and Their Impact on Atmospheric N_2O and O_3," *Philosophical Transactions of the Royal Society of London* 277 (1977): 159.

176. S. Liu, R. Cicerone, and T. Donahue, "Sources and Sinks of Atmospheric N_2O and the Possible Ozone Reduction Due to Industrial Fixed Nitrogen Fertilizers," *Tellus* 29 (1977): 251.

177. See note 35 above.

178. See note 170 above.

179. See recent estimates for these gases, presented in Ciborowski and Abrahamson, note 40 above. Also see note 22 above.

180. Carbon monoxide and NO_x emissions account for about two-thirds of the projected increase in tropospheric ozone abundances. If control of these gases was to be proportional to the control of the long-term accumulation of carbon dioxide that realistically might be realized (e.g., 450 to 600 ppmv, as opposed to uncontrolled levels of 500 to 900 ppmv), then the warming that might be averted through emissions control would be 0.3 to 0.4 degrees Celsius. A doubling of the tropospheric ozone level is assumed in the uncontrolled case. For the path of carbon dioxide in the uncontrolled case, see J. Edmonds et al., *Uncertainty in Future Global Energy Use and Fossil Fuel CO_2 Emissions 1975 to 2075*, DOE/NBB-0081 (Washington, D.C.: U.S. Department of Energy, 1986); R. Rotty, "Electrification: A Prescription for the Ills of Atmospheric CO_2," *Nuclear Science and Engineering*, 90 (1985): 467; and Rogner in note 132 above. With a reduction in the emissions of CFC-11 and CFC-12 of 25 percent, long-term steady state levels of these two constituents together would be about 2.7 ppbv, as opposed to perhaps 6 ppbv in the uncontrolled case. CFC levels of 2.7 ppbv would result in a warming of 0.4 to 0.8 degrees Celsius; CFC levels of 6 ppbv would result in a warming of 0.9 to 1.8 degrees Celsius. For CFC-12 levels with a 25 percent emissions reduction, see J. Hoffman, "The Importance of Knowing Sooner," in Titus in note 72 above, vol. 1, *Overview*.

181. M. Ross and R. Williams, *Our Energy: Regaining Control* (New York: McGraw Hill Book Company, 1981).

182. C. Marchetti, *The Dynamics of Energy Systems and the Logistic Substitution Model*, AR-78-1B (Laxenburg, Austria: International Institute for Applied Systems Analysis, 1978).

183. A. Perry et al., "Energy Supply and Demand Implications of CO_2," *Energy Journal* 7 (1982): 991.

184. The three calculations assume atmospheric concentrations of 500 to 550, 600 to 700, and 700 to 800, respectively. The first of these assumes that preventive action is taken within ten to fifteen years. The estimates assume initial rates of annual growth in fossil fuel combustion of 1.5 to 2 percent. Atmospheric carbon dioxide concentrations for each delay are taken from Perry et al., note 183.

185. F. Dyson and G. Marland, "Technical Fixes for the Climatic Effects of CO_2," in *Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels*, W. Elliott and L. Machta, eds., CONF-770385 (Washington, D.C.: U.S. Department of Energy, 1979).

186. M. Steinberg, H. Cheng and F. Horn, *A Systems Study for the Removal, Recovery and Disposal of Carbon Dioxide From Fossil Fuel Power Plants in the U.S.*, DOE/CH/0016-2 (Washington, D.C.: U.S. Department of Energy, 1984).

187. See Ciborowski and Abrahamson, note 40 above.

SECTION 2: THE PREVENTIVE STRATEGY

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INTRODUCTION TO SECTION 2

Strategic responses to the greenhouse problem--prevention, adaptation, continued study, and compensation--are identified and defined in Section 1. Of these, the preventive response has received the most attention, with the feasibility of the preventive response attracting special attention. Preventive responses are preemptive in nature, seeking to prevent the problem of impending climate change, or at least to limit such changes, through alterations in those policies that result in the emission of industrial gases to the atmosphere. They would result in reduced emissions of the greenhouse gases or their removal from the atmosphere. Some analysts have also envisioned intentional anthropogenic alteration of the optical properties of the atmosphere or of other features of the heat balance as a means of offsetting a greenhouse warming.

A few studies have considered the effectiveness of a large-scale international effort to inject sulfate aerosols into the stratosphere to offset an intensified greenhouse effect. In general, this is not thought to be a feasible solution to the climate change problem, given potential adverse environmental consequences that are associated with it (i.e., intensified acid deposition, effects of the pattern of injection on surface meteorological conditions). The withdrawal of greenhouse constituents from the atmosphere has been found not to be feasible due to the energy requirements of such a removal. It has been found necessary to concentrate on emissions control, which limits preventive control to nondiffuse, highly centralized or regulated sources, like fossil fuel power plants or the energy sector of the industrialized societies.

This implies, among other things, that carbon dioxide is the only gas whose control would be at all meaningful. Emissions of most of the other greenhouse gases (OGGs) probably cannot be controlled. Of the various means of controlling carbon dioxide emissions, purely technical fixes can be excluded from consideration. The removal of carbon dioxide from the effluent streams of coal-fired power plants can be excluded due to the costs of removal and, more importantly, to the small percentage of future emissions that might be affected by such removal (on the order of 25 percent). Preventive action, if it is to come about, must involve restrictions on the combustion of coal and other carbon-based energy sources, and these restrictions must extend to all energy sectors rather than simply to the electrical sector.

This process of narrowing the viable preventive responses to the group of responses involving carbon dioxide and energy policy brings the preventive response into focus. This narrowing focuses much of the preventive effort on the control of carbon dioxide, which implies first that much of the warming due to OGGs must be considered inevitable and second that the control of carbon dioxide must be much more thorough than would be the case were the OGGs controllable or were carbon dioxide the sole greenhouse constituent acting on the climate.

The narrowing also focuses the discussion on energy and on the opportunity for or constraints to a transition to a non-carbon based energy system. There are grounds to believe that various economic and political factors may inhibit the rate of such a transition and, therefore, the degree to which the accumulation of carbon dioxide in the atmosphere can be limited. Over the long-term, the feasibility of a transition to a non-carbon energy system is not in dispute. Few doubt that such a transition will be realized long before all, or even one-third to one-half, of the global coal, tar sands, and oil shale resources are consumed. (Full combustion would probably be accompanied by an aggregate warming in the range of 6 to 10 degrees Celsius.) Rather, the rate of transition over the next half century or so is at issue, along with the feasibility of limiting global commitments to coal, tar sands, and oil shale.

The discussion thus far has been structured around the demands of these constraints as they constrict the purely technical potential for non-carbon or low-carbon energy futures. Vastly improved energy efficiency is usually the central component of low-carbon futures. Were it to be immediately exploited, improved end-use efficiency, it is estimated, would be sufficient to limit the annual energy use from 1985 to 2050 to present levels and limit the cumulative carbon combustion over that period to something like one-twentieth of the total coal and shale oil carbon in the crustal reserves. By contrast, the most conservative, albeit probably the most defensible, description of the constraints to the transition--one that calculates the degree of constraint from those rates of introduction of new energy sources that seem reasonable and that could be maintained for a long period of time--pushes the total carbon consumption to something like one-tenth of total carbon deposits. Higher values would result from a slightly more liberal interpretation of these constraints.

Particular constraints that are discussed in the literature include those arising from the capital costs of a long-term transition and those implicit in the tendency of industrial society to drift to ever higher rates of energy consumption. The premature retirement of existing fossil fuel facilities would involve large capital costs. Capital would be needed to develop and expand new energy industries (e.g., to construct new factories to produce energy production and consumption technology and to construct factories to produce those factories) and to research and develop new energy sources. Finally there would be costs to society's production capacity if less industrially useful energy technologies were to be employed. A significant part of the economy of the industrialized world is organized around fossil fuel production, and energy production generally, and this tends to bias the economic and political system toward a continuation of these activities. Institutions will seek to continue doing the things they do well. Considerable opposition could be expected from the owners of coal and oil reserves, and these interests would find powerful arguments against prevention in the general structure of the international economy, which favors the noncompliance of minor energy consuming nations in cooperative preventive action.

Much of the discussion of constraints to the preventive response has been directed to cost or is political in nature, focusing on those arguments that might be exploited by interests which, for one reason or another, stand opposed to emissions control. However, purely technical considerations also come into play. The feasibility of prevention depends upon one's perception of what might constitute a meaningful level of limitation and on the degree to which society's self-professed ability to limit the atmospheric accumulation of carbon dioxide is consistent with such a level of limitation. The latter depends on the response of the climate. If the sensitivity of the climate is quite high (e.g., a sensitivity of 4 or 5 degrees Celsius), it would be a very difficult matter indeed to limit the warming to a relatively small value, were that the goal.

Hoffman and Seidel offer an overview of some of these issues. They highlight the effect of possible higher climate sensitivities to the greenhouse gases and the practical difficulties of limiting emissions. As the authors note, recent modeling efforts suggest that the sensitivity of mean global temperature to a doubling of the atmospheric concentration of carbon dioxide could easily be double what it was thought to be early in the 1980s. Rather than a warming of 2 degrees Celsius, a doubling of atmospheric carbon dioxide concentrations could result in a warming of 4 degrees Celsius, and this would double the difficulty of limiting the magnitude of future warming.

The authors conclude that the investment, psychological or financial, of current generations in fossil fuel industries extends beyond production technology to consumption technology, infrastructure, the present structure of energy costs, and the general pattern of capital investment, and that these constitute a barrier to a rapid transition to non-carbon energy sources. Preventive responses that center on carbon dioxide are likely to create a situation in global energy markets that encourages individual nations, each 22acting in its own interests, to cheat and exploit any price advantages that might result from the preventive actions of others. It is possible that short-term preventive actions may so lower the market price of fossil fuels as to make irresistible the temptation for the world as a whole to "cheat" sporadically. Control of the other gases is unlikely. Finally, Hoffman and Seidel argue that the lack of certainty about future impacts will generate at least some opposition to preventive action, and that this, with the other constraints, severely limits the prospects for a preventive response over the next forty years. The transition to a new emissions regime will take a considerable amount of time. Policies directed to prevention can be effective, but only in the sense that they can limit the magnitude of future warming, not eliminate the prospect altogether.

Williams et al. investigate the potential for preventive action based on enhanced energy end-use efficiency and on the use of so-called "soft energy" sources. Final energy use and the total atmospheric accumulation of carbon dioxide are calculated for the year 2020. The estimates are based on accepted United Nations population estimates and are calculated to provide enough energy in the developing world to raise the basic living conditions to 1970s Western standards. Estimated Western per capita energy use falls considerably but is still thought sufficient in light of efficiency improvements to allow a 100 percent increase in the consumption of goods and services over 1980 levels. The energy supply scenarios take into account global environmental stresses like deforestation and nuclear proliferation, which often derive from the large-scale production of commercial energy. Particular energy supply strategies are suggested that can minimize the disruption caused by energy use.

Total global energy use in the year 2020 is about 11 terawatts in the Williams et al. scenario, or about the same as at present. The corresponding atmospheric carbon dioxide concentration would be about 388 parts per million (ppmv), or only a slight increase above the present concentration (345 ppmv). Carbon emissions in 2020 would be about the same as at present (5.5 gigatons). At equilibrium, an increase to 388 ppmv would be insignificant climatically, amounting to an increase in mean global temperature of about 0.5 degrees Celsius.

These authors limit their analysis to energy efficiency improvements that could derive from technologies that are already commercially available or now in the prototype stage. However, as the authors note, this analysis ought to be considered as a statement of what could ideally be achieved with the introduction of these more efficient energy technologies and sources and with full saturation in the targeted economic sectors. Obviously, the introduction of the most efficient technologies will take considerable time. The authors also do not consider the economic coherence of their scenario. Nonetheless, Williams et al. do provide a reasonably consistent technical scenario, which if only partly realized would go a long way toward limiting the projected atmospheric buildup of carbon dioxide.

Laurmann assesses the effect of the long time periods needed for energy system transitions. Market penetration is the principal concept around which the author develops his analysis. The concept of market penetration is taken from Marchetti and establishes the rate of absorption of any given technology into commercial markets. The introduction of new energy technologies or sources into energy markets has historically been slow, with fifty to seventy-five years required for any one source to secure a 50 percent market share. Laurmann applies this empirically-derived estimate of market penetration time to the future atmospheric accumulation of carbon dioxide, investigating the degree to which this constant forms a barrier to any attempt, over the next decade or so, to significantly limit the buildup of carbon dioxide. Any value for such an accumulation under a doubling of the preindustrial atmospheric carbon dioxide concentration, or its temperature-change equivalent (a 3 degree Celsius increase), is taken to indicate that action is plausible. This value is easily exceeded in the case of the higher market penetration time but comes in just under it in the case of a fifty-year market penetration time.

Laurmann's analysis suggests that market penetration times constitute a significant barrier to a preventive response. However, as is true of the work of Hoffman and Seidel, such a conclusion depends on the level of climate change against which success or failure is estimated. Relatively low bench marks are often selected for use in evaluations as a matter of convention, but they have never withstood rigorous review. Laurmann's calculations account for the effect of the other gases, which he takes to be equal in effect to 80 percent of the effect of increased atmospheric levels of carbon dioxide.

Firor draws on the literature and on as-yet-unpublished work of his colleagues to summarize the role of the greenhouse gases other than carbon dioxide. He considers primarily methane, nitrous oxide, the chlorofluorocarbons (CFC-11, CFC-12), ozone, and stratospheric water vapor. The present rates of growth in the atmospheric concentrations of these gases are presented. Firor concludes that the effect of these other gases may equal or exceed the effect of carbon dioxide in the next fifty years, and, by considering the range of estimates, suggests that, were all other greenhouse gases considered, the total effect could be between 50 and 300 percent of the effect of carbon dioxide. An estimated OGG warming on the order of 100 percent of the effect of carbon dioxide implies a significant upward revision.

As Firor notes, the policy discussion depends critically on numbers and on the scale of estimated changes. Any significant upward revision of the estimated change in planetary warming changes the terms of the policy debate. Recognition of the effect of the OGGs dramatically changes the physical science foundation of the problem and may necessitate a parallel shift in the policy discussion.

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LIMITS TO PREVENTING A GLOBAL WARMING

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INTRODUCTION

The global warming expected to result from increased atmospheric concentrations of carbon dioxide and other greenhouse gases has led some people to call for immediate actions to prevent climatic change.[1] The greenhouse gases, according to this school of thought, should be treated in the same manner as other pollutants: to the extent that public health or welfare may be at risk, limits should be placed on future emissions of these gases.

Concern over the implications of a greenhouse warming takes many forms. Some feel that a climate change of any magnitude places an unfair burden on future generations.[2] Others are concerned with potentially negative impacts on agriculture[3] or with the inability of the developing world to adjust their fragile economic systems to changing environmental conditions. Still others worry about the risks to coastal lands from the rise in sea level that is likely to accompany any significant warming.[4]

The worth of preventive strategies is far from universally accepted. Some agriculturalists have argued that more atmospheric carbon dioxide, on balance, will be beneficial to society. They note its salutory influence on photosynthesis, which they suggest will more than compensate for its effect on the climate.[5]

This paper does not address the desirability of policies to delay, limit, or prevent climate change; we have intentionally sidestepped this issue. Rather, we shall evaluate the likely effectiveness of such policies. Our findings may discomfort some; it appears that not even the most stringent of the set of feasible preventive policies can prevent significant global warming during the next forty years. Policies aimed at prevention can work, but their effectiveness seems to be limited to reductions in the magnitude of warming in the twenty-first century.

UNREALIZED WARMING: A PHYSICAL LIMIT TO PREVENTION

Since 1860, atmospheric concentrations of carbon dioxide have risen approximately 25 percent. Atmospheric concentrations of other greenhouse gases, including chlorofluorocarbons, methane, and nitrous oxide, have also increased, in some cases by larger percentages. While past increases in greenhouse gases probably have had some warming effect on the earth, not all the warming from past increases in the atmospheric concentrations of the greenhouse gases should have been felt yet. A bank of unrealized warming exists.[6]

This unrealized warming results from the way increased concentrations of greenhouse gases elevate air temperatures. The additional energy trapped by the added greenhouse gases heats the surface of the planet, which warms both the air and the surface of the ocean. Heat is transported downward into the ocean, creating an imbalance between the air surface temperature and the ocean surface temperature that then is reduced by a flux of heat from the air into the water. In this way, the transport of heat into the ocean delays the warming of the atmosphere. The more heat is transported to the deeper layers of the oceans, the longer the time lag. Eventually, however, the top layers of the oceans are warmed to the point at which they come into thermal equilibrium with the air, and at that time the temperature of the system stops increasing.

Because of the thermal lag, one cannot use the equilibrium response due to doubled atmospheric concentrations of carbon dioxide, estimated as 1.5 to 4.5 degrees Celsius by the National Academy of Sciences,[7] to predict the transitional temperature of the earth over time. Since at least half of the infrared absorbing gases now in the atmosphere have been emitted in the last two decades, a large percentage of the ultimate surface air temperature rise from past emissions cannot yet have been realized. Consequently, global temperatures can be expected to increase even if concentrations of greenhouse gases do not rise above current levels. In fact, since emissions of greenhouse gases are growing, the gap between current temperature and equilibrium temperature must also be growing.[8] The size of the gap would be especially large if recent studies at the Goddard Institute for Space Studies[9] and the National Center for Atmospheric Research[10] have correctly estimated the equilibrium warming from doubled atmospheric concentrations of carbon dioxide (4 degrees Celsius per doubled atmospheric carbon dioxide).

The good news is that oceanic heat absorption has buffered us from the global warming. The bad news, however, is that we are committing ourselves to global warming without necessarily being aware of the magnitude of that commitment.

ECONOMIC CONSTRAINTS TO LIMITING GLOBAL WARMING

Discussion of an immediate and successful termination to the emission of greenhouse gases is purely rhetorical. Termination is not a serious policy option. Emissions of all known greenhouse gases (e.g., carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide) are actually increasing, and in the absence of strong governmental intervention to curtail their growth they can be expected to increase appreciably for the forseeable future. Since emission of the greenhouse gases into the atmosphere is a natural consequence of many important economic processes, termination cannot be contemplated without first considering its effects on the economy. This paper will review the economic pressures that exist to increase, rather than to decrease, the various greenhouse gas emissions.

Carbon Dioxide

Carbon dioxide emissions result primarily from the burning of fossil fuel but also from cement manufacturing and possibly from deforestation. Fossil fuels have become the dominant source of energy because of their price, convenience, and physical characteristics. Almost 90 percent of primary commercial energy now comes from fossil fuels.[11] Past decisions have dedicated tremendous amounts of capital to the production, transportation, and consumption of various fossil fuels.

In the absence of directed policies, the speed of any transition from fossil fuels would depend on the free market decisions of energy users over long periods of time. Consumers make energy decisions based on the relative costs of fossil as against non-fossil energy and on the availability of capital for new energy sources. Also important are consumers' abilities to shift from fossil fuels without lowering the value of investments and the relative attractiveness of energy alternatives for the work that consumers wish to perform. Hence, any substantial transition from fossil fuels will take time, given the current costs, infrastructure, technology, and market demands. Estimates of past transitions suggest that a fifty-year period is required for one dominant energy source to replace another.[12]

Large fixed investments in existing energy systems constitute one reason for the length of this lag. Moreover, efforts to reduce fossil fuel use would promote lower fossil fuel prices, making non-fossil energy options comparatively less attractive. The recent world oil glut illustrates this situation: lower oil prices clearly increase the market for larger cars and help sustain the demand for fossil fuel.

International economic competition is another important factor in the length of this lag, since it limits a nation's ability to unilaterally shift away from fossil fuels. A shift to a more expensive non-fossil alternative implies a clear cost disadvantage, and nations that attempt it could find themselves at an economic disadvantage in relation to those that do not. For example, the Environmental Protection Agency study, *Can We Delay A Greenhouse Warming?*[13] estimates that even a 15 percent reduction in U.S. domestic fossil fuel consumption, induced by taxation on all fossil fuels (set at 100 percent for shale oil and adjusted proportionally for all other fuels based on carbon dioxide emissions), would leave worldwide consumption almost unchanged, because prices elsewhere would decrease. Global carbon dioxide emissions would be reduced by only 3 percent.

Actions to achieve substantial improvements in the efficiency of energy use offer another means by which to reduce fossil fuel use. Numerous studies show that opportunities for increased energy end-use efficiency are at least theoretically sufficient to substantially influence energy demand and carbon dioxide emissions.[14] Using mathematical models, proponents of improved energy end-use efficiency have shown that various end uses (i.e., transportation and heating) can be satisfied less expensively through conservation than through the development of new sources of energy. Least-cost proponents advance these studies as a basis for energy efficiency programs, which they suggest represent a feasible alternative to the continued or accelerating combustion of fossil fuels.

Unfortunately, these studies are probably much too optimistic. While clearly mapping a set of market opportunities, they tend to ignore real market obstacles to the sale and acceptance of energy efficiency improvements. Technological uncertainties, transition costs, and institutional inertia constitute serious obstacles to rapid and sustained improvements in energy efficiency. Experience shows that investments that look good on paper often do not sell well. For example, according to many studies, energy conservation in existing housing constitutes a very profitable investment. But in the marketplace such conservation investments have not fared as well as one would expect from the studies. Reasons for this shortfall include consumer skepticism and a lack of financing. Lack of incentive may also be important, since some potential consumers may be renters. Also important may be the real consumer transaction costs, which are often ignored in the studies but which can constitute a large percentage of the real costs. For example, the transaction costs associated with the installation of new furnaces or with insulation can be quite high. The consumer must find a competent, trustworthy vendor for the desired service. The consumer has to take time off work to wait for the contractors. Finally, legal remedies for incorrectly completed work, if such remedies exist, can be expensive and time-consuming. In the real world, obstacles like these have led far fewer homeowners to pursue conservation measures than energy efficiency models predict.[15]

Worse yet, conservation measures also tend to be underutilized in new homes, where they should be easiest to install. Perhaps developers find potential home buyers more sensitive to the visible aspects of the home, to the size of the up-front costs, or to mortgage costs than to energy costs. Or perhaps in some cases the developers do not know how to fully exploit this aspect of consumer preference. Whatever the cause, the facts are clear. Houses are being built which, although they are more efficient than the houses built in the past, still fall far short of achieving full energy savings. Apparently, even ten years after the first oil crisis, the market still has not responded as the authors of the least-cost studies would have hoped.

None of these facts justify failure to implement conservation measures. Nor do they justify failure to support programs that promote enhanced energy end-use efficiency. They do illustrate, however, that time is required for any technology, even a superior one, to penetrate a market.

In summary, options may exist for reducing carbon dioxide emissions. However, a large body of evidence suggests that quick, easy, or inexpensive curtailment of the growth of fossil fuel use is unlikely. Efforts to move away from proven technologies will be difficult and time-consuming, if they are made at all. Finally, the demand for fossil energy is likely to grow as the developing world grows economically. Overall, global policies appear to have a limited capacity to reduce emissions, even drastic global taxes on fossil fuels (for example, taxes set at 300 percent) are probably only sufficient to reduce emissions by one-third in 2025.[16]

Chlorofluorocarbons

Chlorofluorocarbons (CFCs) are used as aerosol propellants throughout the world except in the United States and several other countries that have banned their use in spray cans. Chlorofluorocarbons are also used as refrigerants in heat pumps, refrigerators, and air conditioners; as solvents on almost all printed circuit boards and in some dry cleaning applications; as foam-blowing agents; and in a variety of other industrial processes and products. Chlorofluorocarbons tend to be nontoxic, highly useful substances. For many purposes, they are far superior to their closest substitutes.

Chlorofluorocarbons also are potent greenhouse gases. Increases in atmospheric concentrations of these gases are estimated to have contributed to the global warming experienced during the period between 1970 and 1980. Their effect is thought to have been equal to about 40 percent of the warming experienced during this period from increased atmospheric carbon dioxide concentrations.[17]

Emissions of the chlorofluorocarbons from developed countries are driven primarily by demand in mature industries, a situation in which replacement demand and population growth are driving factors. Rand has predicted a 5 percent growth rate for the chlorofluorocarbons in the United States for CFC 11 and 12.[18] CFC 113 has been an important exception to the characterization of markets as mature in the developed world. The use of CFC 113, a solvent in the electronics industry, has increased much more rapidly than the use of the other chlorofluorocarbons. The increase in the use of CFC 113 demonstrates the rapid growth that can be associated with new markets. In the developing world, many products that utilize chlorofluorocarbons are in the early stages of market penetration, making a rapid increase in the use of CFC 11 and 12 likely in those areas.

Although a variety of possibilities exists for reducing the use of the chlorofluorocarbons, in many cases the nearest substitute is much more expensive or is itself a potential environmental problem (e.g., a toxic substance). Nevertheless, over the long run it may be possible to find economically and environmentally acceptable substitutes for many current uses of chlorofluorocarbons.[19] The most promising avenue for reducing chlorofluorocarbon emission involves prohibiting their use in nonessential aerosols throughout the world. Since other aerosol propellants are actually less expensive than chlorofluorocarbons, this large emissions source constitutes an excellent control target.

Chlorofluorocarbons, like many of the long-lived greenhouse gases, demonstrate the problems that would be encountered in an effort to curtail future greenhouse warming. A worldwide freeze on the growth of chlorofluorocarbon emissions would still allow concentrations to rise fivefold, at which point concentrations would stabilize. And current emissions could be sustained over time only with increasingly stringent controls far beyond those on spray can aerosol uses.

<u>Methane</u>

Atmospheric methane appears to be increasing at 1 percent annually.[20] Considerable uncertainty surrounds the cause of ths increase. Emissions from various sources such as swamps, forests, rice paddies, natural gas transmission, and livestock have not been well quantified. Moreover, the increase of atmospheric carbon monoxide concentrations may be reducing the rate at which methane is scrubbed from the troposphere, thereby increasing atmospheric methane concentrations.[21]

Two aspects of methane release are of interest. It is a strong greenhouse gas and it reacts in the stratosphere to produce water vapor, which at high altitudes is also a potent greenhouse gas.[22] This latter effect has not been calculated or included in the estimates of future global warming made by the Environmental Protection Agency or other groups. However, it could add significantly to total projected temperature change.

Future atmospheric concentrations of methane are difficult to estimate. Rice is a basic foodstuff in much of the world. As the global population expands, the production of rice is likely to grow. It is unclear whether changes in cropping patterns or other biological factors can decrease the methane emissions from rice paddies. Methane emissions will also be difficult to control to the extent that leakage from natural gas pipelines constitutes a significant source of methane release. This is especially true in the case of the Soviet Union, which has inferior pipeline technology. Although further increases in the number of livestock are unlikely to keep pace with population expansion, some further growth is likely. A possibility exists that biotechnology can reduce methanogenesis in livestock; at this time, this is all that can be said. Similarly, as the earth warms, previously negligible sources of methane, such as tundra or methane hydrates, could develop into more important sources of methane. Finally, the magnitude of future carbon monoxide emissions is unclear. Increases are possible if a synthetic fuels industry develops; reductions are possible if clean automobile technologies penetrate most of the world markets.

In light of these considerations, the degree of future warming associated with increased methane concentrations is unclear. Although various measures may provide real opportunities to limit methane emissions, there also exist the possibilities that little can be done or that atmospheric methane concentrations will grow faster than the past rate of growth.

Nitrous Oxide

Atmospheric concentrations of nitrous oxide are increasing at about 0.25 percent per year, apparently as a result of some combination of coal combustion emissions and agricultural practices.[23] If the former dominate, reductions in fossil fuel use or alterations in the way in which we burn fuels could reduce the growth in the atmospheric concentrations of this gas. If agricultural sources predominate, the possibilities for emissions reductions appear more limited. Furthermore, the possibility exists that rising carbon dioxide concentrations could change the nutrient balance of soils and plants, thereby increasing terrestrial nitrous oxide production. In general, an inadequate amount of research is now focused on the sources and sinks of nitrous oxide and the ways in which these may change as the earth warms. Efforts to limit further increases in atmospheric nitrous oxide concentrations obviously require more understanding of these sources and sinks.

Tropospheric Ozone and Other Less Important Greenhouse Gases

At altitudes of 6 to 10 kilometers (km), tropospheric ozone is a strong greenhouse gas. Some atmospheric chemists believe that nitrogen oxide emissions (NO_x) from airplanes may increase the ozone abundance at those altitudes.[24] Airplane emissions are likely to increase with rising civilian and military use and with improved fuel efficiency and hotter jet engines. If nitrogen oxide emissions do in fact increase the ozone amounts at altitudes of 6 to 10 km, a strong greenhouse effect would depend on the time required for alterations in jet engines, and the amount of time involved in such a technological change would not be negligible. A reduced rate of increase in air miles and safety considerations might make such steps undesirable. Again, few studies have addressed these issues.

Concentrations of the other greenhouse gases, such as carbon tetrachloride and methylchloroform, have been observed to be increasing in the atmosphere. In aggregrate, the contribution of the minor trace gases to future global warming may become significant. Generally, it will be difficult to reduce emissions of these gases, since their substitutes often take the form of gases which may themselves have a greenhouse effect.

LIMITS RESULTING FROM A LACK OF KNOWLEDGE AND CONSENSUS

Our discussion has focused so far on the physical, technical, and economic constraints to preventing global warming. An additional constraint involves the lack of certainty and consensus about the desirability of preventive actions. The existing knowledge does not yet provide a convincing case for the desirability of limiting future global warming. Few nations are likely to take unilateral action. Furthermore, even if some nations do become more concerned, the variation in the magnitude of the changes predicted by the climate models is quite large, and this is likely to inhibit action. Such models produce a wide range of estimates regarding regional climate changes, which most directly determine the economic and environmental consequences of increasing greenhouse gas concentrations. The climate models simply do not provide accurate representations of ocean circulation and the ways the enhanced radiative forcing caused by greenhouse gases will alter that circulation. Nor do they include dynamic representations of the way climatically driven changes in vegetation and soils would alter the hydrological cycle. Consequently, models cannot produce forecasts that are reliable at the regional scale. Individual nations can only guess at the value of limiting future warmings without such forecasts. To some, such uncertainty might seem to justify action, but to many, including those who own resources that would be affected by actions to curtail a greenhouse warming, such uncertainty will produce opposition to actions to limit change.

Finally, if a consensus to limit global warming is to be developed, it will be critical to consider the needs of the developing world, where the emission of greenhouse gases into the atmosphere is just beginning. Representatives of these nations have indicated that they will be open to discussions of the "luxuries" of the environmental concerns of rich nations only if they get a share of the economic pie. It will take time to develop an approach that everyone considers fair. The momentum for global warming is significant and ensures that a significant change will take place in the coming decades.

THE NEED TO EXPEDITE RESEARCH

The above arguments underscore the likelihood of unavoidable and potentially significant climate changes through the middle of the next century. Preventive actions, if taken now, can successfully limit further warming, but only with time.

Given the likelihood of significant climate change, the development of reliable regional climate scenarios and the evaluation of their potential effects should be our highest priorities. Such forecasts will not become available without a vastly expanded program of research. In fact, unless our priorities are changed, the rate of climate change over the next two decades is likely to exceed the rate at which scientific uncertainties are eliminated. Because of our current ignorance, it is impossible to state the implications of this situation.

Note: The authors wrote this paper in their private capacity. The views expressed herein do not represent the views of the U.S. Environmental Protection Agency or the U.S. Government.

NOTES

1. D. Scroggin and R. Harris, "The Carbon-Dioxide Problem: Reduction at the Source," *Technology Review 84* (1981): 22; and M. Oppenheimer, "To Delay Global Warming," *New York Times*, November 9, 1983.

2. R. Pomerance, "Testimony on Carbon Dioxide and the Greenhouse Effect," submitted to Committee on Science and Technology, February 28, 1984.

3. D. Abrahamson and P. Ciborowski, "Harvest of Sand," *The Amicus Journal* 5 (1984): 38.

4. M. Barth and J. Titus, eds., *Greenhouse Effect and Sea Level Rise* (New York: Van Nostrand Reinhold, 1984).

5. S. Wittwer, "Carbon Dioxide and Climate Change: An Agricultural Perspective," *Journal of Soil and Water Conservation* 35 (1980): 116.

6. M. Hoffert, A. Callegari, and H. Ching-Tzong, "The Role of Deep Seat Heat Storage in Secular Forcing To Climate Forcing," *Journal of Geophysical Research* 85 (1980): 6667.

7. Carbon Dioxide Assessment Committee, *Changing Climate* (Washington, D.C.: National Academy Press, 1983).

8. J. Hansen et al., "Climate Sensitivity: Analysis of Feedback Mechanisms," in *Climate Processes and Climate Sensitivities*, J. Hansen, and T. Takahashi, eds. (Washington, D.C.: American Geophysical Union, 1984).

9. Ibid.

10. Personal communication, Warren Washington, National Center for Atmospheric Research, 1983.

11. The British Petroleum Company, *BP Statistical Review of World Energy: 1982* (London: British Petroleum Company, 1983).

12. C. Marchetti and N. Nakicenovick, *The Dynamics of Energy Systems and the Logic Substitution Model* (Vienna: International Institute for Applied Systems Analysis, 1979).

13. S. Seidel and D. Keyes, *Can We Delay a Greenhouse Warming?* (Washington, D.C.: U.S. Environmental Protection Agency, 1983).

14. The Energy Productivity Center, *The Least-Cost Energy Strategy*, (Arlington, Va.: Mellon Institute, 1979); and A. Lovins et al., *Least-Cost Energy: Solving the* CO_2 *Problem* (Andover, Mass.: Brick House Publishing Company, 1981).

15. B. Frieden and K. Baker, "The Record of Home Energy Conservation: Saving Bucks, Not BTU's," *Technology Review* 86 (1983): 23.

16. See note 13 above.

17. A. Lacis et al., "Greenhouse Effect of Trace Gases, 1970-80," *Geophysical Research Letters* 8 (1981): 1035.

18. A. Palmer et al., *Economic Implications of Regulating Nonaerosol Chlorofluorocarbon Emissions: An Executive Briefing* (Santa Monica, Calif.: Rand Corporation, 1980).

19. Ibid.

20. R. Rasmussen and M. Khalil, "Atmospheric Methane, (CH_4): Trends and Seasonal Cycles," *Journal Geophysical Research* 86 (1981): 9826.

21. M. Khalil and R. Rasmussen, "Carbon Monoxide in the Earth's Atmosphere: Increasing Trends," *Science* 224 (1984): 5456.

22. W. Wang et al., "Greenhouse Effects Due to Manmade Perturbation of Trace Gases," *Science* 194 (1976): 685.

23. R. Weiss, "The Temporal and Spatial Distribution of Tropospheric Nitrous Oxide," *Journal Geophysical Research* 86 (1981): 7185.

24. D. Wuebbles, F. Luther, and J. Penner, "Effect of Coupled Anthropogenic Perturbations on Stratospheric Ozone," *Journal Geophysical Research* 88 (1983): 1444.

A GLOBAL END-USE ENERGY STRATEGY

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INTRODUCTION

At the present rate of use, the world's remaining recoverable oil resources amount to less than a one hundred-year supply. Two-thirds of these resources are located in Middle Eastern/North African (ME/NAf) countries and in countries with centrally planned economies. The amount left in the rest of the world is about a forty-year supply at the present rate of oil consumption there.[1] These numbers indicate the ephemeral nature of the present oil glut and highlight the need to begin a global transition from oil.

The rural populations of the developing world, which constitute half of the world's population, are also caught up in an energy crisis, even though oil plays only a minor role in their lives. Here people are largely dependent for energy on biomass--mainly fuelwood used for cooking. However, a fuelwood crisis has arisen, since in many areas increased fuelwood demand associated with population growth presently exceeds the rate of fuelwood regeneration through photosynthesis. It has been estimated by the Food and Agricultural Organization (FAO) that about 100 million human beings now suffer "acute scarcity" of fuelwood and about 1 billion suffer a "deficit."[2] Fuelwood gathering involves many hours of drudgery each day, particularly by women and children, and the ecological effects of excessive fuelwood use, particularly deforestation and its effects, amplify this human toil.

Energy availability is a major global problem. But energy availability is only one of several important global problems that must be addressed if humankind is to achieve a sustainable world society. Others include: the global economic crisis, North-South tensions, widespread poverty in developing countries, population growth, food scarcity, humanity's role in changing the global climate, deforestation and desertification, the risk of nuclear war, and nuclear weapons proliferation.

The point of departure of the present analysis is the recognition that all of these other problems are strongly linked to energy and that pursuing solutions to the energy problem without considering these linkages may aggravate these problems. Our analysis seeks to identify a long-term global energy strategy which supports, or at least does not conflict with, solutions of these other global problems. More generally, we seek to articulate the dimensions of a long-run energy strategy that is compatible with considerations of equity, economic efficiency, environmental soundness, long-term human welfare, self-reliance, and peace--the key features of a sustainable world society.

THE ROLE OF ENERGY POLICY IN SOLVING OTHER GLOBAL PROBLEMS

To begin the analysis, we identify important links of the above-mentioned problems to energy and in each case consider the potential contributions of energy planning to the resolution of these problems.

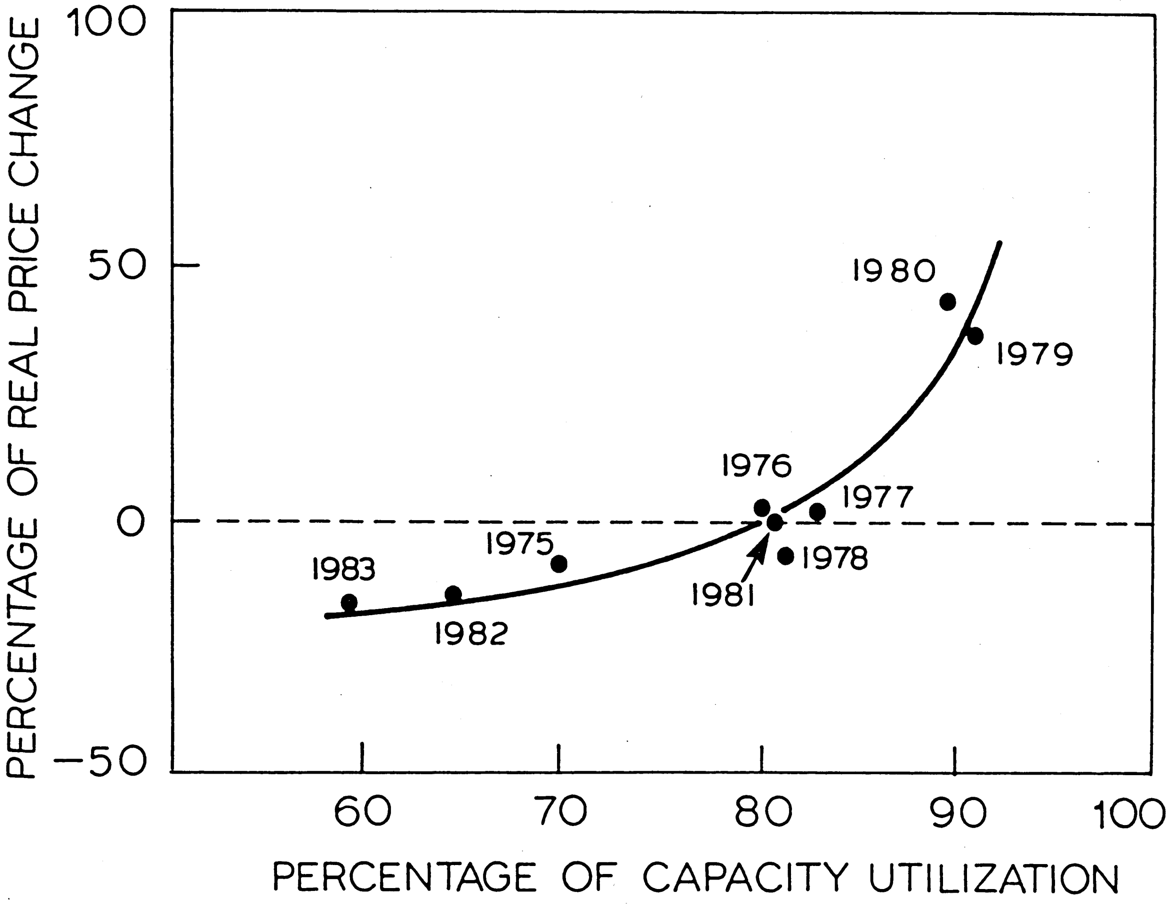
The Economic Crisis

The last decade has been a period of rampant inflation, major global recessions, widespread unemployment, and soaring real interest rates. In addition, recent years have seen the development of an international debt crisis, which could lead to collapse of the global financial system were hard-pressed debtors of the developing world to fail to discharge their debts.

Costly energy has been a major contributing factor to these developments. On average, low- and middle-income developing countries spent, respectively, 61 percent and 37 percent of their export earnings on oil imports in 1981.[3] Also, energy from new sources is generally far more costly than energy now being used. In the United States, the percent of all new plant and equipment expenditures accounted for by capital expenditures on energy supply rose from 25 percent to nearly 40 percent between 1972 and 1982, with essentially no net increase in domestic energy production in this period. In developing countries, investments committed to energy supply expansion increased during the 1970s, on average, from 1 to 2 percent to 2 to 3 percent of gross domestic product (GDP), requiring in 1982 some $25 billion in foreign exchange--over one-third the foreign exchange required for all kinds of investments.[4] This has made capital scarcer for other economic activities.

If less costly ways could be found to meet energy needs, energy planning could help to ease the economic crisis. If the focus of energy planning were to be shifted from supply expansion to the identification of the least costly ways of providing energy services (for space conditioning, lighting, mechanical work, mobility, etc.), large reductions in life-cycle energy costs could be achieved with investments in energy efficiency improvements.[5] Realizing such opportunities can improve economic efficiency and also promote lower world oil prices by restraining world oil demand and sparing the world the burden of tight world market conditions (see Figure 1). To the extent that costly new energy sources are not needed, it can also lead to lower prices for other energy forms.

Figure 1
ORGANIZATION OF PETROLEUM EXPORTING COUNTRIES (OPEC) PRICING BEHAVIOR*



*The percentage of real price change from the previous year is plotted with percent of OPEC production capacity used. The percentage of capacity utilization is equal to the crude oil production divided by the maximum sustainable production for that year. Source: Energy Information Administration, U.S. Department of Energy, *Annual Energy Outlook 1983 with Projections to 1995*, report DOE/EIA-0383(83) (Washington, D.C.: Government Printing Office, 1983).

North-South Tensions

Poor countries of the South account for three-fourths of the world's population but per capita incomes in the South are, on average, only one-tenth as large as those in the rich countries of the North. This income disparity is a crucial factor responsible for the general tensions between North and South, as well as for the crisis characterizing the world economy. Associated problems such as deteriorating commodity prices, northern protectionist barriers against the emerging manufacturing industries of the South, and the vulnerability of southern debtors to rising interest rates have put developing countries at a disadvantage in the global marketplace.

North-South tensions can be eased by working toward the eradication of income disparities by means of policies that foster development in developing countries, including policies that would help make affordable the energy needed to meet development goals.

Poverty in Developing Countries

Not only are North-South disparities large, but within developing countries there are enormous disparities between the elites, which typically account for 10 percent of the population and 30 to 50 percent of all income, and the rest of the population, which lives in abject poverty. The traditional approach to the problem of widespread poverty has been to maximize economic growth and to hope that the benefits of growth would "trickle down" to the poor, and this approach has failed. A policy that targets the satisfaction of basic human needs for food, shelter, sanitary services, health care, education, and meaningful employment is more promising. Energy services are required to satisfy these needs. They must be provided as part of the larger development effort.

Population Growth

Since for the poor, economic pressures tend to favor large families, the population explosion is closely linked to the problem of poverty.[6] Thus, efforts to solve the population problem would be assisted by efforts to satisfy the basic human needs of the poor.

Food Scarcity

Whatever success is achieved in slowing population growth, the problem of feeding an expanding global population will remain a major global challenge for decades. Modernization of agriculture and the associated increased energy inputs are key to meeting food production targets. The FAO estimates that food production in developing countries must double by the year 2000, for which extra energy equivalent to 2.8 million barrels of oil per day would be required.[7] As this is less than the amount of oil *saved* by the United States between 1978 and 1982, it is clear that the challenge has less to do with the quantity of energy required than it does with ensuring that supplies can be directed to agricultural needs.

Global Climatic Change

In a matter of decades, humanity could induce major changes in the global climate as a result of the buildup in the atmosphere of carbon dioxide and the resulting greenhouse effect. The problem is closely related to energy use, since increased atmospheric concentrations of carbon dioxide result from the combustion of fossil fuels. Already in 1979, the atmospheric carbon dioxide level was 1.15 times the preindustrial level, or 334 parts per million (ppmv). Climatologists believe an increase in mean global temperature of 3 degrees Celsius ($\pm$ 1.5 degrees Celsius), with perhaps a two- to three-fold greater warming at the poles, would result from a doubling of atmospheric concentrations of carbon dioxide; the consequent slowdown of the atmospheric heat engine associated with differential equatorial/polar heating rates is expected to lead to significant changes in global weather patterns.[8]

There appear to be no feasible technical fixes to the carbon dioxide problem.[9] The magnitude of the prospective climatic chane can best be limited through reduced dependence on fossil fuels.

Deforestation and Desertification

Between 1952 and 1972, some 30 million hectares of the world's forests were lost per year,[10] while cropland and rangeland losses to desertification averaged 6 million hectares per year.[11] Deforestation arises from the permanent clearing of forest land for agriculture, from fuelwood gathering, and from other overuse of the forest resource; desertification comes in large part with the overuse of marginal lands for agricultural purposes, especially the grazing of livestock. These trends need to be reversed for both environmental and economic reasons. Fuelwood resources could be used renewably, with the level of demand maintained below the regeneration rate, through more efficient use of biomass and better forest management. If agricultural production, including the grazing of livestock, was shifted from marginal to better lands through the use of modern energy-intensive, yield-increasing agricultural techniques, the trend toward desertification could be eased. This is a hopeful prospect since only one-third of all cropland is under heavily mechanized production.[12]

The Risk of Nuclear War

That conflict in the Middle East can draw in and entangle the superpowers and threaten nuclear war is indicated by the experience of October 1973, when the Soviet Union threatened to intervene in the Arab-Israeli war, and the United States, in response, raised the alert status of its nuclear forces.[13] The creation of the U.S. Rapid Deployment Force to assure continued access of the industrialized market economies to Persian Gulf oil, as well as the presence of mobile Soviet forces in the region, indicate the continuing potential for U.S.-Soviet conflict arising from Middle East turmoil. The potential for superpower conflict can be reduced through reduced dependence of the industrialized market economies on Persian Gulf oil.

Nuclear Weapons Proliferation

In 1964, the U.S., the U.S.S.R., France, and Great Britain were the only nuclear weapons states in the world. Since then, China and India have acquired nuclear weapons; several other countries either have gained or soon will possess the capability to produce nuclear weapons. In the coming decades, many more countries could join the nuclear club, particularly if nuclear power comes to be a major energy resource.

An indissoluble link between nuclear weapons and nuclear power arises from the fact that plutonium, a material usable in nuclear weapons, is produced in substantial quantities in nuclear power reactors. There is no technical fix for eliminating this link short of avoiding dependence on the troublesome technologies involved.

The risk of proliferation by governments is far greater with nuclear technologies requiring plutonium recycle than that associated with the present generation of once-through fuel cycles. In the latter case, the acquisition of nuclear weapons would require construction of dedicated facilities for weapons production. This route to nuclear weaponry is deterred both by the difficulties encountered in a governing bureaucracy in achieving consensus as to the desirability of acquiring nuclear weapons and the risk of getting caught and being punished by members of the international community. In contrast, with the plutonium recycle technologies a country acquires nearly all the technology and materials needed to make nuclear weapons quickly (e.g., in a time of international crisis) without ever having to make an explicit decision to acquire such weapons. This route to nuclear weapons, which has come to be called "latent proliferation,"[14] involves low risk to the would-be proliferator and is exceedingly difficult to control institutionally.

By avoiding nuclear fuel cycles that involve the reprocessing of spent reactor fuel and the recycle of recovered plutonium, the risks of proliferation can be greatly reduced. Such fuel cycles must be avoided in all countries, not just in those feared to be proliferation prone; any scheme that would allow plutonium recycle for some countries but not for others would be discriminatory and would ultimately prove to be unstable.[15]

The incentive to reprocess spent fuel and recycle plutonium will remain low as long as uranium prices do not rise too much. If nuclear power develops slowly enough, and especially if nuclear power is regarded as an energy technology of last resort, such a rise in the price of uranium could be avoided.

Technological constraints on the scopes and characters of nuclear power programs by themselves could not halt the horizontal proliferation of nuclear weapons capability to many countries. As long as there is vertical proliferation by the superpowers, other countries will want nuclear weapons as well. The only way to avoid a world in which nuclear weapons are much more widely proliferated is to couple the avoidance of dangerous nuclear power technologies with superpower efforts to move away from weapons of mass destruction.[16]

THE TREATMENT OF THESE PROBLEMS IN OTHER ENERGY ANALYSES

Traditionally, analysts who have dealt with the long-term global energy problem have not sought to identify energy strategies compatible with the solutions of other global problems. Although some recent analyses have explored the long-term effects of particular energy supply constraints,[17] the energy problem has usually been viewed as a narrow engineering challenge centered on the provision of new energy supplies in ways energy suppliers know best, in quantities sufficient to meet future energy needs, as estimated on the basis of crude historical correlations between levels of energy use and human welfare. Projections of future energy requirements made in recent global energy studies by the World Energy Conference (WEC) and the International Institute for Applied Systems Analysis (IIASA),[18] are based on this "supply approach," as is evident in their projected energy requirements for 2020, some two- to three-fold higher than those for 1980. These studies present a view of the global energy future that involves heavy reliance on coal and nuclear power, an emphasis which takes advantage of the abundance of coal and nuclear fuels. But in a world where these projections would be realized, other problems would be exacerbated. For instance, the WEC and IIASA projections imply doubled atmospheric levels of carbon dioxide in the latter half of the next century. The nuclear power projections in these studies imply a serious nuclear weapons proliferation risk; for example, the IIASA nuclear projections imply that by 2020 there would be some 1.8 to 3.0 million kilograms (kg) of plutonium recovered from spent fuel and circulated each year in global commerce; for comparison, some 5 to 10 kg are required to make a nuclear weapon.

These analyses also fail to give adequate attention to the unique problems of the developing countries. For example, while the centralized energy technologies emphasized in conventional energy planning may be applicable to certain urban situations in the developing countries, the energy problems of the rural areas of the developing countries demand quite different strategies. More decentralized solutions, involving energy supplies suitable for widely dispersed industries, are needed for rural areas as the cities are increasingly unable to accommodate the large numbers of people now migrating to urban areas.

THE END-USE APPROACH TO THE GLOBAL ENERGY PROBLEM

In an ongoing global energy project, an attempt is being made to develop a long-term energy strategy that is both technically and economically feasible and consistent with the achievement of a sustainable world society.[19] The present paper explores global aspects of this energy strategy.

We have found that to identify such an energy strategy, it is necessary to shift the focus of analysis from supply to demand and to give attention instead to energy services. This "end-use approach" helps one to better understand the role of energy in society: for example, it can be used to find out the extent to which the energy services needed to satisfy basic human needs are being met[20] and the implications for energy service requirements of ongoing structural changes in the economy.[21] Moreover, improved understanding of the details of energy use can facilitate the discovery of opportunities for cost-saving improvements in end-use technologies.[22] Through the end-use approach it is possible to identify the least costly mix of energy supplies and energy efficiency improvements for providing any given level of energy services.

We have also found that, if the opportunities for energy demand reduction are exploited, substantial flexibility is gained in energy supply planning. The flexibility arises because at a lower overall level of energy demand the number of energy supply options is greater; in contrast, at demand levels as high as in the long-term WEC and IIASA projections, all energy supply options must be pushed to the limits. Lower levels of energy demand allow one the flexibility to choose an energy supply mix that mitigates the externalities posed by overdependence on oil, fossil fuels, and nuclear power or by nonrenewable use of biomass.

A comprehensive global end-use energy demand/supply perspective should be developed as an evolutionary process, from the bottom up. The analysis could begin with country studies that examine present energy use and supply and possible future patterns of demand for energy services, taking into account such factors as climate, demography, the mix of economic activities, social aspirations, etc. Then opportunities for alternative end-use technologies and energy supplies could be described, leading to the formulation of long-term national energy strategies that are consistent with long-term social goals. Individual country strategies could then be aggregated into regional strategies, which in turn could be aggregated into a global strategy.

Since detailed end-use country studies and strategies have been developed for only a few countries, it is not yet possible to put together a global energy strategy according to such an idealized prescription. Nevertheless, it is feasible to formulate a preliminary global energy perspective by extrapolating to the global situation what is known for a few countries.

A BASE CASE ENERGY DEMAND/SUPPLY SCENARIO

The base case global energy demand/supply scenario that will now be described demonstrates that there are energy futures compatible with economic aspirations and responsive to concerns about a broad range of energy-related global problems. Although this scenario lies far outside the range of outcomes forecast in conventional global energy studies, it is both technically and economically feasible.

Our scenario should not be viewed as a forecast. Rather it is one plausible future illustrating the feasibility of a global energy future compatible with the achievement of a sustainable world society. It is based on a set of plausible assumptions illustrating what can be accomplished with energy demand and supply technologies which are already proven or in an advanced state of development. If such an energy future can be identified on the basis of the restrictive assumption that we employ below, there are probably many more energy futures that are also compatible with the achievement of a sustainable world. With this analysis, we hope to provide a more informed basis for energy planning by articulating important but largely unfamiliar choices for the energy future and by showing that the future of energy demand/supply is more a matter of choice than of prediction.

On the demand side, we extrapolate from the results of our analyses for Sweden and the United States to all industrialized countries[23] and from the results of our analysis for a hypothetical developing country to all developing countries. On the supply side, we attempt to show how these needs might be provided for in ways that avoid or mitigate the energy supply-related global problems described above.

We focus on the year 2020. This date is sufficiently far in the future to allow the implementation of programs aimed at the satisfaction of basic human needs in developing countries, and to achieve considerable improvement in living standards beyond the satisfaction of basic human needs. There would also be ample time by then for the widespread adoption of efficient energy end-use technologies. By 2020, the world should be well into a transition to the post-petroleum era, and were conventional energy strategies indeed to be pursued, at that time the carbon dioxide and the nuclear weapons proliferation problems would reach critical proportions. Yet the date is sufficiently close to have an important bearing on present long-range energy planning.

Our analysis is but a first step in an effort to determine how a supply mix compatible with our global goals at the projected energy demand levels might be put together. Since the energy demand/supply balances associated with this exercise are highly aggregated at the global level, our analysis necessarily neglects regional variations in energy demand and supply availability and sheds little light on problems associated with the geographical availability of particular energy resources. Detailed country and regional studies are needed to provide the basis for such analysis.

Energy Demand

Future Per Capita Energy Demand in Industrialized Countries: With only one-fourth of the world's population, the industrialized countries account today for two-thirds of world energy use. Fortunately, it is feasible to substantially reduce the energy intensity of economic activity in the industrialized world. One important factor bearing on future energy demand is the transition in the industrialized world to a post-industrial era characterized by growth in activities that are inherently less energy intensive than economic activities of the industrial era.[24] In addition, there are many cost-effective opportunities for the more efficient use of energy.[25] Our base case energy demand scenario for the industrialized world illustrating these factors is extrapolated from results we have obtained for two countries, the United States and Sweden.[26]

First, our findings for Sweden, which is generally looked to as a model energy-conserving society. While per capita GDP in Sweden is comparable to that in the United States,[27] final energy use per capita is only about three-fifths as large, averaging 5.4 kilowatts (kW) per capita in 1975. Yet our analysis for Sweden reveals major opportunities for energy savings.

To understand these opportunities, we investigated the impact of improved energy-using technology on the demand for energy at various levels of consumption of goods and services. Two different levels of technological improvement were considered: best available technology (that which is judged to be economical today) and advanced technology (for which some success is assumed in ongoing research and development efforts to improve energy efficiency and for which expected costs are in the range of interest). Using the best available technology per capita final energy use in Sweden would be reduced to about 3.5 kW (4.2 kW) for a 50 percent (100 percent) increase in the consumption of goods and services; using advanced technology, which may be more appropriate when looking as far ahead as 2020, per capita consumption would be reduced to 2.7 kW (3.3 kW) for the same increase in the consumption of goods and services.

Our United States country study is also based on the wide use of cost-effective energy end-use technologies. For the U.S. case, projections were made to the year 2020, by which time we showed that it would be feasible to reduce per capita final energy use to 4.3 kW (4.6 kW) from 9.0 kW in 1980, associated with a 50 percent (100 percent) increase in the per capita consumption of goods and services.

In light of these results for Sweden and the United States, and the broad applicability of the technologies involved in these analyses, it is reasonable to expect that on average a 50 percent average reduction in per capita final energy use could be achieved through energy efficiency improvements in industrialized countries, reducing per capita final energy use in these countries by half, from 4.9 kW in 1980 to 2.5 kW by 2020.

A level of 2.5 kW per capita is comparable to what could be realized in Sweden with advanced technology and a 50 percent increase in the per capita consumption of goods and services relative to 1975.* Since in 1975 per capita GDP in Sweden was some 75 percent higher than the average for all industrialized countries,[28] an energy demand level of 2.5 kW could be associated with an increase in the average per capita GDP considerably greater than 50 percent.

Although this level of future per capita energy demand is radically different from that envisaged in previous global energy studies, this energy demand scenario, on the basis of what has emerged from the U.S. and Sweden case studies, would appear to be both technically feasible and economical--i.e., no more, and perhaps less, costly than the amount of energy supply expansion required to provide an equivalent level of energy services with conventional end-use technologies.

While this scenario appears to be feasible, it is unlikely to be realized without public policies that facilitate the exploitation of opportunities for energy efficiency improvement. The needed measures include, among other things, elimination of subsidies for energy supply expansion, transformation of energy utilities from fuel and power suppliers to energy service suppliers, and marginal cost pricing for energy.[29]

The extent to which the opportunities for energy efficiency improvements, which have been identified largely in Organization for Economic

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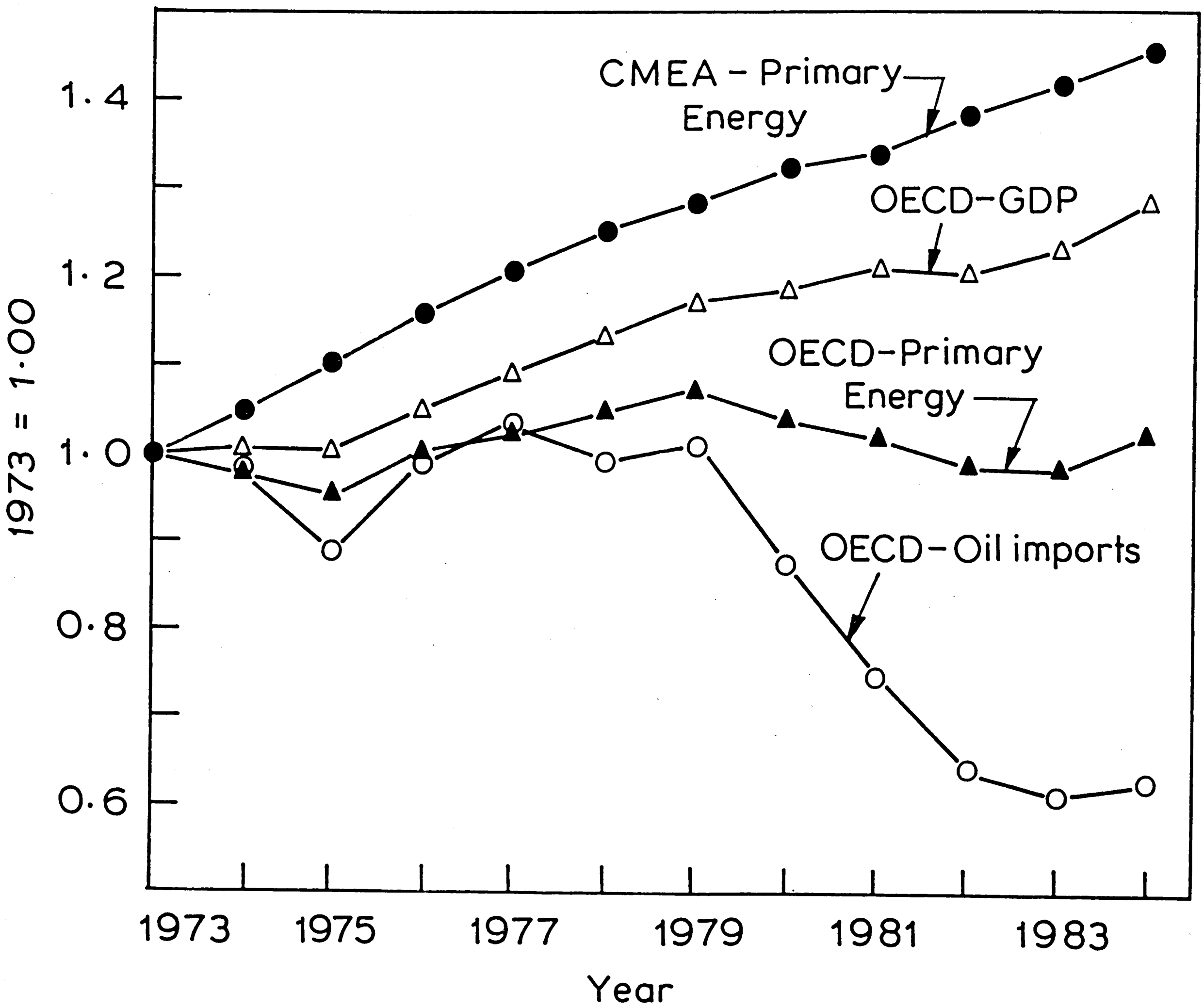
*The reduction in per capita energy demand could vary from country to country and could be quite small for low-income industrialized countries without much affecting the overall average level of future energy demand in industrialized countries. For instance, if per capita energy use were to remain fixed at the 1980 level (2.25 kW) for the six countries with the lowest per capita energy use, the average level of energy use for all industrialized countries would rise only slightly, to 2.58 kW.

Cooperation and Development (OECD) countries, would be seized upon and pursued in Council for Mutual Economic Assistance (CMEA) countries is uncertain. To date, these countries have made little headway in improving energy end-use efficiency (see Figure 2). This constitutes a major uncertainty in this scenario.

Figure 2

TRENDS IN ENERGY USE, GROSS DOMESTIC PRODUCTION, AND OIL IMPORTS, 1973-1984*



CMEA = Council for Mutual Economic Assistance countries
OECD = Organization for Economic Cooperation and Development countries
GDP = Gross domestic production
*Trends are given as a factor of 1973 levels.

Future Per Capita Energy Demand in Developing Countries: At present, per capita energy use in developing countries averages about 0.9 kW, of which some 0.4 kW is non-commercial energy. Most non-commercial energy use is accounted for by the two-thirds of the population who live in rural areas, for the most part isolated from market economies. The challenge for energy planning in developing countries is to assure the availability of energy services to satisfy the basic human needs of the poor, to meet the energy service requirements of a growing population, and to promote a general improvement of the standard of living in an environmentally sound and sustainable way.

How much energy will be needed in developing countries to meet these goals? Since per capita final energy use in developing countries presently averages only 0.9 kW, less than one-fifth of that in industrialized countries, one would think that substantially increased energy use would be required to meet development goals. However, since energy is used very inefficiently at present, this is not necessarily so.

Most commercial energy use is accounted for by a modern sector, which supports mainly the 10 percent or so of the population who live like citizens of industrialized countries, often using energy even less efficiently than citizens of the North. Most energy efficiency improvements identified for the industrialized countries are relevant to the modern sector of developing economies.

Energy efficiency improvements are also relevant for the traditional sector, where energy use is dominated by fuelwood and other bioenergy fuels used for cooking. Per capita energy use for cooking in rural areas is several times as large as that in industrialized countries--in fact it is comparable to per capita energy use for automobiles in Western Europe.

To give an indication of what might be achieved with energy efficiency improvements in the long-term, we have developed an energy budget for a hypothetical country with a mix of energy-using activities similar to that in the mid-1970s for Western Europe (excluding space heating, which is not needed in most developing countries), with the activity levels matched to energy intensities corresponding in energy performance to best available technologies on the market today or to advanced technologies that could be commercialized over a period of about a decade. Remarkably, total final energy use per capita for this scenario is estimated at about 1 kW, or only slightly more than at present.[30]

How is it possible to achieve such a large improvement in the living standard with so little an increase in energy use? Part of the explanation lies in the potential for increasing the efficiency of energy use simply by switching from traditional, inefficiently used, non-commercial fuels to modern energy carriers. The significance of the shift to modern energy carriers is vivid for cooking. The majority of the population in developing countries now uses biomass for cooking at a per capita rate of 1/2 to 1 ton of fuelwood per year--equivalent to an average energy use rate of 250 to 500 watts. However, the rate of energy use for cooking would fall to some 50 watts (the average in Brazilian and Indian houses using liquefied petroleum gas [LPG]) if a switch were made to high-quality gaseous fuels like LPG or biogas. Gas stoves are so much more efficient and controllable than traditional wood stoves. The importance of modern energy carriers is evident from the fact that in 1975 per capita GDP in the WE/JANZ region (Western Europe, Japan, Australia, New Zealand, South Africa, Israel) was ten times that of developing countries, even though per capita final energy use for purposes other than space heating was only 2.3 kW, about two and one-half times the final energy use level in developing countries today.

In addition to the savings associated with the shift to modern energy carriers, considerable further savings can be gained through the adoption of end-use technologies that are more efficient than those now in wide use. For a wide range of such technologies, it would be less costly to provide a given level of energy services with the more energy efficient end-use technology than with conventional end-use technologies and more energy supplies. This has been shown for industrialized countries[31] and for Brazil.[32]

The following are indicative of the technologies that are available: recently developed gas stoves that are 70 percent efficient (and less polluting) than conventional stoves, which have efficiencies around 50 percent;[33] new compact fluorescent light bulbs that are compatible with ordinary incandescent sockets and use one-fourth as much electricity as incandescents; and the most efficient refrigerator-freezer available in 1985, a 301-liter Japanese unit that requires just 406 kilowatt-hours (kWh) per year, about one-fourth of the electricity required by the average refrigerator-freezer in use in the United States.

While most of the technologies assumed for this 1-kW scenario are commercially available today, a few are still in an advanced state of development. For example, the energy performance for steel making is assumed to be the average for the Swedish Plasmasmelt and Elred processes. With these steel-making technologies, only half as much energy is required to produce a ton of steel, as compared with the average Swedish technology in use in 1976.[34]

The WE/JANZ activity levels in this 1-kW scenario should not necessarily be taken as targets for developing countries. In the first place, because technology is continually changing and the utility derived from a given amount of material, like that from energy, is constantly increasing, it would be foolish to target for the future of developing countries levels of materials consumption achieved in the past in industrialized countries. Higher energy costs usually translate into higher costs for basic materials. The rising costs of basic materials in recent years have fostered a wave of innovation in industrialized countries, leading to the introduction of lighter-weight products, more durable goods, the substitution of less costly materials in product manufacture, and less wasteful practices in the use of non-durable goods--trends that are expected to continue.[35] This implies that in the future rates of materials consumption (e.g., per capita consumption rates for steel, paper, and ammonia) considerably lower than those assumed for the 1-kW scenario would be adequate to provide the level of amenities common in the 1970s in the WE/JANZ region.

Moreover, instead of adopting copycat development strategies, long-term development goals should reflect the resource constraints, the comparative advantages, and the unique social needs of developing regions. An alternative to the pattern of development followed in Western Europe might emphasize instead decentralized industry and local self-reliance, and thus might involve less energy-intensive activities than a pattern of development that emphasizes urbanization and the attendant need for long-distance transport, packaging, and storage of foodstuffs and industrial goods.[36] With a strong emphasis on energy efficiency improvement, such an alternative development path could probably be supported with less energy than 1 kW per capita consumption.

Even though the activity levels of our 1-kW scenario should not be blindly pursued by developing countries, the 1-kW analysis shows clearly that living standards in developing countries ranging from those of the present up to those of the WE/JANZ region could be realized without increasing per capita energy use. On the basis of such considerations, we assume an average level of per capita energy use of 1 kW for developing countries in 2020--a level which, with emphasis on energy efficiency improvement and modern energy carriers, would be adequate both to ensure that basic human needs are satisfied and to allow for considerable further improvements in living standards.

Of course, all this should not obscure the difficulties likely to be encountered in the pursuit of development goals. As in the case of development generally, large amounts of capital would be required to introduce widespread use of modern energy carriers and efficient end-use technology. Nevertheless, this analysis suggests that there should be no fundamental energy constraint to development, as our energy supply analysis will show more clearly.

The Demographic Context: In conventional energy demand projections, it is customary to treat population as a given, not affected by energy policy. However, the energy problem would be significantly easier to solve were the pressures of population growth to be eased. This can be seen in the differing energy requirements for the alternative United Nations (U.N.) population projections for the year 2020.[37] Even though a relatively small range is projected (± 10 percent of the medium variant projection of 7.8 billion), total global population is so large by 2020 that small relative changes can have significant impacts on the energy problem. For example, at the present level of per capita energy use, the difference between the high and low U.N. population variants corresponds to an extra energy supply in 2020 equivalent to nearly the present level of world oil production.

We have stressed development strategies that satisfy basic human needs as a part of the overall effort needed to deal with the population problem. We shall assume for our base case scenario that efforts to satisfy basic human needs would be reflected in slower population growth than would otherwise be the case. Since it is not possible at this time to quantify the impact of a basic human needs policy on population growth, we adopt the low U.N. population variant for our base case energy demand scenario--1.24 and 5.71 billion for industrialized and developing countries respectively in 2020, up from 1.11 billion and 3.32 billion in 1980.

Global Energy Demand: Assuming for industrialized countries a 50 percent reduction in per capita final energy use between 1980 and 2020, and the low U.N. population variant for the year 2020, total final energy use by industrialized countries would be reduced from 5.5 terawatts (TW) in 1980 to 3.1 TW in 2020. Assuming for developing countries a per capita final energy use level of 1.0 W in 2020, total final energy use there would increase from 2.9 TW in 1980 to 5.7 TW in 2020.[38]

Global final energy demand, however, would be about the same in 2020 as in 1980, and the developing countries' share would increase from one-third to two-thirds of the total.[39] Figure 3 shows the global energy demand level for 2020 and the distribution of demand between developing and industrialized countries in terms of primary energy (which includes the energy conversion, transmission, and distribution losses for the assumed supply mix) for our base case scenario, for the alternative WEC and IIASA scenarios, and for 1980. This figure shows that the major difference between our base case scenario and the energy scenarios presented in the 1982 WEC energy study and the 1981 IIASA energy study lies in the treatment of the industrialized countries. Primary demand for developing countries in our base case scenario is 1.3 kW per capita, which is the same as the average value for the WEC high and low scenarios and only slightly less than the average of 1.5 kW for the average of the IIASA high and low scenarios. In light of the much greater emphasis given here to energy efficiency improvement, the 1.3 kW of primary energy in our base case scenario corresponds to a much higher living standard.

While the level of global energy demand would not change much between 1980 and 2020 in our base case scenario, we expect that there would be a marked shift to higher quality energy carriers. In particular, we assume a continuation of the ongoing electrification of the global energy economy, increasing electricity's share of final demand from 10 percent in 1980 to 18 percent in 2020.[40] This implies a doubling of electricity production between 1980 and 2020.

Energy Supply

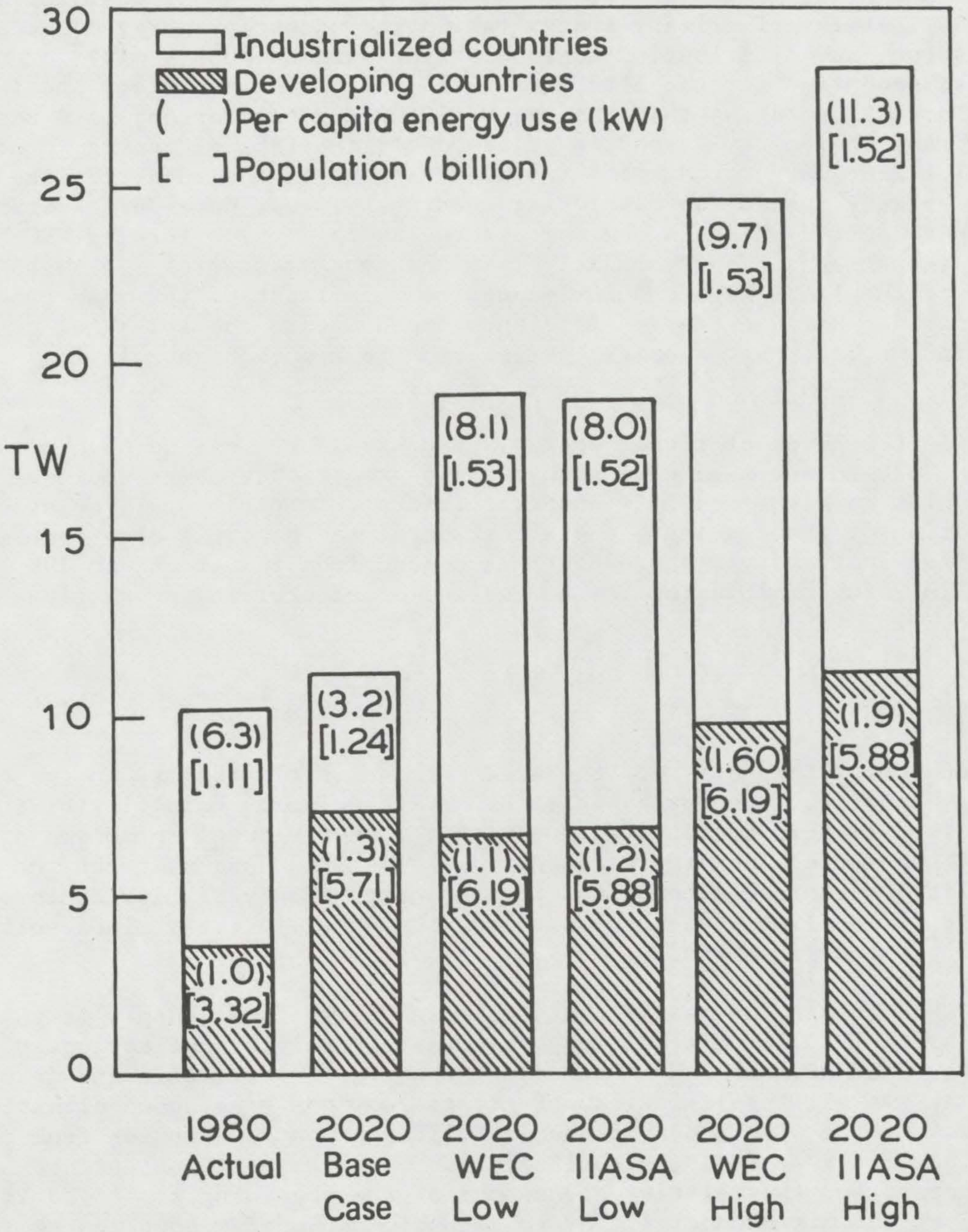
When energy demand is not too great, there is flexibility in the choice of energy supplies. We now explore the extent to which this flexibility can be exploited to help society to cope with the energy supply problems aggravated by conventional energy strategies. Rather than speculate on the possibility of radical alterations in the energy supply mix, we explore the prospects for dealing with these problems through relatively minor shifts from the present situation.

In this spirit, we assume that the total fossil fuel supply is the same in 2020 as in 1980, with remaining demand met largely by nuclear power, hydropower, and biomass. We then adjust the mix of coal, oil, and natural gas in the overall fossil fuel supply to reflect concerns about climatic change associated with the atmospheric buildup of carbon dioxide from the combustion of fossil fuels, global security, and the world oil price, as well as to account for the relative abundances of the remaining fossil fuels. We also adjust the mix of nuclear, hydro, and biomass energy supplies to reflect our concern about proliferation, and land-use impacts and impacts on the environment.

While the use of each individual fuel in 2020 differs little from the present level in our base case scenario, it is radically different from what is envisaged for the year 2020 in conventional energy forecasts. Figure 4 shows, for example, that in the WEC and IIASA scenarios fossil fuel use in 2020 would be about double that for our base case scenario and nuclear energy use would be four to seven times as large.

Figure 3

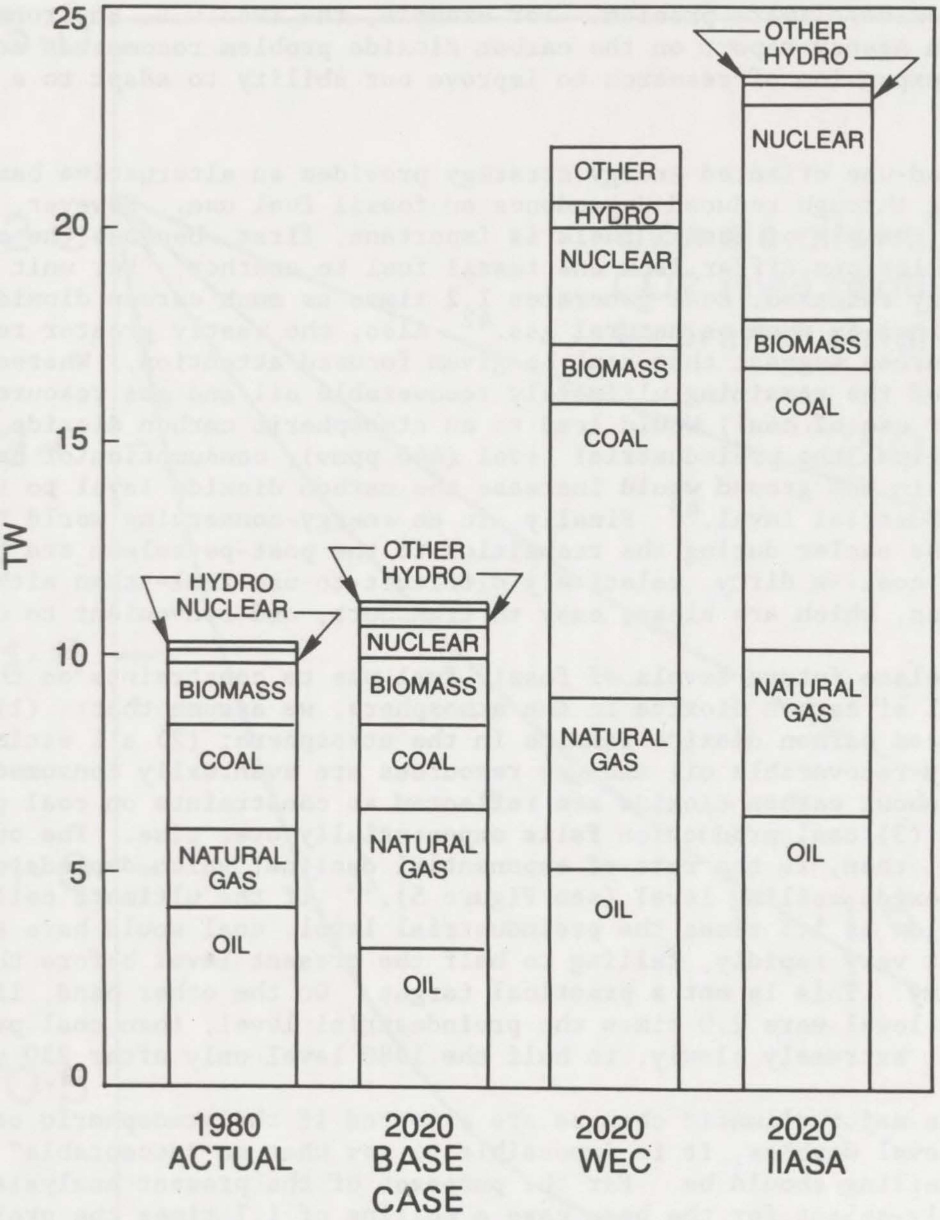
ALTERNATIVE PROJECTIONS OF GLOBAL PRIMARY ENERGY USE (in terawatts) TO THE YEAR 2020, DISAGGREGATED BY CONSUMING REGION



WEC = World Energy Conference; source: J.R. Frisch, *Energy 2000-2020...Where Are We Going? Regional Stresses* (London: Conservation Commission of the World Energy Conference, 1982).

IIASA = International Institute for Applied Systems Analysis; source: W. Haefele et al., *Energy in a Finite World: A Global Systems Analysis* (Cambridge, Mass.: Ballinger Publishing Co., 1981).

Figure 4
ALTERNATIVE PROJECTIONS OF GLOBAL PRIMARY ENERGY USE (in terawatts) TO THE YEAR 2020, DISAGGREGATED BY PRIMARY ENERGY SOURCE*



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IIASA = International Institute for Applied Systems Analysis; source: W. Haefele et al., *Energy in a Finite World: A Global Systems Analysis* (Cambridge, Mass.: Ballinger Publishing Co., 1981).

*WEC and IIASA projections are averages of the high and low projections presented in those global energy studies.

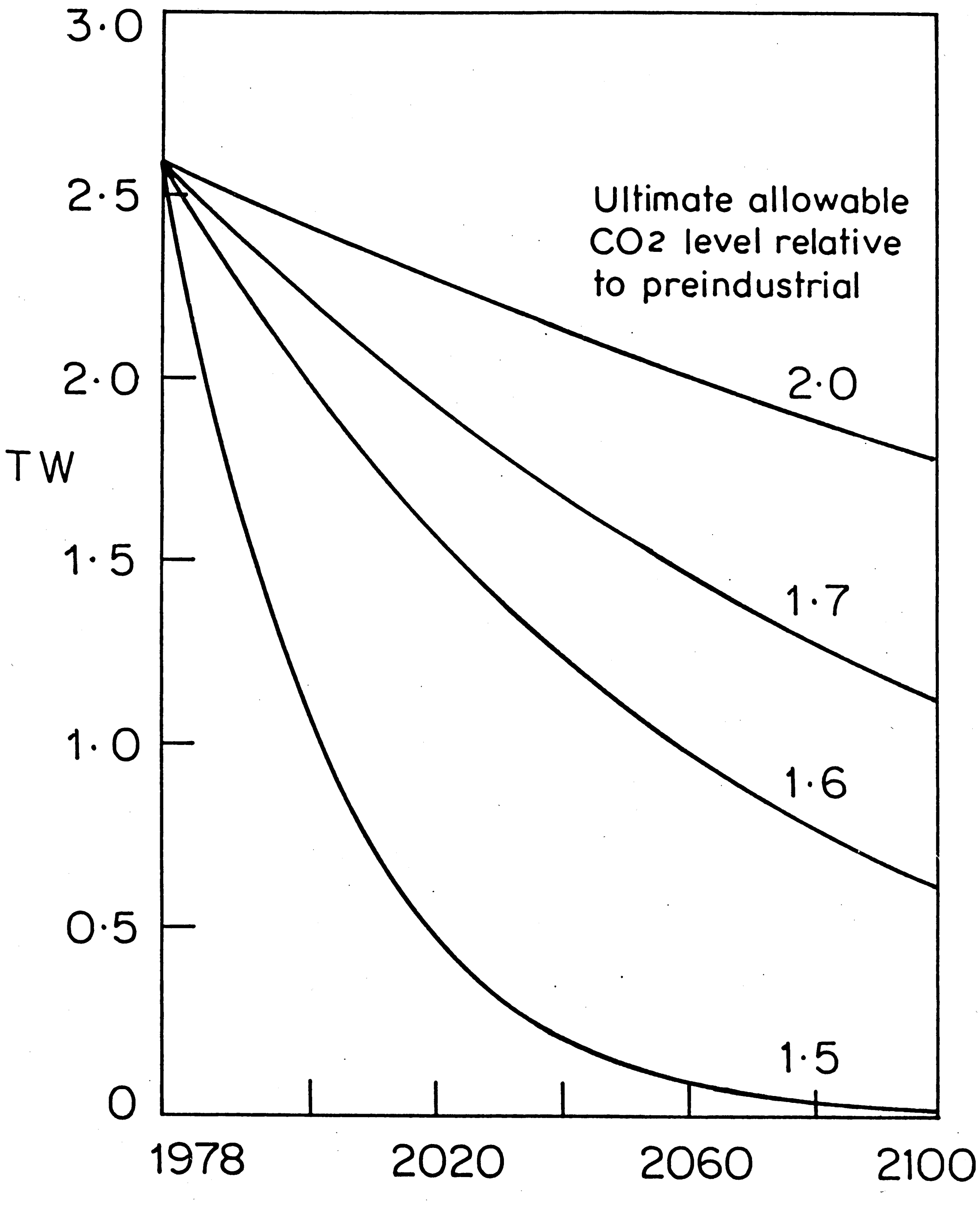
Atmospheric Carbon Dioxide and the Burning of Fossil Fuels: The prospect that the atmospheric carbon dioxide level would double and create a major climatic change in the latter half of the next century has generated a rapidly growing literature on strategies for societal accommodation to the carbon dioxide/climate problem. For example, the 1983 U.S. Environmental Protection Agency report on the carbon dioxide problem recommends acceleration and expansion of research to improve our ability to adapt to a warmer climate.[41]

An end-use oriented energy strategy provides an alternative basis for responding through reduced dependence on fossil fuel use. However, in addition, the mix of fossil fuels is important, first, because the carbon dioxide emissions differ from one fossil fuel to another. Per unit of fossil fuel energy released, coal generates 1.2 times as much carbon dioxide as oil and 1.8 times as much as natural gas.[42] Also, the vastly greater remaining coal resources suggest that coal be given focused attention. Whereas consumption of the remaining ultimately recoverable oil and gas resources (with no further use of coal) would lead to an atmospheric carbon dioxide level only 1.5 times the preindustrial level (440 ppmv), consumption of half the coal left in the ground would increase the carbon dioxide level to four times the preindustrial level.[43] Finally, in an energy-conserving world it may prove to be easier during the transition to the post-petroleum era to make do with less coal--a dirty, relatively difficult-to-use fuel--than either oil or natural gas, which are clean, easy to transport, and convenient to use.

To relate future levels of fossil fuel use to constraints on the ultimate level of carbon dioxide in the atmosphere, we assume that: (1) half of the released carbon dioxide remains in the atmosphere; (2) all estimated ultimately recoverable oil and gas resources are eventually consumed, so that concerns about carbon dioxide are reflected as constraints on coal production; and (3) coal production falls exponentially over time. The one free parameter, then, is the rate of exponential decline, which depends on the carbon dioxide ceiling level (see Figure 5).[44] If the ultimate ceiling were to be as low as 1.5 times the preindustrial level, coal would have to be phased out very rapidly, falling to half the present level before the turn of the century. This is not a practical target. On the other hand, if the allowable level were 2.0 times the preindustrial level, then coal production could fall extremely slowly, to half the 1980 level only after 230 years.

While major climatic changes are expected if the atmospheric carbon dioxide level doubles, it is impossible to say what an "acceptable" carbon dioxide ceiling should be. For the purposes of the present analysis, we arbitrarily select for the base case a ceiling of 1.7 times the preindustrial level (490 ppmv), which implies a fall in coal use to half its present level only after 100 years and a 20 percent decline in coal use between 1980 and 2020. In our base case scenario, by 2020, the atmospheric carbon dioxide level would be about 1.3 times the preindustrial level (380 ppmv). The level of coal use would be only 20 to 40 percent as high in 2020 as in the WEC and IIASA scenarios (see Figure 6). In 2020, emissions of carbon dioxide from the burning of all fossil fuels would be only 40 to 60 percent as large as in the IIASA and WEC scenarios.

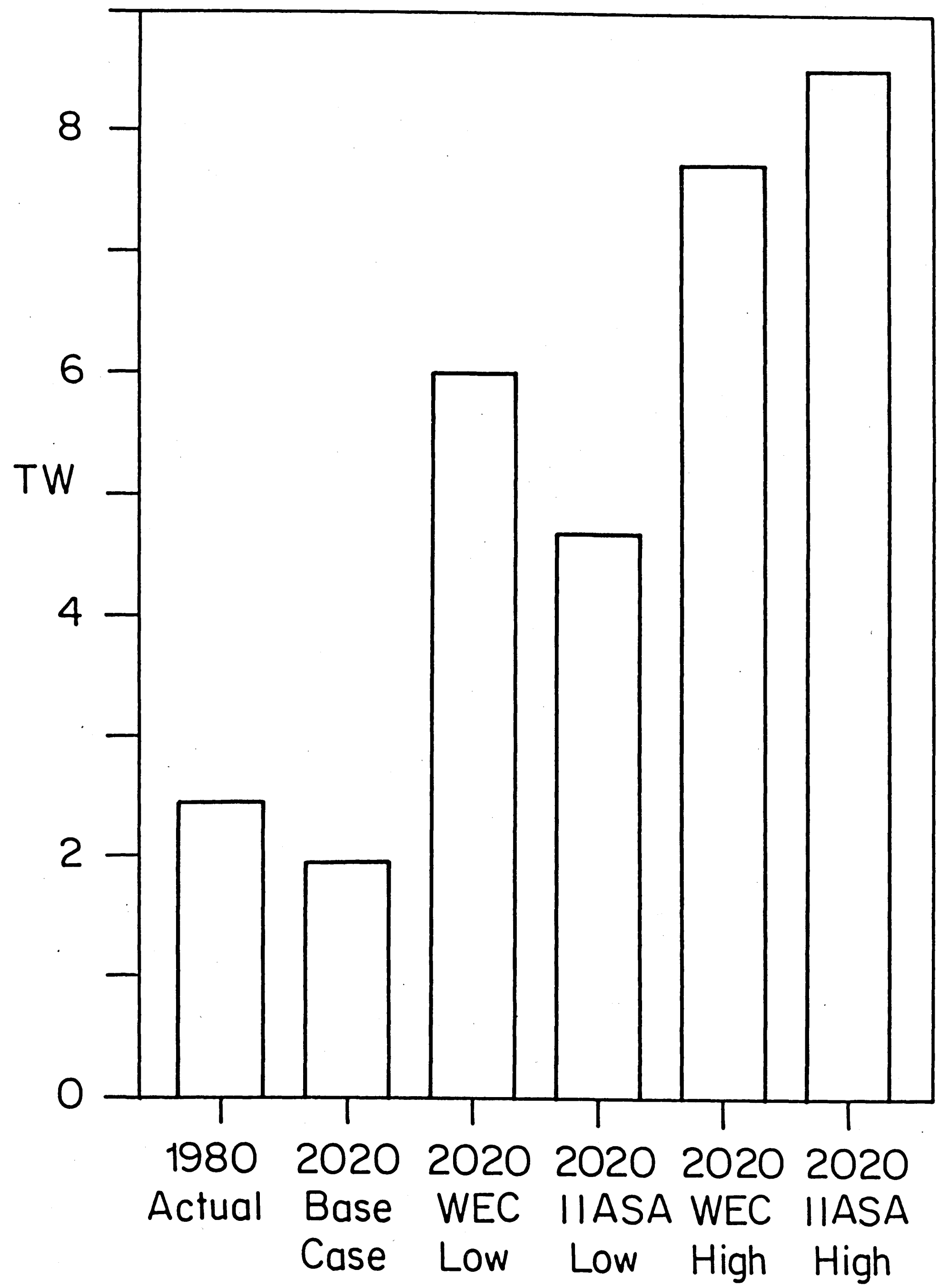
Figure 5
CONSTRAINED ANNUAL GLOBAL COAL PRODUCTION (in terawatts) AS A FUNCTION OF THE ALLOWABLE ULTIMATE ATMOSPHERIC CARBON DIOXIDE LEVEL*



*Assuming that the carbon dioxide constraint is reflected entirely as a constraint on the use of coal.

Figure 6

ALTERNATIVE PROJECTIONS OF GLOBAL COAL PRODUCTION (in terawatts)



WEC = World Energy Conference; source: J.R. Frisch, *Energy 2000-2020...Where Are We Going? Regional Stresses* (London: Conservation Commission of the World Energy Conference, 1982).

IIASA = International Institute for Applied Systems Analysis; source: W. Haefele et al., *Energy in a Finite World: A Global Systems Analysis* (Cambridge, Mass.: Ballinger Publishing Co., 1981).

Despite the slow rate of coal phase-out implicit in this scenario, control of atmospheric carbon dioxide concentrations through restriction on coal use poses major economic and political challenges. The carbon dioxide ceiling we have assumed limits the usable coal resource to about one-fourth of the amount of coal available at prices less than one-half the world oil price in 1982.[45] Nevertheless, even with this constraint, coal would remain a major energy resource for a long time to come; the cumulative allowable production is equivalent to a 150-year supply at the present rate of usage.

The fact that almost 90 percent of the coal left in the ground is concentrated in just three countries (the Soviet Union, the United States, and China)[46] makes the prospects for control brighter than would be the case were the resources to be distributed widely throughout the world. Because of the uneven distribution, agreement among just these countries could have a major impact on coal use.

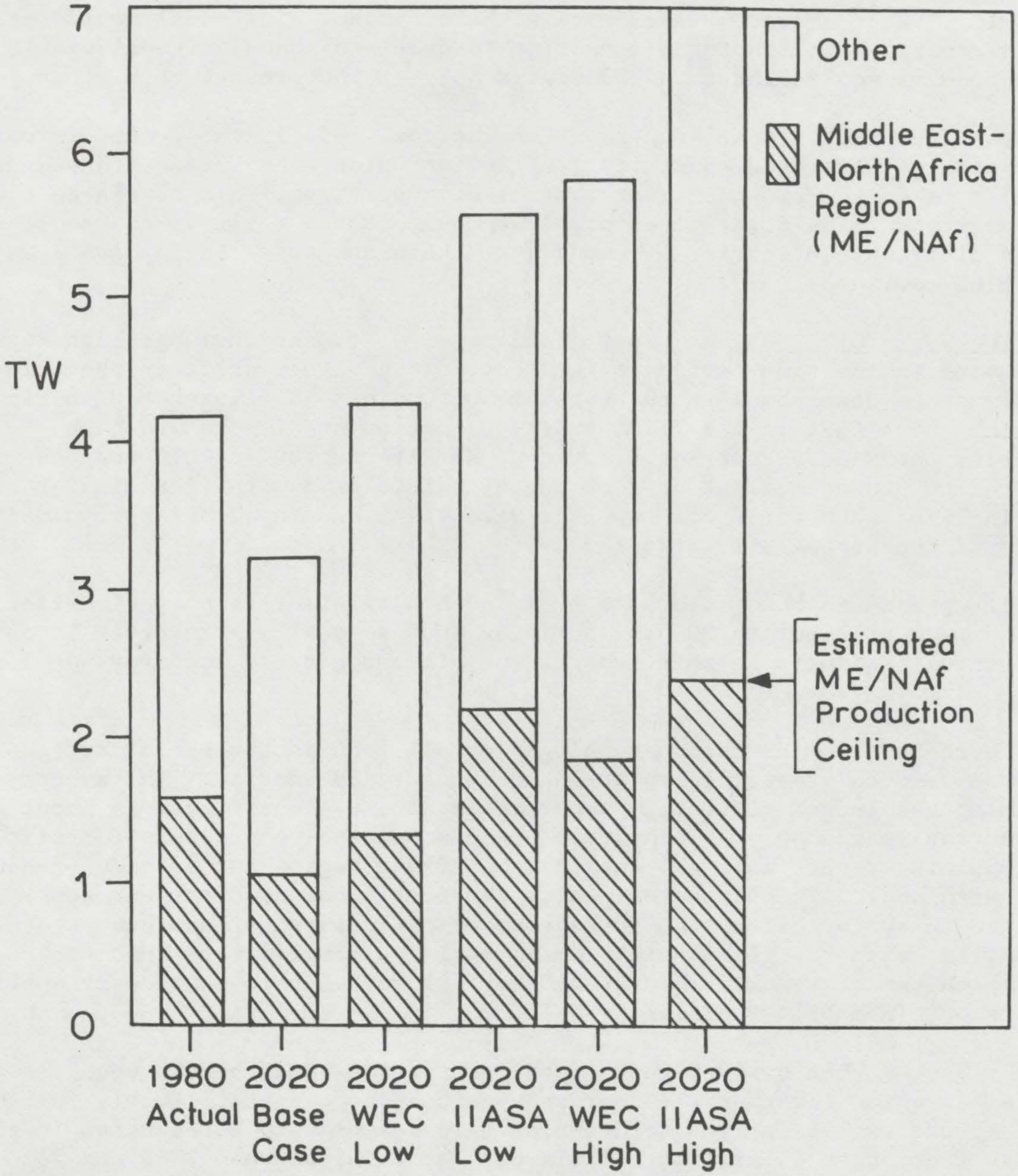
<u>The World Oil Problem</u>: Most global energy studies envisage high future oil demand in the time period of interest, along with a shift of the balance of oil market power back to the Persian Gulf. This is illustrated in Figure 7, which shows that in the IIASA energy scenarios and in the WEC high scenario, the Middle East/North African (ME/NAf) region in 2020 would be required to produce oil at or near capacity levels--a situation similar to that in 1979, when world oil supplies were tight and the Iranian revolution triggered the second oil price shock.[47]

It appears to be possible to avoid such a tight oil supply situation for the entire period out to 2020 by pursuing end-use energy strategies in conjunction with efforts to shift the mix of oil and gas use to favor natural gas.

There is about as much natural gas as oil left in the world, but the gas resource is much greater in relation to current consumption. The amount of remaining gas judged ultimately recoverable at the global level is about a two hundred-year supply,[48] compared to a one hundred-year supply for oil;[49] the remaining recoverable gas outside the ME/NAf region and outside of countries with centrally planned economies is about a one hundred-year supply, compared to 40 for oil at the current consumption rate. Thus, one strategy for dealing with the global oil problem would be to give more emphasis to gas, which can be readily substituted for oil not only in stationary applications but in mobile vehicles as well.[50]

We assume that by 2020 gas and oil production rates become equal (see Figure 4), which together with our assumptions about overall fossil fuel use and coal use implies a 1.85-fold increase in gas use but a reduction in global oil use from 59 to 45 million barrels per day (MBD) between 1980 and 2020. At this lower level of world oil demand, there would probably be adequate oil supplies available outside the ME/NAf region at production costs lower than $30 per barrel (in 1982 dollars) to sustain dependence on the ME/NAf region at the 1983 world oil glut level of 15 MBD.[51] Such a scenario implies much greater global security and far lower oil prices than in the WEC and IIASA scenarios, and perhaps even stable oil prices for the entire period out to 2020. As a result, oil would be a more dependable and affordable energy source and more available for essential development purposes in developing countries during the critical transition period to the post-petroleum era.

Figure 7
ALTERNATIVE PROJECTIONS OF GLOBAL OIL PRODUCTION (in terawatts), DISAGGREGATED INTO THE MIDDLE EAST/NORTH AFRICAN (ME/NAF) REGION AND THE REST OF THE WORLD



WEC = World Energy Conference; source: J.R. Frisch, *Energy 2000-2020...Where Are We Going? Regional Stresses* (London: Conservation Commission of the World Energy Conference, 1982).

IIASA = International Institute for Applied Systems Analysis; source: W. Haefele et al., *Energy in a Finite World: A Global Systems Analysis* (Cambridge, Mass.: Ballinger Publishing Co., 1981).

Nuclear Weapons Proliferation and Nuclear Power: Regarding the nuclear power-nuclear weapons connection, it is widely believed that the "genie is out of the bottle," so that we must learn to live with the risks of a proliferated world. Indeed, the genie would be out of the bottle if the WEC or IIASA nuclear power projections were borne out. In the IIASA and WEC studies, nuclear power is projected to grow to levels ten to thirty times the 1980 level by 2020 (see Figure 8). But these projections are not necessarily destiny.

If nuclear power growth were sufficiently slow that the economic incentive to recycle plutonium were to remain low everywhere (by avoiding uranium scarcity), the risks of latent proliferation by non-nuclear weapons states and of merging weapons and civilian nuclear power programs in weapons states would be reduced considerably.

Since the economics of reprocessing and recycle are not now favorable and would be only marginally favorable at very high uranium prices, avoiding reprocessing and plutonium recycle, though politically challenging, is in principle much easier to accomplish today than was thought possible just a few years ago.[52]

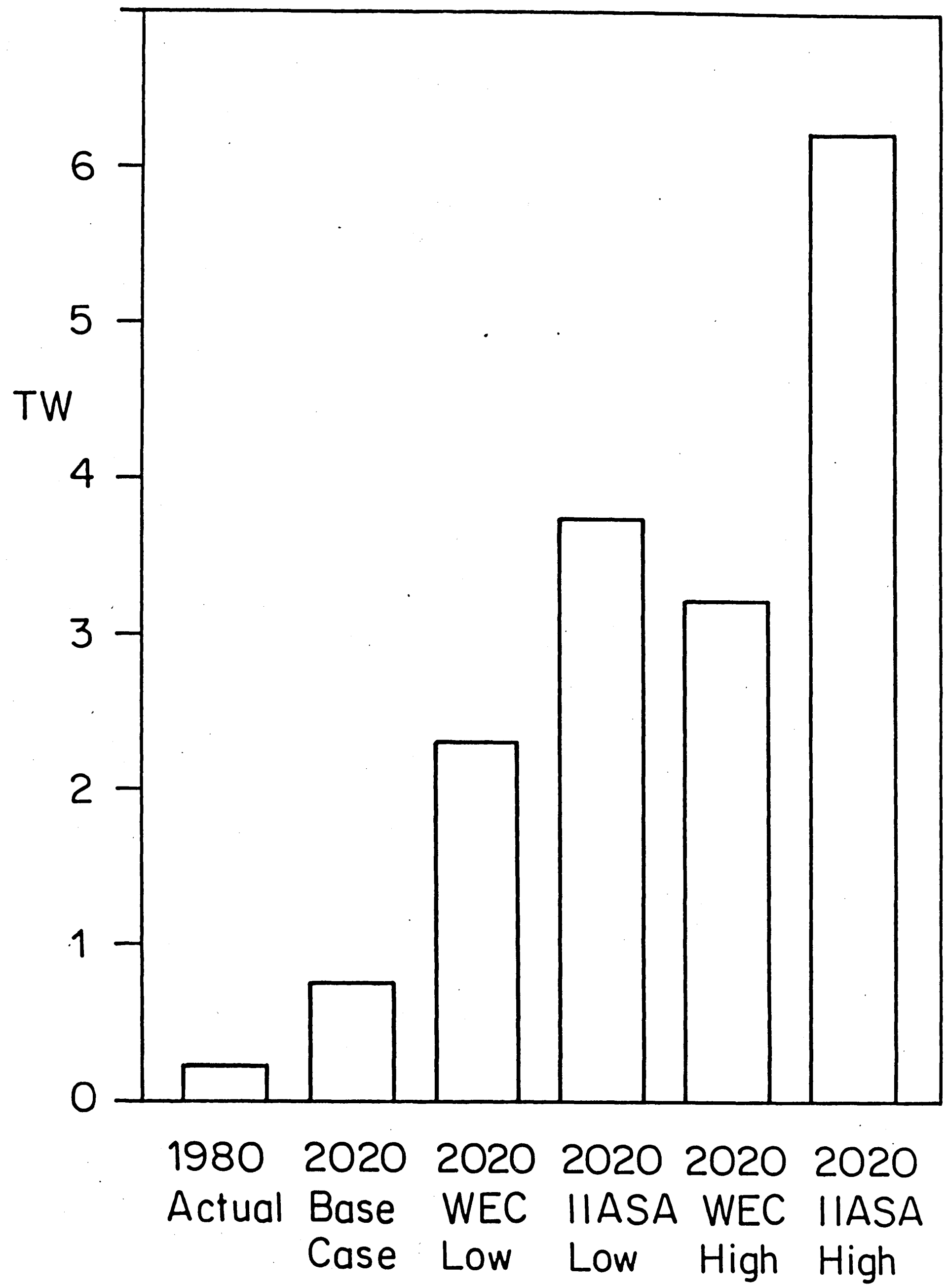
Since even a ban on nuclear fuel reprocessing and plutonium recycle would not prevent proliferation through the clandestine recovery of plutonium from spent fuel--the risk of which increases with the extent of worldwide nuclear power development--it would seem desirable to go further and make nuclear power an energy technology of last resort, limited to those situations where alternatives are not available.

We adopted this perspective in constructing the base case scenario, for which we assumed that installed nuclear generating capacity increases from the 1980 level of 120 gigawatt electricity (GW[e]) to some 460 (GW[e]) (approximately the level generally expected for the year 2000)[53] and then levels off. This implies that beyond the turn of the century the only nuclear plants that would be built would be those that replace retired units.

Roles for Renewable Resources: The global risks posed by dependence on oil, fossil fuels generally, and nuclear power can be lessened through greater dependence on renewable energy sources. However, the prospects of heavy reliance on renewable resources are far more speculative at the present time than the prospects for reduced dependence on conventional energy sources through the use of much more efficient energy end-use technologies. Moreover, large-scale development of some renewable energy resources, if not done carefully, can also pose land-use conflicts or pose other problems. For example, as we have pointed out, the present pattern of non-renewable biomass use for energy and other purposes is a major cause of deforestation.

Nevertheless, renewables can play an important role in the overall global energy budget. Hydropower, wind and photovoltaic energy, and bioenergy in particular are among the more promising renewable energy sourc88es, which with careful planning can be significant energy sources.

Figure 8
ALTERNATIVE PROJECTIONS OF PRIMARY ENERGY USE (in terawatts)
ASSOCIATED WITH NUCLEAR POWER GENERATION



WEC = World Energy Conference; source: J.R. Frisch, *Energy 2000-2020...Where Are We Going? Regional Stresses* (London: Conservation Commission of the World Energy Conference, 1982).

IIASA = International Institute for Applied Systems Analysis; source: W. Haefele et al., *Energy in a Finite World: A Global Systems Analysis* (Cambridge, Mass.: Ballinger Publishing Co., 1981).

For our base case scenario, we assume that these sources meet energy requirements in excess of what can be provided with conventional energy sources in light of the constraints we have assumed to limit the use of fossil and nuclear energy sources.

We do not suggest that the level and/or mix of renewable resources we have chosen for 2020 (see Figure 4) is optimal.[54] Rather, we have chosen a level and a mix which we feel are plausible and which would not obviously be significantly constrained by potential land-use conflicts or other limitations on the use of these resources.

Hydropower: Among renewable power generation sources, hydropower is fully proven and is especially promising in developing countries, where only 7 percent of economical reserves have been developed to date. Hydropower, which is often much less costly to develop than thermal power, provides the opportunity for many developing countries to become more self-reliant in energy.

We assume for the base case scenario that the hydro share of total electricity increases from 20 percent in 1980 to 25 percent in 2020, by which time about 40 percent of the economic hydro potential (or 20 percent of the technically usable potential) would be developed.[55] This level of hydro development is sufficiently far from the technical limit of the resource that it need not involve sites that would be particulary disruptive ecologically. Moreover, the assumed pace of hydro expansion is sufficiently modest (2 percent average annual growth) that expansion could be carefully integrated into the overall development process, thereby taking into account the range of social and ecological concerns that have been raised about hydro development.

Wind and Photovoltaics: Wind power is also a potentially important renewable power source. Large mass-produced wind machines appear to be competitive in windy areas with conventional sources of electric power.[56] The most promising wind regimes lie in industrialized countries, in several of which commercial wind energy systems have been built.

While not yet commercially established, photovoltaic technology holds great promise, especially if recent innovations such as amorphous silicon solar cells are as successful as predicted.[57]

Owing to the commercial uncertainties surrounding photovoltaics, we make no separate estimate of the level of use of this technology but instead consider wind and photovoltaic technologies together and assume that these sources together account for 5 percent of total electricity use in 2020.

Fuel-Fired Thermal Power Plants: We assume that electricity requirements in excess of that which is provided by nuclear power, hydropower, wind, and photovoltaics will be provided by conventional central station fuel-fired thermal power plants or cogeneration plants. Assuming that 15 percent of the electrical demand could be met by cogeneration (a percentage which reflects our analysis of the industrial cogeneration potential in the United States), the amount of electricity required from fuel-fired central station thermal power plants should be about the same in 2020 as in 1980, despite a doubling of the overall use of electricity.[58]

Biomass Energy Sources: Biomass is widely regarded as poor people's energy--an energy source unfit for a modern society. This perception makes it difficult for many people to take seriously any notions of significant bioenergy development. Yet bioenergy sources have many attractive aspects. Used directly, biomass is a fuel that is usually less costly than oil and is often competitive with coal. For the production of synthetic gaseous or liquid fuels, biomass is in many ways superior to coal: it has much less sulfur than coal, little ash, and, because of its looser molecular structure, it can be gasified at a lower temperature than coal. Grown on a renewable basis, biomass can be used as a chemical fuel, the production and use of which leads to no net increase in the atmospheric carbon dioxide level. Lastly, the production of modern gaseous and liquid energy carriers from biomass sources also promotes self-reliance among fossil fuel-poor but biomass-rich countries.

For our base case scenario, we assume that half of all cogenerated electricity (e.g., cogeneration in the forest products and agricultural processing industries) is based on biomass, requiring some 0.2 TW of primary biomass energy.[59] In addition, we assume that for direct use applications, some 1 TW (one-eighth of all direct fuel use) of solids, liquids, and gases would be required from biomass sources,[60] owing to our assumed constraint on the overall fossil fuel supply. Assuming that biomass feedstocks are converted to useful solid, liquid, and gaseous energy carriers at an average conversion efficiency of 70 percent, some 1.4 TW of primary biomass energy would be required to make these fuels, bringing the total primary biomass energy requirements for our base case scenario to 1.6 TW,[61] which is only slightly higher than the use of bioenergy sources in 1980 (see Figure 4).

We assume here that attempts would be made to utilize bioenergy on a renewable basis, thereby countering deforestation trends associated with current non-renewable uses of biomass. Toward this end, we focus attention on two biomass sources, the careful use of which could support efforts to reverse the ongoing process of deforestation: organic wastes and biomass grown for energy purposes.

Global production of organic wastes (forest product industry wastes, crop residues, manure, and urban refuse), is enormous, amounting in 1980 to about 2.8 TW, or an amount some two-thirds as large as world oil production. Assuming that the production of organic wastes increases in proportion to population, it would reach 4.1 TW by 2020.[62] However, because of the competing uses for these wastes,[63] we assume in our base case scenario that only 0.8 TW (one-fifth of the total) is recovered for energy purposes.

With this level of organic waste utilization, an equal amount of biomass would have to be grown for energy purposes. An annual production of some 1.4 billion tons of dry biomass per year is required to provide 0.8 TW of biomass energy. Given the relatively low productivities of existing forests, we instead assume managed biomass production for energy use or for multiple purposes on biomass plantations or farms or woodlots. With managed biomass production productivities can be much higher than in natural forests. For the purposes of the present analysis, we assume that the mean recoverable biomass productivity from plantations is 10 dry tons per hectare per year. While this is far less than what has been achieved under very favorable circumstances, there is not enough good long-term data available upon which to indicate reliably much higher productivities.[64] Such a level of annual productivity implies a need in 2020 for some 140 million hectares, which is on the order of 4 percent of the world's forest area. Hence, in the case of energy plantations, as in the case of organic waste utilization, it is clear that the demands on the biomass system are rather modest and would not seem to be limited by any significant land use or other constraints.

Overview of Energy Supply for the Base Case Scenario: The primary energy supply for the base case scenario is shown in Figure 4, along with the actual supply of 1980 and the supply requirements of the WEC and IIASA scenarios. We have made no attempt to assemble an energy supply mix that is optimal in an economic sense. Rather, the supply mix for our base case scenario is highly plausible and compatible with efforts to solve important global problems having strong links to energy.

What is perhaps most striking in a comparision of the supply levels and mixes for our base case scenario and the WEC and IIASA scenarios is that, while our finding, that it appears to be both technically and economically feasible to find energy strategies compatible with and supportive of the solutions to other important global problems, is a "radical result," it is the WEC and IIASA energy supply scenarios which are radically different from the present situation and which, if pursued and realized, would require that society face and overcome formidable economic and institutional hurdles. Our base case scenario involves no major changes from the present situation--the overall level of fossil fuel use is unchanged, the renewable share is up only modestly (from 16 percent in 1980 to 19 percent in 2020), and no exotic energy sources would be required. In short, the energy supply problem would be quite manageable.

SENSITIVITY ANALYSIS

Our analysis has shown that for the assumptions underlying our base case scenario, a plausible energy future can be described which is compatible with and supportive of the solutions of global problems other than energy. How dependent is this outcome on the various assumptions? To address this issue we present a sensitivity analysis, considering in turn biomass and then oil and gas as swing energy sources--meaning that the levels of these supplies are adjusted to bring energy supply and demand into balance as variations are made in the scenario assumptions relating to population, per capita energy use, the atmospheric level of carbon dioxide, and nuclear power.

Biomass as the Swing Energy Source

Biomass is a potentially important swing energy source because: it is a widely available renewable energy source that can be readily utilized with technologies at hand or brought to commercialization quickly; its use on a renewable basis would not aggravate the global carbon dioxide problem; and the development of biomass resources for energy purposes would constitute an important part of a global afforestation effort.

Given the uncertainties surrounding the extent to which organic wastes can be used for energy purposes, we assume that organic waste use for energy in 2020 cannot exceed 1.0 TW, or one-fifth of the total organic waste generation rate.[65] We further assume that plantations and organic wastes contribute equally to the biomass supply until the organic waste use level reaches 1.0 TW and that all additional biomass is from plantations.

A useful index for measuring the biomass production effort is the average rate at which new plantations (in million hectares per year) have to be brought into production to assure the availability of sufficient biomass in 2020 to meet the targeted biomass supply levels. We shall refer to this index as the plantation expansion rate (PER).* For our base case scenario, this rate would be 4.6 million hectares per year, which is comparable to the present PER for fuelwood plantations in developing countries.[66]

We now discuss in turn the sensitivity of the PER to changes in several assumptions underlying our analysis.**

<u>Population</u>: We have already noted that total energy supply requirements in 2020 are a sensitive function of population. With plantation energy as the swing energy source, the PER is even more sensitive to population (see Figure 9).

The PER increases from less than 5 million to 14 million (22 million) hectares per year as the population increases from the low to the medium (high) U.N. variant for 2020, a calculation which underscores the importance of efforts to slow population growth.

The biomass effort clearly becomes much more challenging at the higher population growth rates. But even the more ambitious bioenergy development efforts may be feasible or desirable, since even with the high population variant the required PER is still low in relation to the global deforestation rate. According to FAO statistics, the world's forest area decreased from 4,400 million hectares in 1952 to 3,800 million hectares in 1972, or at an annual rate of 30 million hectares per year in this period.[67] Hence, a substantial reforestation effort may be needed to reverse the ongoing process of deforestation.

At the higher PER values, competition between bioenergy and food production becomes an issue. However, the best use of land may involve complementary rather than competitive strategies for bioenergy and food

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*The rotation period for plantations is assumed to be five years, so that biomass harvested in 2020 must be planted in the period from 1985 to 2015.

**In all alternatives to the base case scenario, we assume that: (1) electricity accounts for 18 percent of final energy demand; (2) hydro (wind and photovoltaics) accounts for 25 percent (5 percent) of electricity production; (3) cogeneration accounts for 15 percent of electricity production, with a fifty-fifty mix of fossil fuels and biomass; (4) the nuclear electricity level is fixed at 0.3 TW unless specified otherwise; (5) the remainder of electricity production is by fossil fuels in central station plants.

production. With this approach, agricultural production would be restricted to the better lands and agricultural productivity increased through enhanced inputs of energy (through tractors, fertilizers, irrigation, etc.), while biomass for energy purposes would be grown on the more marginal lands. Tree farms with rotations of five to ten years or more would probably constitute a more sustainable use of marginal lands than would agricultural production.

Per Capita Energy Use: Figure 9 illustrates the impacts on the PER of alternative per capita energy demand levels, specifically the impacts of alternative combinations (x,y), where

x = per capita energy use rate for developing countries and
y = per capita energy use rate for industrialized countries.

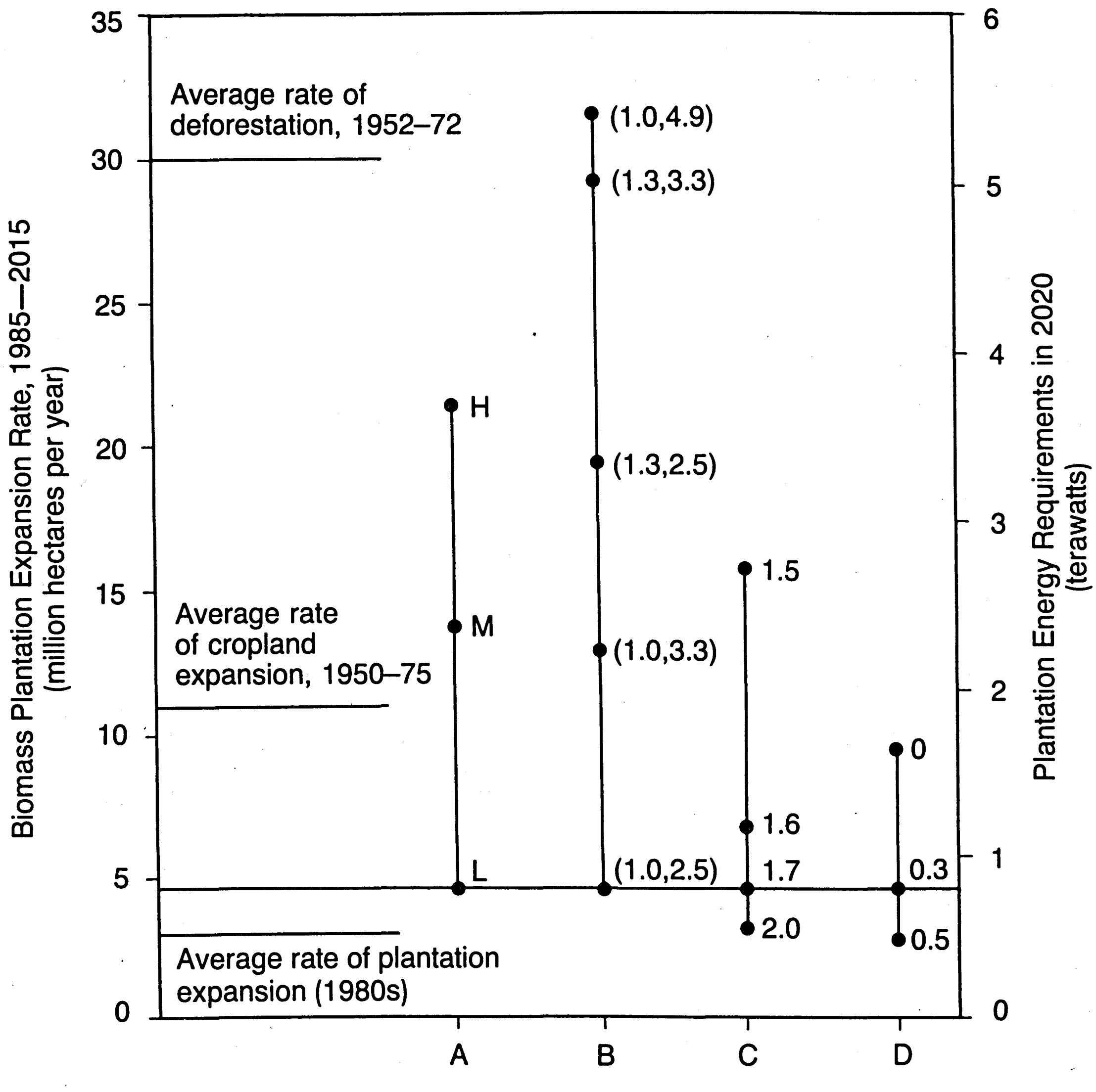
For developing countries, we consider as an alternative to the base case a case involving a 50 percent increase in per capita final energy use between 1980 and 2020 to 1.3 kW. This rate of final energy use corresponds to a primary energy use rate of about 1.7 kW, which is near the high end of the WEC and IIASA projections (1.1 to 1.6 kW and 1.2 to 1.9 kW, respectively) for 2020. This alternative energy use rate implies only modest improvements in the efficiency of energy-using technologies in developing countries.

For industrialized countries, we consider as alternatives to the base case levels of 3.3 kW and 4.9 kW per capita, representing considerably less ambitious conservation efforts than that which characterizes our base case scenario. The 3.3 kW case involves per capita final energy use in 2020 which is one-third less than in 1980 and is equal to the 1980 final energy use level for the WE/JANZ region. In the 4.9 kW case, energy efficiency would improve between 1980 and 2020 just enough to offset economic growth. An indication of the modesty of the associated conservation effort in this latter case is provided by a comparison with OECD economic and energy performance between 1973 and 1984, a period in which real per capita GDP increased 18 percent while per capita primary energy use declined 6 percent.

Figure 9 illustrates the impacts of alternative assumptions about per capita energy demand on the requirements for bioenergy development, assuming that biomass is the swing fuel. This figure shows that the (x,y) = (1.0 kW, 3.3 kW) scenario would involve a PER comparable to the average rate of cropland expansion between 1950 and 1975, while the (1.3 kW, 2.5 kW), (1.3 kW, 3.3 kW), and (1.0 kW, 4.9 kW) scenarios would require PER values in the range 20 million to 30 million hectares per year, some two to three times the average rate of cropland expansion and hence formidable undertakings.

The Atmospheric Carbon Dioxide Level: The ultimate level of carbon dioxide buildup in the atmosphere could be varied by accelerating or slowing the rate of coal phase-out through the substitution of biomass for coal. Figure 9 shows how variations in the carbon dioxide ceiling in the range 1.5 to 2.0 times the preindustrial level would affect biomass plantation requirements. This figure shows that the PER is relatively insensitive to the atmospheric carbon dioxide ceiling for ceilings in the range 1.6 to 2.0. To reduce the ceiling to 1.5, however, requires a PER more than triple that for the base case. The major impediment to realizing a 1.5 ceiling level, however, would probably be not so much its implications for biomass production

Figure 9
THE RESULTS OF SENSITIVITY ANALYSIS*



A = population (H = United Nations high variant; M = U.N. medium variant; L = U.N. low variant

B = per capita final energy demand (in Kilowatts) (developing countries; industrialized countries)

C = atmospheric carbon dioxide level relative to the preindustrial level

D = nuclear electricity supply (in terawatts)

*Biomass is the swing energy source to bring energy supply and demand into balance as various scenario assumptions are altered. Shown here are the biomass requirements from energy plantations, farms, and/or woodlots, both in terms of the required global energy production rate in 2020 and in terms of the average plantation expansion rate in the period from 1985 to 2015 that is required to ensure that enough biomass is available for harvesting in 2020 to meet global bioenergy requirements.

as the prospect of major dislocations in the coal industry associated with rapid coal phase-out. In this case, coal use would have to decline about 4 percent per year to a level by 2020 that is just one-fifth of that in 1980.

We have assumed in this analysis that eventually all oil and gas supplies would be consumed. But there are conceivable circumstances in which this assumption might be relaxed. For instance, one of the most promising energy supply technologies in the offing involves the use of amorphous silicon solar cells, perhaps laid out flat on simple support structures in desert areas, to produce hydrogen through electrolysis. Our preliminary analysis indicates that if present industry expectations regarding the costs of amorphous silicon solar cell panels were to be realized, it might be feasible to produce hydrogen at costs competitive with the costs of oil and natural gas.[68] If this turns out to be feasible, substitution of hydrogen for all fossil fuels worldwide in the period from 2020 to 2050 would result in an ultimate atmospheric carbon dioxide concentration of only 1.4 times the preindustrial level, or 400 ppmv.[69] The required land area would be on the order of half the state of Texas, or about 2 percent of the world's warm deserts.[70]

Nuclear Power: We consider two alternative nuclear power levels consistent with our philosophy that nuclear power should be an energy source of last resort: 0 TW and 0.5 TW, compared to 0.3 TW in the base case scenario. The former involves a complete phase-out of nuclear power, with no more nuclear plants built beyond those now under construction. Our high nuclear power scenario involves the same rate of nuclear power expansion in the period from 2000 to 2020 as in the period 1980 to 2000; in this scenario, new plants would be built between 2000 and 2020 at a rate of thirty plants of 1 GW(e) average capacity per year,[71] with installed nuclear generating capacity reaching 770 GW(e) by the year 2020.

It is noteworthy that these alternative scenarios do not have a significant impact on the PER, which changes from 5 million hectares per year in the base case to 3 (10) million hectares if the nuclear power use rate changes from 0.3 TW to 0.5 (0.0) TW (see Figure 9).

Overall, nuclear power would not have a major impact on the global energy picture unless it were widely used throughout the world at levels several times higher than the maximum assumed in this analysis and under such circumstances that the risks of proliferation would be large as well.

Oil and Natural Gas as the Swing Fuels When Energy Demand Is High

In the above sensitivity analysis, we have shown that at high energy demand levels it would be a major challenge to provide the extra energy required with biomass sources alone. However, it is probably unnecessarily constraining to limit the marginal energy supply options to biomass. In particular, our base case levels of oil and gas production are lower than those projected in other global energy studies (see Figure 4) and may be lower than is necessary to keep the world oil price to reasonable levels or to insulate the rest of the world from overdependence on Middle Eastern oil and the disruption of oil supplies.

To examine this issue, we describe a high energy demand scenario in which the aggregate final energy demand is 1.0 kW per capita in developing countries and 4.9 kW per capita in industrial countries.[72] For the supply mix, we assume the same conditions as for the cases in which biomass is the swing fuel, except that:

- The biomass supply is limited to 3 TW (twice the 1980 level), one-third of which would come from organic wastes (one-fourth of all organic wastes) and two-thirds from plantations, corresponding to a PER of 12 million hectares per year between 1985 and 2015, approximately the rate of cropland expansion between 1950 and 1975.

- The extra demand not met by biomass is met instead through increased oil and natural gas production, the levels of which are assumed to be equal by 2020.

- Oil production outside the ME/NAf region is assumed to increase enough to limit the need for oil from the ME/NAf region to 15 MBD, the 1980 glut level.[73]

Here are some of the highlights of this scenario:

- Primary energy demand would increase from 10 TW in 1980 to 15 TW in 2020, a level which is still only about two-thirds as large as in the WEC and IIASA scenarios (see Figure 4).

- Electricity demand would grow at less than half the 5 percent per year average growth rate of the 1970s.[74]

- While oil use would be about the same as in 1980, the assumed expansion in natural gas production implies an increase in the sum of oil and gas use from 6 TW in 1980 to 9 TW in 2020.[75] The corresponding levels in the WEC and IIASA scenarios are 9 and 10 TW, respectively (see Figure 4).

- It may still be feasible under this scenario to maintain the world oil price at or near the present level through 2020, since the demand for non-ME/NAf oil would be comparable to the estimated remaining supplies of non-ME/NAf oil with production costs less than $30 per barrel.[76]

- The ultimate level of carbon dioxide in the atmosphere would be the same as in the base case scenario, since only the rate of oil and gas consumption would be increased. Total fossil fuel emissions in 2020 would still be only 60 percent as large as in the WEC and IIASA scenarios.[77]

- The level of nuclear power development would be the same as in the base case, so that the proliferation problem would not be exacerbated.

- The level of hydropower development for 2020 would be only about half of the 1976 WEC estimate of economically exploitable hydro resources.

It would seem from these numbers that most of our concerns relating to energy supply could be dealt with in the high demand scenario. Why, therefore, should energy planners seek to attain the energy demand levels associated with base case scenario, which involves a much higher level of energy efficiency improvement, if roughly the same objectives could be realized at the higher demand level? There are two reasons to strive for the lower demand level.

First, as we have repeatedly stressed, it is probably cheaper at today's energy prices to provide energy services with the higher efficiency end-use technologies that would characterize the base case scenario than with more energy supplies and less efficient end-use technologies. As a consequence, the base case scenario would probably be associated with a higher standard of living in 2020 than the high-demand scenario.

In addition, it is desirable to seek a lower demand level to provide a significant margin for error in planning. As energy demand rises, the ability of society to plan around environmental problems declines.

For the demand levels of the high demand scenario, relative stability in world oil prices through 2020 depends on two assumptions: (1) that natural gas production can be expanded two and one-half fold between 1980 and 2020 to a level comparable to that projected in the WEC and IIASA high scenarios; and (2) that low-cost oil resources outside the ME/NAf region are indeed as large as estimated in the IIASA study so that production outside the ME/NAf region would be sufficient to keep dependence on ME/NAf oil to the 1983 oil glut level.[78]

It may be feasible to realize the production goals asssumed above, but it would nonetheless be challenging and there would be little room for deviation. It is very likely, for example, that if world oil demand were higher than the level assumed for this scenario, most of the extra demand would have to be met by ME/NAf producers. If world oil demand were just one-fourth higher than in the high demand scenario (corresponding to a mere 7 percent increase in world energy use), and if the extra demand had to be met with increased ME/NAf production, that region would have to produce at near capacity levels[79]--a condition that would undoubtedly mean a much higher oil price and greatly reduced global security.

Alternatively, the incremental energy demand could be met through coal and/or nuclear power expansion, but this would be at the expense of solutions to the atmospheric carbon dioxide and nuclear weapons proliferation problems. Of course, the commercial success of new technologies such as amorphous silicon solar cells might enable expanded energy demand without exacerbating these problems, but such technologies cannot be counted on at this time.

CONCLUSION

The present analysis shows that it appears to be technically and economically feasible to: (1) meet basic human needs and considerably improve living standards in the developing world without increasing per capita energy use levels through a shift to modern energy carriers and more efficient use of energy in both the modern and traditional sectors; and (2) provide a continuing improvement in living standards in industrialized countries while reducing per capita energy use by half over the period between 1980 and 2020, a reduction that is possible as a consequence of the many opportunities for more efficient use of energy as well of ongoing structural changes in industrialized economies.

At the global level, these findings imply that ambitious economic goals can be realized in the period between 1980 and 2020 without increasing the overall level of primary energy requirements. However, a continuing shift to higher-quality energy carriers is required. For developing countries, this involves transition from the present situation--in which nearly half of primary energy requirements are provided by fuelwood, used largely for cooking--to wide use of modern solid, liquid, and gaseous fuels. For developing and industrialized countries alike, this implies a much greater degree of electrification of the world energy economy than at present.

Our analysis shows that as long as global energy demand is not too large, there can be considerable flexibility in the choice of energy supplies, the mix of which can be adjusted so as to evolve an energy strategy consistent with the solutions of other major global problems: dependence on Persian Gulf oil can be reduced, thereby reducing the upward pressure on world oil prices and improving global security; expansion of fossil fuel use can be avoided, thereby reducing the risks associated with the atmospheric buildup of carbon dioxide; and growth of nuclear power can be curbed, thereby reducing the risks of nuclear weapons proliferation.

We have not shown that our scenario energy balances are consistent with what can be achieved on a regional or country basis; that exercise remains to be carried out. As we have repeatedly stressed, a comprehensive global perspective on the energy problem must result from the integration of perspectives for individual countries and regions. But our analysis does suggest that there are no obvious global constraints to an energy future that is consistent with the solutions to other important global problems. Thus it provides a motivation for pursuing detailed country and regional analyses along similar lines.

Our sensitivity analysis shows further that emphasis on energy efficiency improvement constitutes a robust approach to the problems we have posed: the identification of an energy strategy consistent with the goals we have established would not require that energy demand levels reach precisely the levels of the base case scenario; a comfortable margin would exist for planning error. But our analysis has also shown that there would be little room to maneuver were demand to increase to the level of our high demand scenario. Our analysis thus highlights the importance of pursuing an energy course in which total global energy use changes little over the next several decades, as the net result of adopting energy efficiency improvements that offset the expanded demand for energy services resulting from population and economic growth.

This course would require new policies that would facilitate the development of industries that deliver not energy but the services that energy provides.[80] These new industries would be made up in part of existing companies (e.g., some utilities) converted from being purveyors of energy supplies into being purveyors of energy services as well. And it would be made up in part of entirely new industries that deal exclusively in the marketing and servicing of energy-efficient equipment for businesses and individual energy consumers (e.g., the energy management firms that are now emerging in the U.S. to serve commercial and industrial businesses).

Bringing about a fundamental reordering of the energy problem--from preoccupation with supply expansion to concern for the economically efficient provision of energy services--would not be easy. But pursuing any alternative supply-oriented energy course would not be easier. The supply approach to the energy problem is foundering. The last several years have witnessed some of the most costly dry holes in the history of petroleum exploration. At the same time, the falling world oil price has stymied efforts to develop supply alternatives to oil; in the U.S. attempts to launch a synthetic fuels industry have collapsed. The very survival of the nuclear power industry is threatened in some parts of the world. In relation to such problems, the challenges encountered in the development of an effective energy service industry do not seem to be so formidable.

If the end-use approach really catches on, it may actually prove to be easier to implement than is indicated by our analysis. Our analysis has been restricted to technologies that are either already commercialized or are in an advanced state of development, with fairly well-defined energy performance characteristics. We have made no attempt to guess wholly new end-use technologies or to identify technological limits for future improvements in energy efficiency. Yet it is clear that there is room for much more innovation than that which we have described. The technologies on which we have focussed have energy performances that are still far from thermodynamic limits, and we are only now beginning to see the fruits of research and development efforts on end-use technologies that were initiated in the aftermath of the first oil crisis, the beginning of the era of high-cost energy.

To sum up, the end-use strategy we have described, which emphasizes energy efficiency improvements in industrialized and developing countries alike, is not dependent on technological breakthroughs. It is economically feasible in the sense that investments in energy efficiency involve direct lifecycle costs per unit energy saved that are less than or equal to the per unit costs of investments in additional energy supply. The present inadequate industrial infrastructure for energy services marketing constitutes the major impediment to an end-use energy strategy.

It would seem to us that it is worth the challenge to society to see that the needed infrastructure is established, in light of the clear advantage of this approach to energy, which facilitates the formulation of an energy strategy consistent with and supportive of the achievement of a sustainable world.

Note: This paper is based on *Energy for a Sustainable World*, by J. Goldemberg et al. (New Delhi: Wiley Eastern, 1987).

NOTES

1.

Estimated Ultimately Recoverable Oil Resources and Oil Consumption

Region[a]	Resources (TW-yrs)[b]	1978 Consumption (TW-yrs)[c]
NA	39.7	1.28
USSR/EE	66.3	0.56
WE/JANZ	22.7	1.22
LA	32.6	0.23
AF/SEA	30.0	0.21
ME/NAf	154.8	0.11
C/CPA	18.1	0.12
Total	364.2	3.73

(a) NA = North America; USSR/EE = Union of Soviet Socialist Republics and Eastern Europe; WE/JANZ = Western Europe, Japan, Australia, New Zealand, South Africa, and Israel; LA = Latin America; AF/SEA = Africa, South Asia, and Southeast Asia; ME/NAf = Middle East and North Africa; C/CPA = China and other centrally planned Asian economies.

(b) See: W. Haefele et al., *Energy in a Finite World: A Global Systems Analysis* (Cambridge, Mass.: Ballinger Publishing Co., 1981), table 2.6.

(c) See: J.-R. Frisch, *Energy 2000-2020...Where Are We Going? Regional Stresses* (London: Conservation Commission of the World Energy Conference, 1982).

2. Forestry Department, Food and Agricultural Organization, "A Global Reconnaissance Survey of the Fuelwood Supply/Requirement Situation," report to the Technical Panel on Fuelwood and Charcoal of the Preparatory Committee for the United Nations Conference on New and Renewable Energy, Rome, 1981.

3. World Bank, *World Bank Development Report 1984* (New York: Oxford University Press, 1984).

4. World Bank, *The Energy Transition in Developing Countries* (Washington, D.C.: World Bank, 1983).

5. T. Johansson and R. Williams, "An End-Use Energy Strategy for Industrialized Countries," this volume.

6. See note 3 above.

7. Food and Agricultural Organization, *Agriculture: Toward 2000* (Rome: Food and Agricultural Organization, 1981).

8. Carbon Dioxide Assessment Committee, National Research Council, *Changing Climate* (Washington D.C.: National Academy Press, 1983).

9. W. Kellogg and R. Schware, *Climate Change and Society: The Consequences of Increasing Atmospheric Carbon Dioxide* (Boulder, Colo.: Westview Press, 1981).

10. B. Bolin et al., *The Global Carbon Cycle*, Scope 13 (Chichester, U.K.: John Wiley and Sons, 1979).

11. M. Biswas, "United Nations Conference on Desertification in Retrospect" Laxenberg, Austria: International Institute for Applied Systems Analysis, 1978.

12. Personal communication, David Pimentel, Cornell University, 1985.

13. B. Blechman and D. Hart, *International Security* 7 (1982): 132.

14. H. Feiveson, "Proliferation Resistant Nuclear Fuel Cycles," *Annual Review of Energy* 3 (1978): 357.

15. H. Feiveson and J. Goldemberg, "Denuclearisation," *Economic and Political Weekly* XV (1980): 1,546.

16. Ibid.

17. There have been several global energy studies that depart from the traditional supply orientation. One study (U. Columbo and O. Bernardini, *Low Growth Scenario and the Perspective for Western Europe*, report of the Panel on Low Energy Growth, Commission for the European Communities, 1979) exploring an energy supply-constrained global energy future for the year 2030 (16 terawatts [TW] of primary energy use), shares a number of features with the present one, including an emphasis on energy efficiency, although our analysis indicates a much greater potential for energy efficiency improvement. A 1983 study (D. Rose, M. Miller and C. Agnew, *Global Energy Futures and CO_2-Induced Climate Change*, report MITEL 83-015, Cambridge, Mass.: Massachusetts Institute of Technology, 1983) exploring alternative energy strategies for coping with the CO_2 problem, found that improved energy efficiency offers the single most important opportunity to ameliorate the CO_2 buildup and described several viable scenarios with demand levels in the neighborhood of 15 TW for the year 2025. A 1981 study (A. Lovins et al., *Energy Strategy for Low Climate Risk*, report for the German Federal Environmental Agency, Bonn, 1981) is perhaps the first global study to stress the importance of pursuing alernative energy strategies, including energy efficiency improvements, as a means of coping with the CO_2 problem. Its targeted global primary energy use level for the year 2030 is 5.2 TW. One of the main reasons this is so low is that the authors assume that per capita energy use in

developing countries can be reduced to 0.25 kW (about one-fourth of the 1980 level). We are skeptical that development needs can be satisfied with such a low level of energy use.

18. For the WEC projections, see Frisch in note 1(c) above; for the IIASA projections, see Haefele et al. in note 1(b) above.

19. J. Goldemberg et al., "An End-Use Oriented Global Energy Strategy," *Annual Review of Energy* 10 (1985): 613; see also J. Goldemberg et al., *Energy for a Sustainable World* (New Delhi: Wiley Eastern, 1987).

20. J. Goldemberg et al., "Basic Needs and Much More with One Kilowatt Per Capita," *Ambio* 14 no. 4-5 (1985): 190.

21. E. Larson, M. Ross, and R. Williams, "Beyond the Era of Materials," *Scientific American* 254 no. 6 (1986): 34.

22. See note 5 above.

23. See note 5 above.

24. See note 21 above.

25. See note 5 above.

26. See note 5 above.

27. In 1975, per capita GNP averaged $11,050 (1982 dollars) in Sweden and $6,250 in the WE/JANZ region; see Bureau of the Census, U.S. Department of Commerce, *Statistical Abstract of the United States 1984* (Washington, D.C.: Government Printing Office, 1984). The per capita GDP level for all industrialized countries in 1975 was about the same as that of the WE/JANZ region.

28. Ibid.

29. See note 19 above.

30. See next page.

Footnote 30.

Table 1.

FINAL ENERGY USE PER CAPITA FOR A HYPOTHETICAL DEVELOPING COUNTRY IN A WARM CLIMATE WITH AMENITIES (EXCEPT FOR SPACE HEATING) COMPARABLE TO THOSE IN THE WE/JANZ REGION IN THE 1970s BUT WITH CURRENTLY BEST AVAILABLE OR ADVANCED ENERGY END-USE TECHNOLOGIES

	Activity Level[a]	Technology, Performance[a]	Electricity	Fuel	Totals
Residential[b]	4 persons/household (HH)				
Cooking	Brazilian cooking level[c]	70% efficient gas stove[d]		34	
Hot water	50 liters of hot water/capita/day[e]	Heat pump water heater, coefficient of performance=2.5[f]	29.0		
Refrigeration	1 315-liter refrigerator-freezer/HH	Electrolux, 475 kWh/year[g]	13.5		
Lights	New Jersey, U.S. level of lighting[h]	Compact fluorescent bulbs[h]	3.8		
TV	1 color TV/HH, 4 hours/day	75-watt unit	3.1		
Clothes washer	1/HH, 1 cycle/day	0.2 kWh/cycle[i]	2.1		
Subtotal			51	34	85
Commercial	5.4 sq. meters floor space/capita[j]	Performance of Harnosand Building (all uses, except space heating)[k]	22	--	22
Transportation					
Automobiles	0.19 autos/capita, 15,000 km/car/yr[j]	Cummins/NASA Lewis car, 3.0 liter/100 km[l]		107	
Intercity bus	1850 passenger(p)-km/capita[j]	3/4 energy intensity in 1975[m]		26	
Passenger train	3175 (p)-km/capita[j,n]	3/4 energy intensity in 1975[o]	4.5	32	
Urban mass transit	520 (p)-km/capita[j,p]	3/4 energy intensity in 1975[o]	2.0	8	
Air travel	345 (p)-km/capita[j]	1/2 U.S. energy intensity in 1980[q]		21	
Truck freight	1495 ton(t)-km/capita[j]	0.67 megajoules(MJ)/t-km[r]		32	
Rail freight	814 (t)-km/capita[j]	Electric rail @ 0.18 MJ/t-km[s]	5	--	
Water freight	1/2 OECD Europe average, 1978[t]	60% of OECD energy intensity[u]		50	
Subtotal			12	276	288
Manufacturing					
Raw steel	320 kg/capita[v]	Average, Plasmasmelt-Elred processes[w]	28	77	
Cement	479 kg/capita[x]	Swedish average in 1983[y]	6	54	
Primary aluminum	9.7 kg/capita[x]	Alcoa process[z]	11	26	
Paper, paperboard	106 kg/capita[aa]	Average of 1977 Swedish designs[bb]	11	24	
Nitrogen fertilizer	26 kg N/capita[cc]	Ammonia derived from methane[dd]	--	36	
Other[ee]	Swedish industrial mix with 1975 W. European level of GDP/capita	Energy intensity for Swedish industry w/ 1975 level of goods and services and advanced technology[gg]	65	212	
Subtotal[ff]			121	429	550
Agriculture	Average for WE/JANZ region, 1975	3/4 of WE/JANZ energy intensity[hh]	4	41	45
Mining, construction	Average for WE/JANZ region, 1975	3/4 of WE/JANZ energy intensity	--	59	59
Totals			210	839	1049

(a) The values for the average activity levels and energy intensities identified for the WE/JANZ region in 1975 are from A. Khan and A. Holzl, *Evolution of Future Demands Till 2030 in Different World Regions: An Assessment Made for the Two IIASA Scenarios*, IIASA report RR-82-14 (Laxenburg, Austria, 1982).

(b) Activity levels for the residential sector are estimates, owing to lack of data for the WE/JANZ region.

(c) An average of one 13-kg cannister of LPG per month for a family of five, corresponding to a per capita fuel consumption rate of 49 watts for an ordinary gas stove with a burner efficiency of about 50 percent.

(d) Low NO_x-emitting units, with efficiency of 70 percent, developed by Thermoelectron Corporation for the Gas Research Institute. See note 33.

(e) The U.S. average is about 100 liters per capita per day.

(f) For water heated from 20 to 50 degrees Celsius. Assumes heat pump performance comparable to that of the most efficient heat pump water heaters available in the United States in 1982.

(g) The most energy-efficient two-door refrigerator-freezer available in Europe in 1982.

(h) Assumes that five compact fluorescent light bulbs, which draw 18 watts but put out as much light as 75-watt incandescent bulbs, are used on average four hours a day.

(i) Typical value for U.S. washing machines.

(j) Average for the WE/JANZ region in 1975.

(k) The most energy-efficient commercial building in Sweden in 1981, the time it was built, using 0.13 gigajoules (GJ) of electricity per square meter of floor area for all purposes other than space heating. See Johansson and Williams, "An End-Use Energy Strategy for Industrialized Countries," this volume.

(l) The Cummins/NASA Lewis car is a design for a 1360 kg, four- to five-passenger car in a Ford Tempo body, with a four-cylinder, direct-injection, spark-assisted, multi-fuel capable, adiabatic diesel engine with turbo-compounding.

(m) The average energy intensity of intercity buses was 0.60 megajoules per passenger kilometer (MJ/p-km) in 1975. The assumed 25 percent reduction is based on the introduction of adiabatic diesel engines with turbo-compounding.

(n) Ratio of seventy to thirty in the diesel/electric mix.

(o) The average energy intensity of passenger trains of 0.60 MJ/p-km for diesel units and 0.20 MJ/p-km for electric units, and of urban mass transit of 1.13 MJ/p-km for diesel buses and 0.41 MJ/p-km for electric mass transit in 1975. The assumed 25 percent reduction in energy intensity of both is based on a switch to adiabatic diesels with turbo-compounding and the use of electric motor control technology.

(p) Ratio of sixty to forty in the diesel/electric mix.

(q) The average 1980 energy intensity for U.S. air travel was 3.8 MJ/p-km. The assumed 50 percent reduction in energy intensity is based on improvements described in F. von Hippel, "U.S. Transportation Energy Demand," Center for Energy and Environmental Studies report 111, Princeton University, Princeton, N.J., 1981.

(r) The assumed energy intensity is one-third less than the simple average today in Sweden for single-unit trucks (1.26 MJ per ton-km) and combination trucks (0.76 MJ per ton-km), to take into account improvements via use of adiabatic diesels with turbo-compounding.

(s) Average energy intensity for electric rail in Sweden, with an average load of 300 tons and an average load factor of about 40 percent.

(t) The 119 kg of oil use per capita for water freight in 1978 in OECD Europe is assumed to be reduced in half due to reduced use of oil, which accounted for 58 percent and 29 percent of 1977 Western European import and export tonnage respectively.

(u) A 40 percent reduction in fuel intensity is assumed, reflecting innovations such as the adiabatic diesel and turbo-compounding.

(v) OECD European average, 1978.

(w) Assumes a fifty-fifty mix of the Elred process (requiring 10.7 GJ of fuel and 1.3 GJ of electricity per ton) and the Plasmasmelt process (requiring 4.6 GJ of fuel and 4.2 GJ of electricity per ton). See note 5 above.

(x) OECD European average, 1980.

(y) Assumes an energy intensity of 3.56 GJ of fuel and 0.40 GJ of electricity per ton (the 1983 Swedish average).

(z) Assumes an energy intensity of 84 GJ per ton of fuel (the 1978 U.S. average) and 36 GJ of electricity (the requirements for the Alcoa process now being developed). See T. Beck, "Improvements in Energy Efficiency of Industrial Electrochemical Processes," report ANL/OEPM-77-2, prepared for the Office of Electrochemical Project Management, Argonne National Laboratory, 1977.

(aa) OECD European average, 1979.

(bb) Assumes an energy intensity of 7.3 GJ of fuel and 3.2 GJ of electricity per ton (the average for 1977 Swedish designs). See P. Steen et al., *Energy: For What and How Much?* (Stockholm, Sweden: Liber Forlag, 1981) in Swedish.

(cc) OECD European average, 1979-80.

(dd) Assumes an energy intensity of 44 GJ of fuel per ton of nitrogen in ammonia (the value with steam reforming of natural gas in a new fertilizer plant). See D. Waitzman et al., "Fertilizer from Coal," paper prepared by the Division of Chemical Development, Tennessee Valley Authority, presented at the Faculty Institute on Coal Production Technology and Utilization, Oak Ridge Associated Universities, Oak Ridge, Tenn., 1978.

(ee) The difference between the manufacturing total and the sum of the items calculated explicitly. Energy usage associated with "other" for the non-manufacturing sectors is negligible.

(ff) The overall level of energy use for industry is obtained by multiplying the assumed industrial energy intensity by 0.55 times the Swedish per capita GDP in 1975; the average Western European per capita GDP was 55 percent of the Swedish value at that time. It is assumed that electricity accounts for 22 percent of final energy demand for industry, the percentage for Sweden in 1975.

(gg) See T. Johansson et al., "Sweden Beyond Oil: The Efficient Use of Energy," Science 219 (1983): 355.

(hh) The assumed reduction in energy intensity is based on innovations such as the use of advanced diesel engines.

31. See note 5 above.

32. H. Geller, "The Potential for Electricity Conservation in Brazil," Companhia Energetica de Sao Paulo, Sao Paulo, 1985.

33. K. Shukla and J. Hurley, "Development of and Efficient, Low NO_x Domestic Gas Range Cook Top," report prepared for Thermoelectron Corporation, Waltham, Mass., 1983.

34. See note 5 above.

35. See note 21 above.

36. For example, see Colombo and Bernardini in note 17 above.

37.

Alternative U.N. Global Population Projections (in billions)

	1980	2020 Low	2020 Medium	2020 High
Industrial countries	1.11	1.24	1.35	1.44
Developing countries	3.32	5.71	6.47	7.14
World	4.43	6.95	7.82	8.58

Source: United Nations, *World Population Prospects as Assessed in 1980* (New York: United Nations, 1981).

38.

The Main Energy Demand Features of Our Base Case Energy Scenario

	Indust. Countries 1980	Indust. Countries 2020	Devel. Countries 1980	Devel. Countries 2020	World 1980	World 2020
Population[a] (billions)	1.11	1.24	3.32	5.71	4.43	6.95
Final energy use[b] (TW)						
Fuels	4.77		2.77		7.54	7.23
Electricity	0.70		0.13		0.83	1.58[c]
Total	5.47	3.10	2.90	5.71	8.37	8.81
Per capita final energy use (kW)	4.92	2.5	0.87	1.0	1.89	1.27

(a) The 1980 U.N. low variant population projection.
(b) Defined as the total fuel (including bunkers) and electricity consumed by final consumers; excludes losses in the generation, transmission, and distribution of electricity, and the consumption of petroleum fuels by refineries.
(c) The electrical fraction of global final energy demand is assumed to be 0.8 times that for the U.S. country study. See note 5 above.

39. See note 38 above.

40. See note 38 above.

41. S. Seidel and D. Keyes, *Can We Delay a Greenhouse Warming?* (Washington, D.C.: U.S. Environmental Protection Agency, 1983).

42. Per TW-year of oil, natural gas, and coal consumption, respectively, 0.63, 0.43, and 0.78 billion tons or gigatons (GT) of carbon are released. The carbon dioxide level in 1979 was 708.5 GT (334 ppmv). The preindustrial level is assumed to have been 615 GT (290 ppmv), and 50 percent of emitted carbon dioxide is assumed to remain in the atmosphere. Ultimately recoverable resources are presently estimated at 365 TW-years for oil (see note 1 above) and 349 TW-years for natural gas (see note 48 below), and if completely exploited would add carbon to the atmosphere as carbon dioxide in the amount

$$0.5 \times [0.63 \times 365 + 0.43 \times 349] = 190 \text{ GT}$$

or 0.31 times the preindustrial atmospheric level. If half of the world's geological coal resources (8,535 TW-years) were eventually used up, the amount of net carbon buildup in the atmosphere as carbon dioxide would be

$$0.5 \times 0.5 \times 0.78 \times 8{,}535 = 1{,}660 \text{ GT},$$

or 2.7 times the preindustrial level.

Geological Resources of Coal
(in trillion tons coal equivalent [Ttce])

	Ttce	TW-Years[a]	Percentage
U.S.S.R.	4.41	4096	48
U.S.	2.33	2164	25
China	1.31	1217	14
Other	1.14	1059	12
Total	9.19	8535	100

Source: World Energy Conference, *World Energy Resources 1985-2000* (Guildford, U.K.: IPC Science and Technology Press, 1978).

(a) For a heating value of 29.3 GJ per metric ton coal equivalent.

43. See note 42 above.

44. Coal production in a given year is assumed to be proportional to the remaining coal resources that might eventually be used without exceeding a specified ceiling on the atmospheric carbon dioxide level. For the above assumptions about oil and gas use (see note 42 above), the allowable coal production schedule as a function of various atmospheric carbon dioxide ceilings would be:

Coal Production as a Function of Atmosphere CO_2 Ceilings

CO_2 Level as a Fraction of Pre-industrial Level	Total Production (in TW-yrs)	Production for Example Years (in TW-years) 1978	2000	2020	2040	2100
1.50	65.50	2.59	1.09	0.49	0.22	0.02
1.60	223.20	2.59	2.01	1.59	1.26	0.63
1.70	380.91	2.59	2.23	1.95	1.70	1.13
1.80	538.62	2.59	2.33	2.12	1.92	1.44
1.90	696.33	2.59	2.39	2.22	2.06	1.65
2.00	854.04	2.59	2.42	2.28	2.15	1.79

45. In Haefele et al., note 1 above, it is estimated that global coal resources recoverable at a cost of up to $40 per ton (in 1982 dollars); [$25 per ton in 1975 dollars] amount to 560 TW-years (606 GT), with 1,019 TW-years (1,105 GT) available in the cost range $40 to $80 per ton. Coal at $80 per ton is equivalent to oil at $17 per barrel, or one-half the world oil price in 1982.

46. See note 42 above.

47.

Regional Distribution of World Oil Production,
Base Case, WEC, and IIASA Scenarios
(in million barrels per day)

	1979	1980	1981	1982	1983	2020 Base Case[a]	2020 WEC Low	2020 WEC High	2020 IIASA Low	2020 IIASA High
ME/NAf	25.9	22.4	19.0	16.3	14.9	15	19	26	31	34
Rest	39.9	40.4	40.2	40.7	41.5	30	41	56	47	64
Total	65.8	62.8	59.2	57.0	56.4	45	60	82	78	98

(a) Base case scenario.

48.

Estimated Ultimately Recoverable Natual Gas Resources
and Natural Gas Consumption

Region	Resources, 1977[a] (in TW-years)	Consumption, 1978[b] (in TW)
NA	60.5	0.74
U.S.S.R./EE	96.4	0.47
WE/JANZ	23.1	0.27
LA	20.9	0.07
Af/SEA	18.4	0.02
ME/NAf	117.1	0.04
C/CPA	12.5	0.01
Total	348.9	1.62

(a) See: Haefele et al. in note 1(b) above, table 2.7.

(b) See: Frisch in note 1(c) above.

49. See note 1 above.

50. One possibility is to use compressed natural gas (CNG) directly as motor vehicle fuel. See J. West and L. Brown, *Compressed Natural Gas*, publication P14 (Aukland: New Zealand Energy Research and Development Committee, 1979). In Italy, some 270,000 vehicles were operated on CNG in 1980; New Zealand plans to convert 150,000 vehicles to CNG by 1985; both Canada and Australia are gearing up for major conversions.

51. If world oil demand fell from 4.18 TW in 1980 to the base case scenario level of 3.21 TW in 2020, the required cumulative world oil production, from 1981 to 2020 would be some 148 TW-years in this period. If in the period from 1983 to 2020 production in the ME/NAf region were maintained at the 1983 world "oil glut" level of 1.06 TW (15 million barrels per day), cumulative oil requirements from regions other than the ME/NAf region in this period would amount to

$$148 - (1.36 \times 3) - (1.06 \times 37) = 104.7 \text{ TW-years.}$$

For comparison, world oil resources remaining outside the ME/NAf region and estimated to be ultimately recoverable at a price less than $26 per barrel (1982 dollars) amount to some 132 TW-years. See Haefele et al. in note 1(b) above.

52. D. Albright and H. Feiveson, "Plutonium Recycle and the Problem of Nuclear Proliferation," Center for Energy and Environmental Studies, report 206 (Princeton, N.J.: Princeton University, 1986).

53.

Official Projections of Nuclear Electricity Production
for Market Economies
(in TW of continuous production)

Region	1980[a]	2000
U.S.	0.0315	0.080-0.082[b]
Other OECD	0.0346	0.097-0.104[b]
Other Market Economies	0.0016	0.018-0.027[b]
U.S.S.R.	0.0071	0.065-0.124[c]
Eastern Europe and Cuba	0.0027	0.026[c]
Total	0.0774	0.286-0.337[d]

(a) See: The British Petroleum Company, *BP Statistical Review of World Energy* (London, 1982).

(b) See: Office of Policy, Planning, and Analysis, *Energy Projections to the Year 2010*, technical report in support of the national energy plan, DOE/PE-0029/2 (Washington, D.C.: Department of Energy, 1983).

(c) See: International Energy Agency, *World Energy Outlook* (Paris: Organization for Economic Cooperation and Development, 1982).

(d) Assuming a 65 percent average capacity factor, the corresponding global installed capacity in the year 2000 would be 440 to 518 GW(e).

54. The total final demand for all fuels is 7.23 TW. (See note 38 above.) The demand for biomass fuels is the difference between this total and the final use of fossil fuels. The latter is calculated as follows. Assuming that three-fourths of central station power generation is based on coal converted at 40 percent conversion efficiency, coal used for direct purposes would be

$$1.94 - 0.75 \times 2.5 \times 0.66 = 0.70 \text{ TW}.$$

Assuming that one-fourth of central station power generation is based on the use of natural gas in steam-injected gas turbines at 50 percent conversion efficiency and that one-half of the fossil fuel-based cogeneration is natural gas fired, for which 1.5 units of extra fuel is needed to produce each unit of electricity, natural gas use for direct purposes would be

$$3.21 - 0.25 \times 2.0 \times 0.66 - 0.5 \times 1.5 \times 0.13 = 2.78 \text{ TW}.$$

Assuming that one-half of fossil fuel-based cogeneration is based on oil, for which 1.5 units of extra fuel is needed to produce each unit of electricity, and that 10 percent of gross oil use is consumed in refining operations, oil use for direct purposes would be

$$3.21 - 0.5 \times 1.5 \times 0.13 - 0.1 \times 3.21 = 2.79 \text{ TW.}$$

Thus direct fuel requirements from biomass would be

$$7.23 - 0.70 - 2.78 - 2.79 = 0.96 \text{ TW}$$

Assuming average conversion losses of 30 perent in producing final energy carriers from biomass, the total amount of biomass required for direct fuels use would be 1.37 TW. Also, some 0.21 TW would be required to produce 0.14 TW of cogenerated electricity, assuming the same conversion efficiency as for cogenerated electricity production with fossil fuels.

Global Electricity Supply Mix: Base Case
(in TW)

	1980	2020
Hydro	0.19	0.46[a]
Wind and photovoltaics	--	0.09[b]
Cogeneration		
Biomass	--	0.14[c]
Fossil fuel	--	0.13[c]
Central station		
Nuclear	0.08[d]	0.30[e]
Fossil fuel	0.66	0.66[f]
Total	0.93[g]	1.78[g]

(a) Hydro is assumed to make up 25 percent of the electricity supply (4,030 TW-hours per year [TWh/year]). This is two-fifths of the global economic hydro potential (9,700 TWh/year) and one-fifth of the global technical potential (19,400 TWh/year), as estimated in 1976 by the World Energy Conference. See E. Armstrong, "Hydraulic Resources," in *Renewable Energy Resources: The Full Reports to the Conservation Commission of the World Energy Conference* (Gilford, U.K.: IPC Sciences and Technology Press, 1978). The 1976 WEC estimates of the economic hydro potential are probably low in light of subsequent electricity price increases and better resources estimates (e.g., more recent estimates for Brazil and India that indicate economic potentials higher by some 75 percent than the 1976 WEC estimates for these countries).

(b) Wind and photovoltaics together are assumed to make up 5 percent of the electricity supply. Owing to the large uncertainties in the future of photovoltaic technology, the wind/photovoltaics mix is not disaggregated. In the event that photovoltaics technology is not commercialized, all of this electricity would be provided by wind. In Haefele et al., note 1(b) above, it is estimated that the technical potential for wind power globally is 3 TW and that the "realizable" potential is 1 TW. Thompson estimated a recoverable wind energy potential of 0.9 TW for the 16 percent of the North American land area where the wind energy density is in excess of 400 watts per square meter, using Boeing Mod-2 windmills (2.5 megawatts each) spaced 1.5 kilometers (km) apart. See G. Thompson, "The Prospects for Wind and Wave Power in North America," Center for Energy and Environmental Studies report 11, Princeton, N.J.: Princeton University, 1981.

(c) The cogeneration fraction of total electricity production is assumed to be 15 percent, the same as the percentage which we estimate could be provided in the U.S. in 2020 by the major steam-using industries. A fifty-fifty mix of biomass and fossil fuels is assumed for fuel input.
(d) Includes a small amount of geothermal.

(e) The nuclear electricity level assumed for 2020 is equal to the level officially forecast for the year 2000. See note 53 above.

(f) Central station power generation based on fossil fossil fuels is assumed to be the residual.

(g) Electricity demand (see note 38 above) is divided by 0.89 to account for transportation and distribution losses.

Global Primary Energy Supply Mix: Base Case
(in TW)

	1980	2020
Nuclear power	0.22[a]	0.75[b,c]
Hydro[d]	0.19	0.46[c]
Wind and photovoltaic[d]	--	0.09[c]
Fossil fuels[e]		
Coal	2.44	1.94
Oil	4.18	3.21
Natural gas	1.74	3.21
Subtotal	8.36	8.36[f]
Biomass		
Organic wastes		0.79[g]
Plantations	____	0.79
Subtotal	1.49[h]	1.58
Total	10.30	11.20

(a) Assumes that 2.8 units of fuel are required to produce 1 unit of electricity in thermal power plants in 1980.

(b) Assumes that 2.5 units of fuel are required to produce 1 unit of electricity in nuclear and coal-fired thermal power plants in 2020.

(c) See base case global electricity supply mix above.

(d) Assumes the primary energy consumption associated with hydro, wind, and photovoltaic electricity production to be the energy value of the output of these systems.

(e) Assumes that on average 1.5 units of fuel are required to produce 1 unit of cogenerated electricity.

(f) Total fossil fuel consumption is assumed to be the same as in 1980.

(g) Assumes that half of the biomass is provided by organic wastes and half by managed biomass production. The level of organic waste use for energy purposes corresponds to about one-fifth of the estimated organic waste production in 2020. See note 62 below.

(h) Bioenergy data for less developed countries are from D. Hall, G. Barnard, and P. Moss, *Biomass for Energy in the Developing World* (Oxford, U.K.: Pergamon Press, 1982). United States bioenergy consumption by the paper and pulp industry, 1.1 exajoules (EJ) in 1980, are from American Paper Institute, *Statistics of Paper, Paperboard, and Woodpulp* (New York: American Paper Institute, 1981). Data for U.S. wood consumption for household fuel, 0.87 EJ, are from Energy Information Administration, *Housing Characteristics, 1980*, a report contributing to the Residential Energy Consumption Survey, (Washington, D.C.: U.S. Department of Energy, 1982). Data for non-commercial energy use in other industrialized market economies are from International Energy Agency, *Energy Balances of OECD Countries, 1976-1980* (Paris: Organization for Economic Cooperation and Development, 1982). Data for fuelwood consumption for Eastern Europe and the Soviet Union are from United Nations, *1979 Yearbook of World Energy Statistics* (New York: United Nations, 1981).

55. For the assumed global electricity supply mix for our base case scenario, see note 54 above.

56. National Swedish Board for Energy Source Development, "Wind Energy in the Swedish Power System: the First Phase of an Investigation on Wind Power Integration in the Swedish Power System," NE 1982:12, Stockholm, 1982.

57. E. Demeo and R. Taylor, "Solar Photovoltaic Power Systems: An Electric Utility R&D Perspective," *Science* 220 (1984): 245.

58. See note 55 above.

59. For the assumed global primary energy supply mix for our base case scenario, see note 54 above.

60. See notes 38 and 39 above.

61. See note 59 above.

62. Global Organic Waste Production
(in TW)

	1980	2020
Forest product industry wastes		
United States[a]	0.11	0.14
Rest of world[b]	0.27	0.44
Crop residues		
Industrialized countries[c]	0.51	0.57
Developing countries[c]	0.60	1.04
Manure		
Industrialized countries[c]	0.38	0.42
Developing countries[c]	0.73	1.26
Urban refuse		
United States[d]	0.046	0.060
Other industrialized countries[e]	0.090	0.096
Developing countries[f]	0.034	0.058
Total	2.77	4.084

(a) U.S. 1979 roundwood production was 1.53 cubic meters (CM) per capita. See United Nations, *1979-1980 Statistical Yearbook* (New York: United Nations, 1981). Residue production per unit of roundwood production was 0.406, 0.377, and 0.203 from manufacturing residues, logging residues, and stand improvement cuttings, respectively. See Office of Technology Assessment, *Energy from Biological Processes*. Vol. 2. Technical and Environmental Analysis (Washington, D.C.: Office of Technology Assessment, 1980). These same values are assumed to hold for 1980 (2020), when the U.S. population was (is expected to be) 228 million (296 million). At 10 GJ/CM, total residue production in 1980 (2020) was (would be) 3.42 EJ (4.53 EJ).

(b) It is assumed that residue production in the rest of the world is like that in the European Economic Community (EEC), where the ratio of residues to roundwood production is 0.32. See W. Paly and P. Chartier, *Energy from Biomass in Europe* (London: Applied Science Publishers, 1980). Roundwood production outside the U.S. in 1979 was 0.65 CM per capita. See United Nations, in note (a) above. Residue production would be 8.61 EJ (13.83 EJ) for a population in 1980 (2020) of 4.14 billion (6.65 billion).

(c) It is assumed that per capita production rates are the same as in 1975. See T. Taylor, R. Taylor, and S. Weiss, "Worldwide Data Related to Potentials for Widescale Use of Renewable Energy," Center for Energy and Environmental Studies report 132, Princeton, N.J.: Princeton University, 1982.

(d) It is assumed that the present rate of U.S. urban refuse generation (1.63 kg per capita per day, with an average heating value of 10.7 MJ per kg) persists.

(e) It is assumed that the present rate of EEC refuse generation (1.0 kg per capita per day, with an average heating value of 8.8 MJ per kg) applies on average to all industrialized countries outside the United States in both 1980 and 2020. See U.S. Environmental Protection Agency, "Refuse-Fired Energy Systems in Europe: An Evaluation of Design Practices," executive summary, publication SW 771, Office of Water and Waste Management, Washington D.C.: Environmental Protection Agency, 1979.

(f) It is assumed that one-tenth of the population (the urban elite) generates urban refuse at the European rate.

63. While in principle a high level of crop residue recovery might be achieved by harvesting techniques that recover residues simultaneously with the primary products, only part of these wastes would be available for energy purposes. In developing countries, crop residues are often used as fodder for livestock. And some residues will have to be left behind to provide nutrients and to maintain soil quality. However, to the extent that crop residues and manure are utilized for biogas production, it may often be feasible to return the nutrient-rich residuum from the biodigesters to the soil for such purposes. In the case of forest residues, it may be necessary to restrict removals to the larger pieces, leaving behind the leaves or needles and twigs, in which the nutrients tend to be concentrated.

64. Various studies indicate bioenergy productivities on managed plantations ranging from about 7 dry tonnes per hectare per year (mesquite, saltbush, kochia) in arid regions to 10-15 tons (willow, poplar) in Sweden to 40-60 tons (eucalyptus, leucaena) in Brazil or India. However, these estimates are often based on unusually good experience for limited plots with especially favorable growing conditions. For energy planning purposes, more long-term experience on large plantations is needed before making projections based on high productivities. Foresters and ecologists with whom we discussed these issues did not feel that an average productivity of 10 tons per hectare per year was excessive for large-scale production on managed plantations or energy farms.

65. See notes 59 and 62 above.

66. In 1980, the amount of reforestation in seventy-six developing countries (excluding China) amounted to 1.15 million hectares. See Food and Agriculture Organization/Economic Commission for Europe, *Forest Resources 1980* (Rome: Food and Agriculture Organization, 1985). Between 1950 and 1979, 100 million hectares in China were replanted in forests, but only 28 million hectares of replanted area yielded surviving forests. Over the ten-year period from 1972 to 1981, the rate of planting averaged 4.7 million hectares per year. In many areas, the survival rate has increased recently to 50 percent or more. The official Chinese policy is to increase forest area at an annual rate of 3.5 million hectares per

year, from 122 million hectares in 1981 to 192 million hectares in 2000. See B. Zhu, "Afforestation and Energy for China," draft report prepared at the Center for Energy and Environmental Studies, Princeton University, Princeton, N.J., 1984.

67. See note 10 above.

68. Goldemberg et al., *Energy for a Sustainable World*, in note 19, appendix A.

69. In the base case fossil fuel use scenario (see note 59 above), the total carbon added to the atmosphere as carbon dioxide and which remains there as a result of fuel combustion in the period from 1980 to 2020 would be 101.2 GT, with 46.6 GT from oil combustion, 21.3 GT from natural gas combustion, and 33.3 GT from coal combustion for the carbon release assumptions presented in note 42.

Oil: 0.5 x 0.5 x (4.18 + 3.21) x 40 yrs x 0.63 = 46.6 GT
Natural gas: 0.5 x 0.5 x (1.74 + 3.21) x 40 yrs x 0.43 = 21.3 GT

Coal: 0.5 x 2.44 x [1 - exp(-40 x 0.0068)]/0.0068 x 0.78 = 33.3 GT

If fossil fuel use were then to decline linearly to zero from 2020 to 2050, the cumulative carbon dioxide buildup in this period would be

0.5 x 0.5 x 30 x [3.21 x (0.63 + 0.43) + 1.94 x 0.78] = 36.9 GT

and the ultimate level of carbon in the atmosphere (as carbon dioxide) would be 847 GT (399 ppmv), or 1.38 times the preindustrial level:

708.5 + 101.2 + 36.9 = 847 GT (399 ppmv).

70. To estimate the solar collector area required to provide hydrogen through electrolysis from amorphous silicon solar cells at the 2020 base case level of fossil fuel consumption (8.4 TW), we assume: (1) an average insolation rate of 200 watts per square meter for sunny (desert) areas; (2) an average efficiency of amorphous silicon solar cells of 15 percent, a practical target value for tandem, multi-layered cells, according to a 1984 Electrical Power Review Institute review (see note 57 above); and (3) an average efficiency for electrolysis of 80 percent. Under these conditions, the collector area required would be some 0.350 million square kilometers, or an area half the size of the state of Texas (0.691 million square kilometers), or 2 percent of the area of warm deserts of the world (17.8 million square kilometers).

71. Assuming that: (1) nuclear power plants last thirty years; (2) the installed capacity is 0 GW in 1970, 120 GW in 1980, and 460 GW in 2000; and (3) the rate of construction is constant from 1970 to 1980 and from 1980 to 2000, then the rate of replacement construction in the period from 2000 to 2020 would be

1/20 x [120 + (460-120)/20 x 10] = 14.5 GW per year.

Likewise, the rate of net additions in the period from 2000 to 2020 would be

[770 - 460]/20 = 15.5 GW per year.

72.

Main Energy Demand Features High Energy Demand Scenario

	Industrialized Countries		Developing Countries		World	
	1980	2020	1980	2020	1980	2020
Population[a] (in billions)	1.11	1.24	3.32	5.71	4.43	6.95
Final energy use (in TW)						
Fuels	4.77		2.77		7.54	9.67
Electricity	0.70	—	0.13	—	0.83	2.12[b]
Total	5.47	6.08	2.90	5.71	8.37	11.79
Per capita final energy use (in kW)	4.92	4.9[c]	0.87	1.0[c]	1.89	1.70

(a) The U.N. low variant population projection.

(b) Assumes that electricity accounts for 18 percent of final energy use in 2020.

(c) Assumes that per capita energy use in industrialized (developing) countries in 2020 is about the same as in 1980, or 4.9 kW (1.0 kW).

73.

The Distribution of World Oil Production
(in MBD)

	Production, Recent Years					Projections			
	1979	1980	1981	1982	1983	2020			
						BC[a]	HD[b]	WEC[c]	IIASA[c]
ME/NAf	25.9	22.4	19.0	16.3	14.9	15	15	22.5	32.5
Rest	39.9	40.4	40.2	40.7	41.5	30	48	48.5	55.5
Total	65.8	62.8	59.2	57.0	56.4	45	63	71.0	88.0

(a) Our base case scenario.

(b) Our high demand scenario.

(c) Average of low and high scenarios.

74.

Global Electricity Supply Mix, High Demand Scenario
(in average TW produced at power plants)

	1980	2020
Hydro	0.19	0.60[a]
Wind and photovoltaics	--	0.12[b]
Cogeneration		
Biomass	--	0.18[c]
Fossil fuel	--	0.18[c]
Central station		
Nuclear	0.08	0.30[d]
Fossil fuel	0.66	1.00[e]
Total	0.93[f]	2.38[f]

(a) As in the base case, it is assumed that one-fourth of the electricity supply (5,300 TWh/year) is hydro. For comparison, the 1976 WEC estimate of the global economic potential is 9,700 TWh/year.

(b) As in the base case, it is assumed that 5 percent of the total electricity supply is wind and photovoltaics.

(c) As in the base case, it is assumed that the cogeneration fraction of total electricity production is 15 percent, with a fifty-fifty mix of biomass and fossil fuel inputs.

(d) As in the base case, it is assumed that in 2020 nuclear electricity is produced at the level officially forecast for 2000.

(e) Assumes that central station power generation based on fossil fuels is the residual.

(f) Electricity production is equal to the electricity demand level (see note 72 above) divided by 0.89 to account for transportation and distribution losses.

75.

Global Primary Energy Supply Mix, High Demand Scenario
(in TW)

	1980	2020
Nuclear power	0.22	0.75[a]
Hydro	0.19	0.60[a]
Wind and photovoltaic electricity	--	0.12[a]
Fossil Fuels		
Coal	2.44	1.95
Oil	4.18	4.46[b]
Natural gas	1.74	4.46[b]
Subtotal	8.36	10.87
Biomass		
Organic wastes		1.01[c]
Plantations		2.00[d]
Subtotal	1.49	3.01
Total	10.3	15.34

(a) See note 74 above.

(b) Oil and gas production levels (assumed to be equal) are the residual.

(c) Assumes that one-fourth of the produced organic wastes can be recovered for energy purposes.

(d) Assumes that the PER between 1985 and 2015 is limited to 12 million hectares per year; that the average plantation yield is 10 tons per year; and that wood has a heating value of 18 GJ per dry ton. Under these conditions, some 3.5 billion tons of wood would be harvested on 350 million hectares in 2020.

76. If world oil demand increased from 4.18 TW in 1980 to the high demand scenario level of 4.46 TW in 2020, the required cumulative world oil production from 1981 to 2020 would be some 173 TW-years in this period. If in the period from 1983 to 2020 production in the ME/NAf region were maintained at the 1983 world "oil glut" level of 1.06 TW (15 MBD), cumulative oil requirements from regions other than the ME/NAf region in this period would amount to some

$$173 - (1.36 \times 3) - (1.06 \times 37) = 130 \text{ TW-years.}$$

For comparison, it is estimated in Haefele et al., note 1(b) above, that the remaining non-ME/NAf world oil resources that are ultimately recoverable at a price less than $26 per barrel (1982 dollars) are some 132 TW-years.

77. Using the carbon dioxide production coefficients given in note 42 above, for alternative fossil fuels, and assuming that half of the released carbon dioxide stays in the atmosphere, we obtain the following net additions of carbon to the atmosphere in 2020:

Base case scenario	4.9 GT
High demand scenario	6.2 GT
WEC scenarios (average of high and low)	10.2 GT
IIASA scenarios (average of high and low)	10.8 GT

78. See note 73 above.

79. In Haefele et al., note 1(b) above, it is estimated that the peak oil production capacity for the ME/NAf region in the period from 2020 to 2030 will be some 34 million barrels per day (2.4 TW).

80. See Goldemberg et al., *Energy for a Sustainable World* in note 19 above, chapter 5.

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MARKET PENETRATION AS AN IMPEDIMENT TO REPLACEMENT OF FOSSIL FUELS IN THE CARBON DIOXIDE ENVIRONMENTAL PROBLEM

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INTRODUCTION

In 1975, Marchetti extended the use of the logistic transition curve as a descriptor for the market growth of an emergent technology to the depiction of the replacement path for one of the world's primary energy sources by another.[1] He then used this empirically-based microeconomic property, once applied to the global scale, not only to describe past global energy transitions but also to predict future transitions. This insight, when applied to the carbon dioxide/climate change issue, was seminal in transforming what was in essence a scientific curiosity into a significant environmental issue with important and pressing policy implications.

Basing his results on careful and extensive analysis of the historical record, Marchetti concluded that the time for takeover of one form of the world's primary energy source by another was very long, and cited fifty years as a minimum time for an increase from a 1 percent to a 50 percent market share of the replacement technology. Moreover, he claimed that this estimate was applicable to future shifts in energy use. Since, in the mid-70s, fifty years was the consensus estimate for the onset of a critical greenhouse warming from the projected increased use of fossil fuels, the application of Marchetti's findings implied that immediate steps to replace fossil by non-fossil energy sources would be needed to avert environmental disaster. Absent this coincidence in timing of the environmental insult with the response time required to handle it, the carbon dioxide/climate change problem seemed to most to be far too distant and too uncertain to warrant concern--an attitude that is now returning with postponement of the timing of a significant carbon dioxide-induced climatic impact following the recent reductions in projected economic and energy growth rates. The pragmatic rationale for such a stance is clear: time- and growth-discounting, even at very low rates, reduce the present-day costs of catastrophically expensive future impacts, for instance those that occur fifty or one hundred years from now, to minor proportions. In contrast to an assessment based on technical considerations, stress alternatively could be placed on the intergenerational costs of this long-range problem, posed as a moral question concerning the welfare of the yet unborn. Adherents of this second viewpoint attach little importance to discounting arguments, so their attitude would be little changed were the market penetration time impediment to the transition to a non-fossil economy to turn out to be illusory. As we shall discuss later, the latter possibility cannot be ruled out--an outcome of considerable importance to some analysts even if not to all viewers of this environmental problem.

The latest reductions in projected energy growth rates considerably delay the most likely date for significant climatic impacts resulting from increasing atmospheric carbon dioxide levels compared with estimates made as recently as five years ago. The earlier projections were for continued long-term exponential growth, whereas current thinking suggests a reduced rate of growth of fossil fuel use later in the twenty-first century, as well as an overall diminution of average growth compared with earlier estimates. The present-day significance of the carbon dioxide problem is thereby reduced in a major way, even accepting the irreducibility of market penetration times. However, such a conclusion is not yet warranted for two reasons: firstly, uncertainty in the timing and magnitude of the carbon dioxide-induced warming is large and the possibility of much more severe or earlier impacts cannot be ignored; and secondly, projections of recently observed trends in the atmospheric concentrations of other trace greenhouse gases imply that the total heating effect of these gases plus carbon dioxide can impact climate within the fifty-year minimum market penetration time given by Marchetti.

Even though it is now ten years since Marchetti first published his findings, little has been done to place this rather surprising and oft times controversial thesis on a surer theoretical footing. His claim for the irreducibility of the market penetration time for possible future energy transitions is the most worrisome feature of the situation. Unfortunately, although some characteristics of the socioeconomic systems of the world can be postulated as important determinants of admissible rates of introduction of new energy forms, not even semi-quantitative evaluation of their roles has been possible to date. Applicability of the thesis to the world's energy future still rests on the extrapolation of empirical evidence, with no causal description available to back it up, and we are in no better position for judging its relevancy to the carbon dioxide issue at this time than we were when Marchetti first raised it. The review given in this paper, therefore, can do little more than outline the consequences of Marchetti's model, assuming it to be valid, and discuss the underlying aspects of the energy system that need to be studied in order, in the future, to determine whether energy penetration lag is truly an impediment to a transition away from the use of fossil fuels.

THE HISTORICAL EVIDENCE

Market penetration time models as applied to new, and particularly to new technology-based, products have been under investigation for over twenty years. The best-known of these that incorporates the logistic penetration time function used by Marchetti is due to Fisher and Pry,[2] who chiefly concerned themselves with product replacement for a given end use taken over by a new technological line. Original consideration of the subject was offered by Mansfield ten years earlier,[3] with applications to major U.S. industries, such as railroads, coal, and steel. Blackman amplified Mansfield's work with the introduction of the same analytic form as used by Fisher and Pry and Marchetti.[4] It is important to note that this logistic functional form

$$F = \frac{1}{1 + \exp - \alpha\,(t - t_o)} \qquad (1)$$

originally was selected to describe the temporal transition of the market share, F, of the new technology from 0 at $t = -\infty$ to 1 at $t = +\infty$, because, as a simple analytic S-shaped curve, it happened to fit the data. There was no claim for deeper significance than this. The empirical evidence for its match to numerous data is now extensive; Marchetti cites 300 tests he has made of the formalism.[5]

A rudimentary explanation for the reasonableness of Equation 1 can be adduced through the differential form of the equation, which as

$$\frac{dF}{dt} = \alpha F (1-F) \qquad (2)$$

states that the rate of growth of the fractional share of the new product is proportional both to its degree of penetration and to the residual market size. The above description applies to the case in which a single product, an energy source in our case, is supplanted by another. This is usually an oversimplification, and Marchetti modified the method so that it could be applied to a multicomponent system.[6] A more sophisticated rationale for this situation has been given by Auer,[7] but with no practical consequences for us. Marchetti's results for past world energy use transitions are shown in Figure 1, using his multicomponent approach. The solid lines follow the historic data, and in this logarithmic plot, F/(1-F) versus time (t), follows a straight line when obeying the simple logistic form

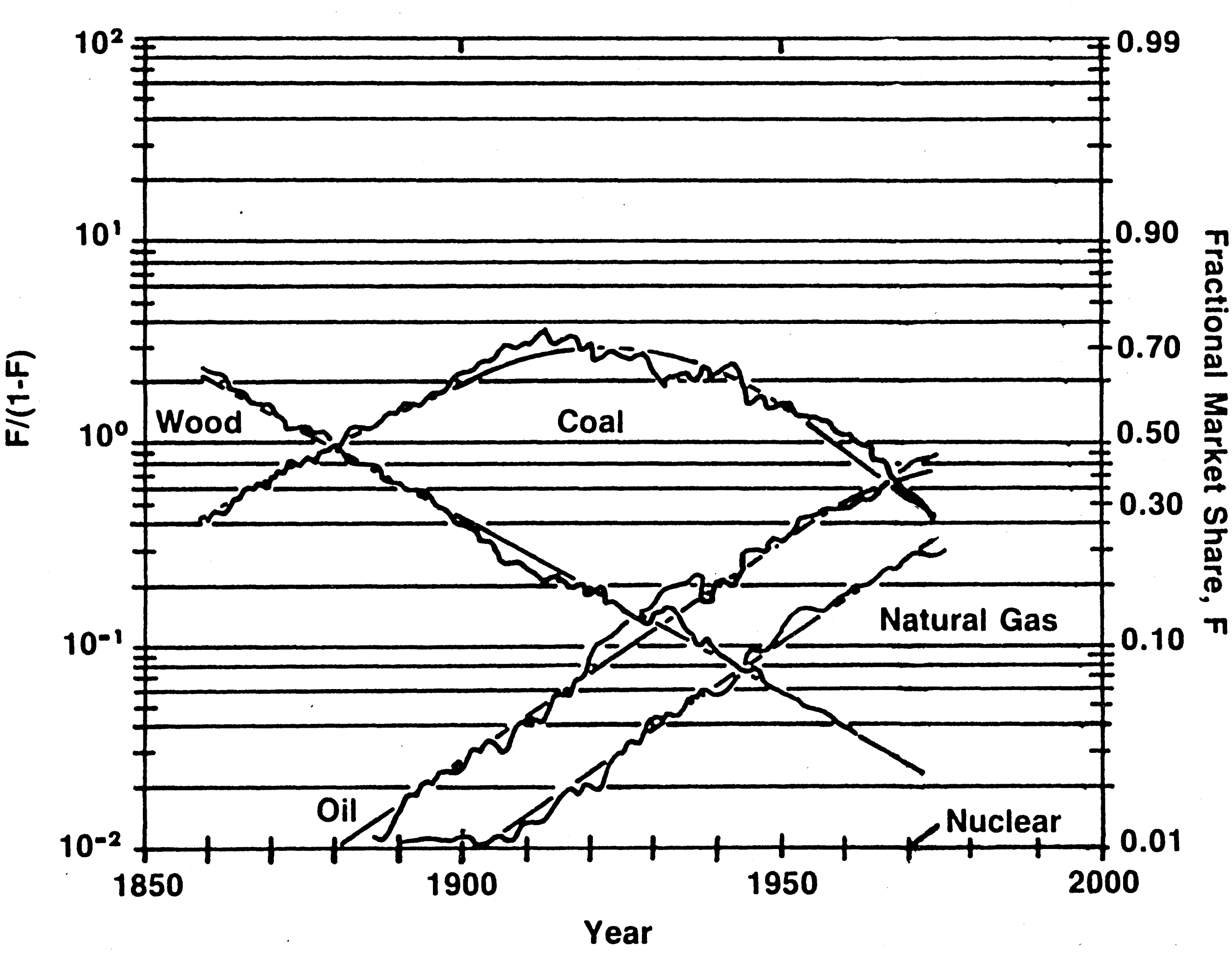
$$\ln F/(1-F) = \alpha (t-t_o) \qquad (3)$$

The market penetration time, or time constant, t_p, for a given component pair is defined somewhat arbitrarily as the time taken for the new technology share to grow from 1 percent to 50 percent of the total market. The emergent world markets for wood, coal and oil, t_p had values between 90 and 100 years (see Figure 1). Marchetti's upper estimate for a penetration time of 100 years for a future energy source derives from this result.

We might add parenthetically that the market penetration time constant was defined by Fisher and Pry as the time taken for market share to increase from 10 percent to 90 percent, but this turns out to be numerically very close to the 1 percent to 50 percent figure, assuming the logistic form. In fact, it can be shown that

$$t_p\ (1\%-50\%) = 1.0457\ t_p\ (10\%-90\%) \qquad (4)$$

Figure 1
PAST MARKET PENETRATION OF THE WORLD'S PRIMARY ENERGY SOURCES

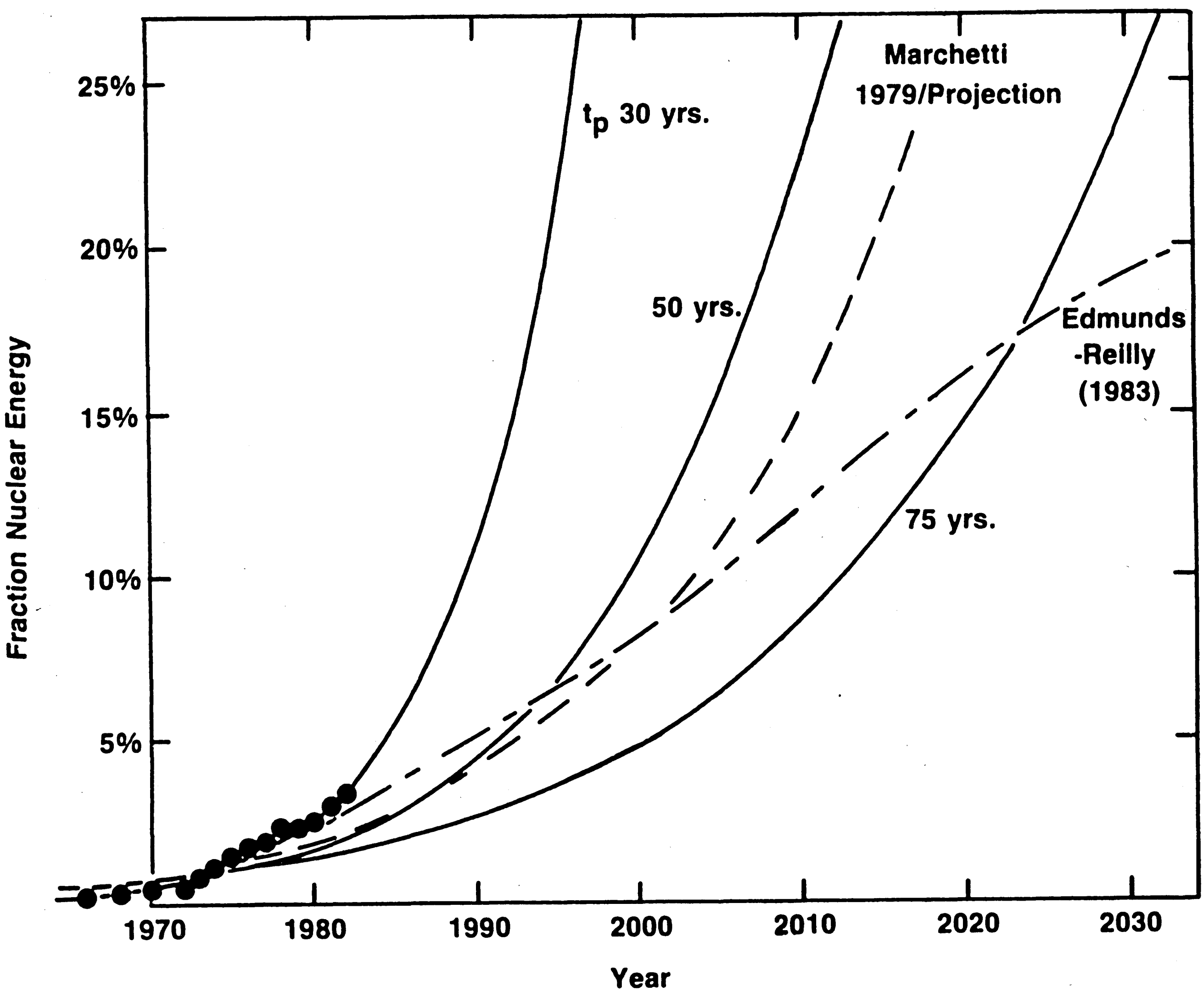


Adapted from C. Marchetti, "Primary Energy Substitution Model: On the Interaction Between Energy and Society," *Chemical Economy and Engineering Review* 7, (1975): 9.

The data available to Marchetti in 1975 on nuclear energy growth were too meager to enable an estimate of the time constant for nuclear energy to be made. The latest information on the growth of nuclear energy use is presented in Figure 2. Here, in addition to the reported annual nuclear power consumption values through 1982, shown as dots, we have plotted logistic growth curves with thirty-, fifty-, and seventy-five-year time constants, as well as Marchetti's own projection of nuclear energy growth,[8] plus one of the latest projections, that of Edmonds and Reilly, for nuclear growth based on a detailed world energy/macroeconomic model.[9] The depiction in Figure 2 is notable in two regards. First, we see a major difference between the apparent logistic trend of nuclear energy growth (approximating the t_p = 30 years value) and the Edmonds and Relly prjection. The latter, we should emphasize, is typical of other current projections. The apparent discrepancy can be explained through the long planning and construction lead times: nuclear plants currently coming on line reflect plans made several (probably more than ten) years ago, before the advent of reduced energy demand in the developed world and prior to the time of increasing public hostility to the installation of nuclear generating capacity. Presumably, in the future nuclear growth will fall below the logistic extrapolation.

The second significant feature of the data is that they appear to contradict Marchetti's claim for a fifty- to one-hundred-year market penetration time. However, there are reasons why the latter conclusion need not apply. Thus one may argue that early initial penetration could be extremely high if actively promoted and capitalized through national programs. Later

Figure 2
PAST AND PROJECTED FUTURE WORLD NUCLEAR ENERGY PRODUCTION
AS A FUNCTION OF TOTAL ENERGY USE*



t_p = the time for increase from 1 percent to 50 percent of market share
*Logistic growth curves assume a 1 percent market share by 1975.
Nuclear data are from Energy Information Agency, *1982 International Energy Annual Report*, DOE-EIA-0219 (82) (Washington, D.C.: U.S. Department of Energy, Office of Energy, Markets and End Use, 1983).

on, when the new industry starts to compete with the old in a major way, penetration my slow. In addition, most of the growth of nuclear energy depicted in Figure 2 occurred in developed countries; the results should therefore not be considered as typical for world conditions, and Marchetti himself has pointed out that the time constants for primary energy penetration have historically been shorter for smaller geographical scales.[10] For example, he suggests that a time constant as short as thirty years would be applicable to Western Europe, with recent evidence for increased use of natural gas confirming this observation. By contrast, U.S. primary energy substitution, excluding nuclear, has been relatively slow, with time constants of the order of seventy to eighty years. Hence, Marchetti's empirical conclusions on the effects of scale and degree of socioeconomic development are important features of market penetration and imply that the changing proportion of energy use between the developed and developing countries must be taken into account when trying to predict future energy penetration rates.[11]

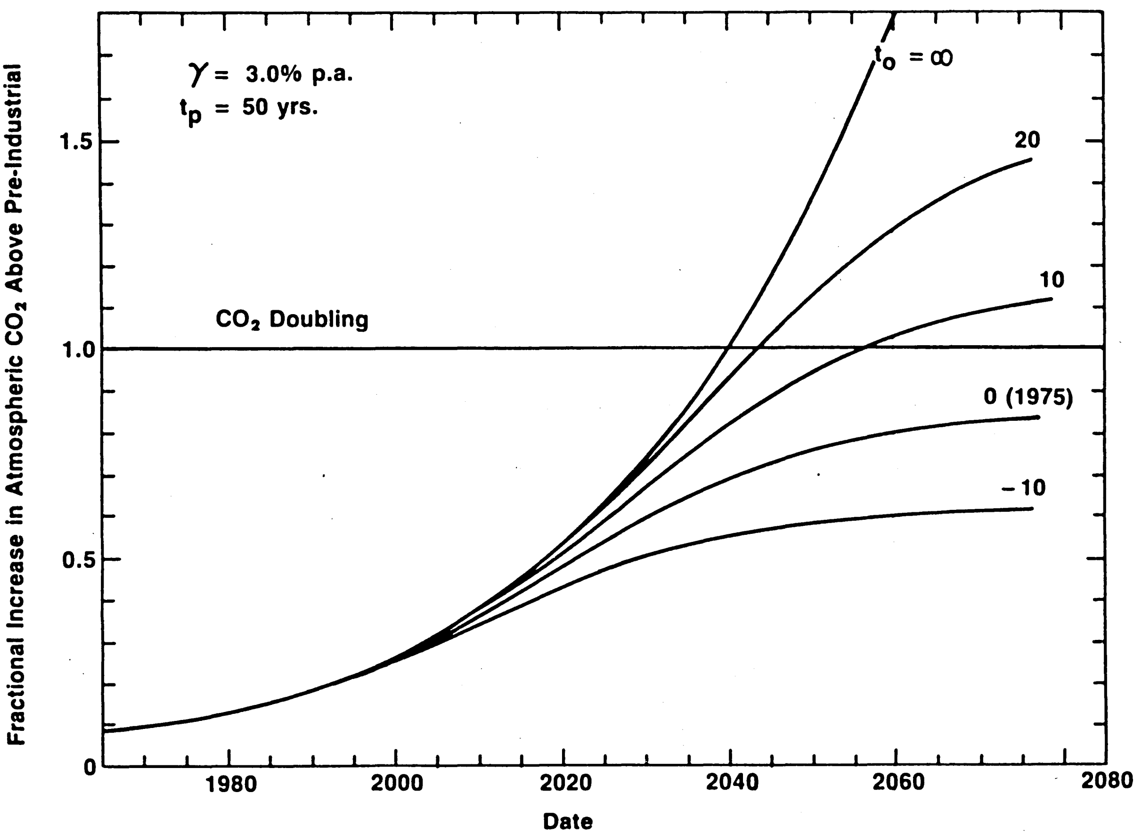
APPLICATION OF THE LOGISTIC MARKET PENETRATION TIME FORMULATION TO THE CARBON DIOXIDE PROBLEM

It is an easy exercise to apply the simple logistic replacement formula (Formula 1) to an assumed two-component primary global energy system--fossil and non-fossil--to determine the effect of alternative fossil/non-fossil energy futures on atmospheric carbon dioxide levels. Figures 3 through 6 show the results of such an exercise, using a constant fractional retention model for the amount of carbon dioxide left in the atmosphere upon the combustion of fossil fuels. This fraction was taken as 56 percent, based on past observations, and is a reasonable approximation for atmospheric carbon dioxide levels at least as high as double the preindustrial value, provided the deforestation contribution is not too large.[12] If the latter situation holds, the long-term carbon dioxide level for a prescribed future energy use will fall below the values given in the figures. The results in Figures 3 through 6 are plotted for a variety of market penetration time constants, t_p, and initiation times for the introduction of some non-fossil fuel, which we assume as a replacement for the world's currently fossil fuel- dominated energy production. The latter are identified by values for the time by which non-fossil energy has risen to occupy 1 percent of the market, referenced to a base date of 1975.

These illustrative calculations demonstrate the conditions and assumptions concerning energy growth and market penetration time, under which characteristic atmospheric carbon dioxide concentrations approach threatening levels. We assume that the carbon dioxide doubling state, indicated by the heavy horizontal lines, represents such a condition. For several reasons, these should not be taken as faithful projections of possible futures; they are presented to indicate those values of the parameters t_p and t_o that could give difficulty were a move to non-fossil energy use to be dictated. The simplification to a two-component system makes it impossible to properly represent the role of hydro power; it is currently a significant factor in overall supply, but it cannot rise enough to play a noticeable role in the abatement of carbon dioxide growth. We have, therefore, lumped hydro power in with the fossil component, as we have also done for current production of energy from biomass. It would be possible to refine the calculations to correctly incorporate such items, but this is hardly merited in view of our effort to present only the overall nature of the difficulties encountered in the energy transition process. Excessive detail tends to suggest a degree of precision that is not warranted by the data.

Figures 3 through 6 are also idealized in assuming continued fixed exponential growth of total energy use, γ, with values varying between 2 percent and 5 percent per annum. Projections of energy use made prior to the energy crises of the 1970s typically assumed constant exponential rates, varying from the 5 percent at the beginning of the decade, to 3 percent towards its end. There have been a few very lone-term projections that have accounted for population stabilization,[13] such as the International Institute for Applied Systems Analysis (IIASA) projections. Most current studies project decreasing rates of energy growth starting sometime early in the next century, as, for example, in the Edmonds and Reilly projection shown in Figure 2. We feel, however, that broad conclusions regarding the importance of market penetration time lags should not be affected by omission or departures from exponentiality, at least when considering medium time scale phenomena that are contained within a fifty-year market penetration time. We consider

Figure 3
GROWTH OF CO_2 CONCENTRATION FOR LOGISTIC NON-FOSSIL REPLACEMENT OF FOSSIL FUELS*



*Total energy growth is assumed to be exponential at an annual rate, γ, of 3 percent. Market penetration time constant, t_p, is fifty years; various non-fossil entry dates, t_o, for a 1 percent penetration (relative to 1965) are shown.

the latter a reasonable lower limit according to the historical data collected by Marchetti. Of greater significance is the very large uncertainty in the long-term energy projections; an aspect that will be discussed later in this paper.

The curves in Figure 3 were calculated for an overall energy growth rate of 3 percent per annum, an acceptable figure in the late 1970s but an overestimate according to most of today's forecasts, which lie in the 2 percent per annum range. At the 3 percent per annum growth rate, assuming all of this was to result from accelerating fossil fuel combustion, atmospheric levels of carbon dioxide would double by about 2040, at which time global temperatures would have risen by about 2.5 degrees Celsius.[14] The latter figure is highly uncertain and is likely to be biased upward because of the delaying effect of the ocean's thermal inertia, which is not included in these equilibrium calculations of climate change.

Figure 7 shows several projections of average global temperature increase for a fixed 3 percent per annum exponential energy growth rate and for an approximately 2 percent per annum rate projection made by Rotty in 1980.[15] We have also indicated on the abscissa the revision in timing of the climate

Figure 4
ATMOSPHERIC CO_2 INCREASE FOR A TOTAL EXPONENTIAL ENERGY USE GROWTH RATE OF 4 PERCENT PER ANNUM

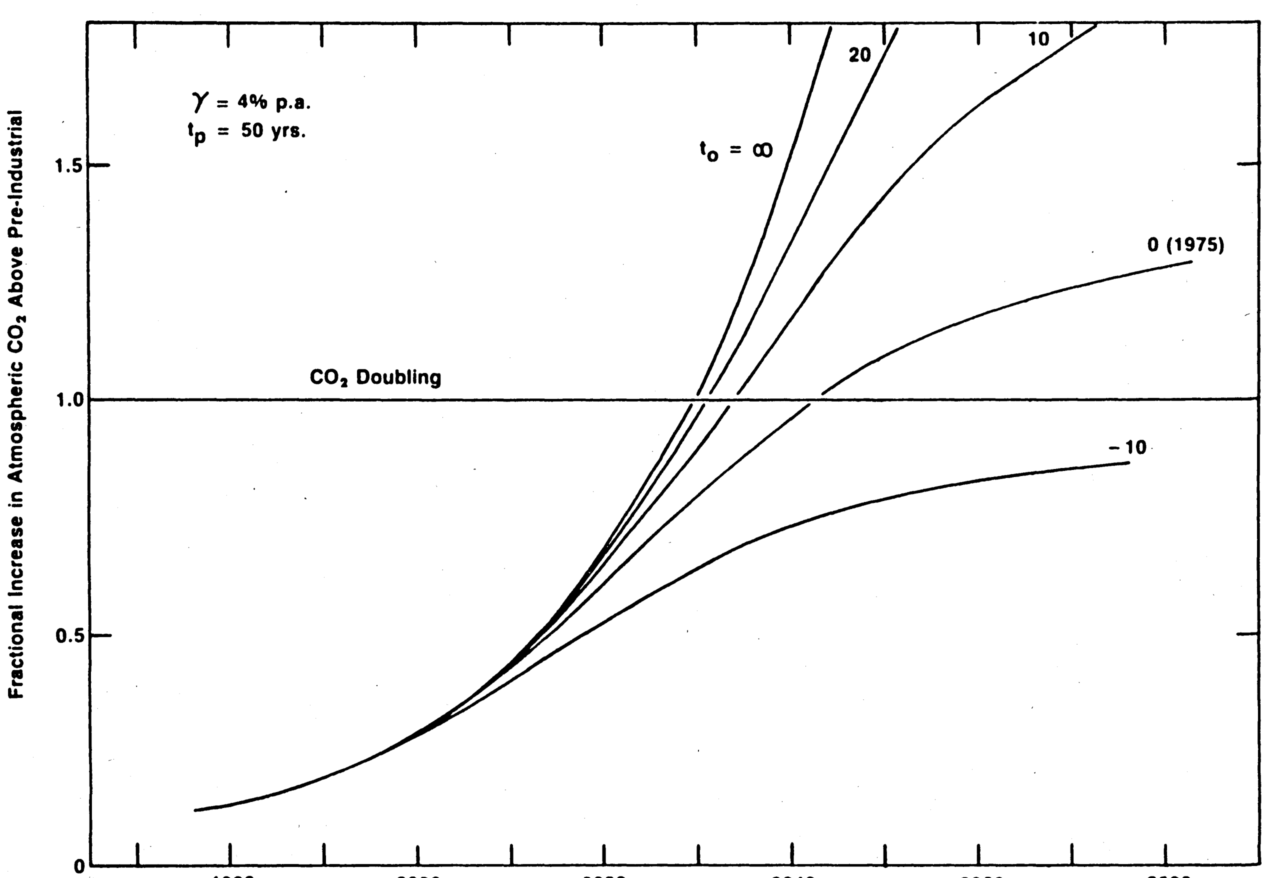
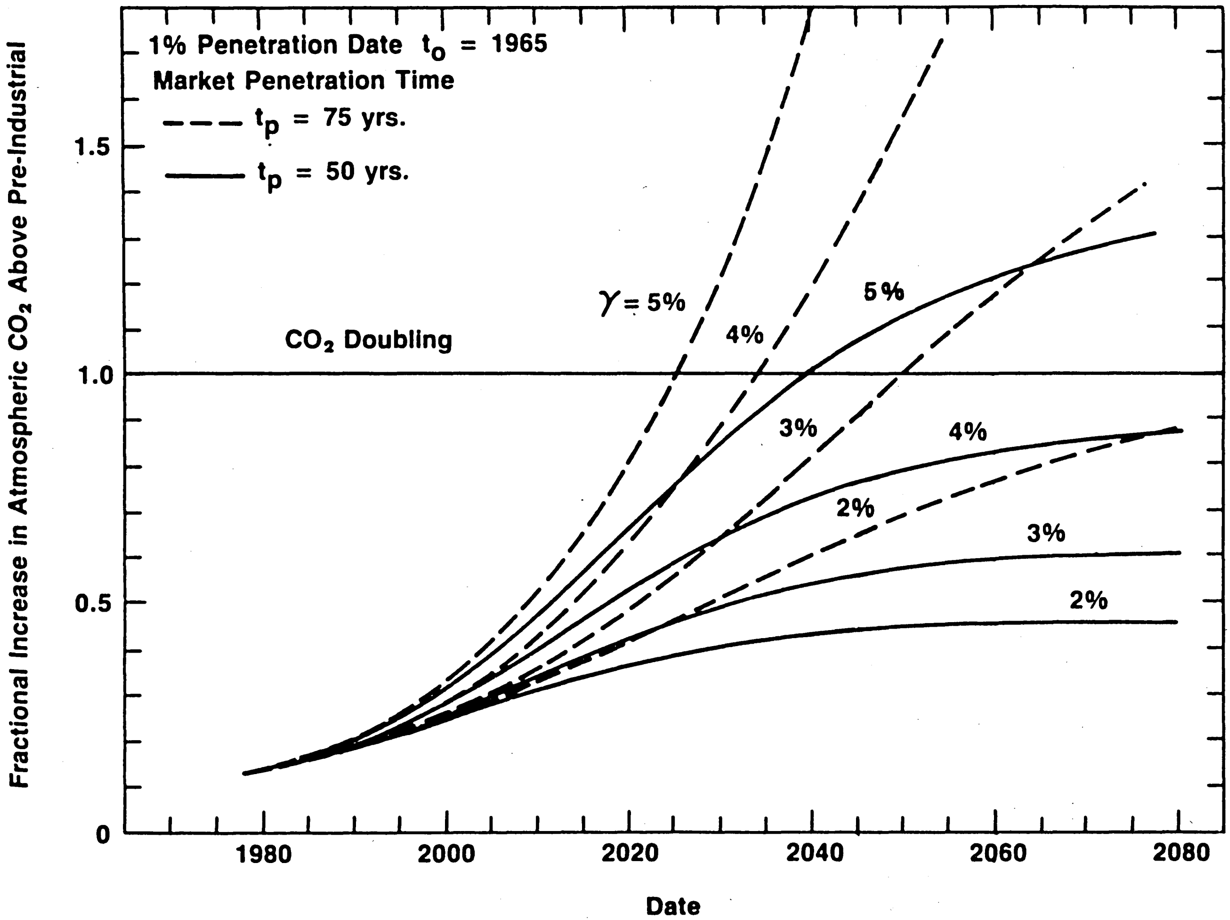


Figure 5
ATMOSPHERIC CO_2 INCREASE FOR VARIOUS TOTAL EXPONENTIAL ENERGY GROWTH RATES (γ)*



*Non-fossil fuel's share was 1 percent of the market in 1965.

change due to a twenty-year lag from ocean thermal inertia effects. Figure 7 also introduces another important feature of the greenhouse warming, the effect of infrared-absorbing trace gases other than carbon dioxide. The solid lines in the figure show the effect of these additional greenhouse gases, which, if we accept Ramanathan's estimate of the effect of these other gases (OGGs), essentially eliminate the effect on global climate of a reduction in annual rate of increase in fossil fuel use from 3 percent to about 2 percent per annum.[16] Overall, the effect is a return to the mid-1970s' viewpoint on timing and criticality of the anticipated anthropogenically-produced climate changes. Ramanathan estimated an additional warming from the OGGs equal to about 80 percent of the warming expected from carbon dioxide alone, a value thought to be too low today.[17] An increase by 100 percent or even more is believed possible.**

**But it would be difficult to account for the current absence of a clear climatic change signal if the supplement is too large.[18] An analysis of the implication of OGG growth has yet to be undertaken.

In studying the significance of the non-fossil market penetration results presented in Figures 3 through 6, we thus believe that, so long as we take the carbon dioxide doubling levels shown on the figures as indicative of serious climatic impact and assume that present growth in the concentrations of the other greenhouse gas concentrations continues, it should be assumed that a 3 percent per annum energy growth rate is more representative of a likely future than is a lower rate. Alternatively, we could use the lower, 2 percent, growth rate and take a lower carbon dioxide concentration as indicative of significant impact. Following the latter argument, the range of carbon dioxide levels that should be considered critical correspond to increases of between 50 percent and 100 percent above the preindustrial level, the upper limit allowing for no effect from the additional trace gases and the lower for both carbon dioxide and the OGGs. A critical level is defined as that which, in conjunction with the OGGs, would increase mean global temperature 2.5 degrees Celsius.

Figure 6
ATMOSPHERIC CO_2 INCREASE FOR A TOTAL EXPONENTIAL ENERGY GROWTH RATE OF 2 PERCENT PER ANNUM

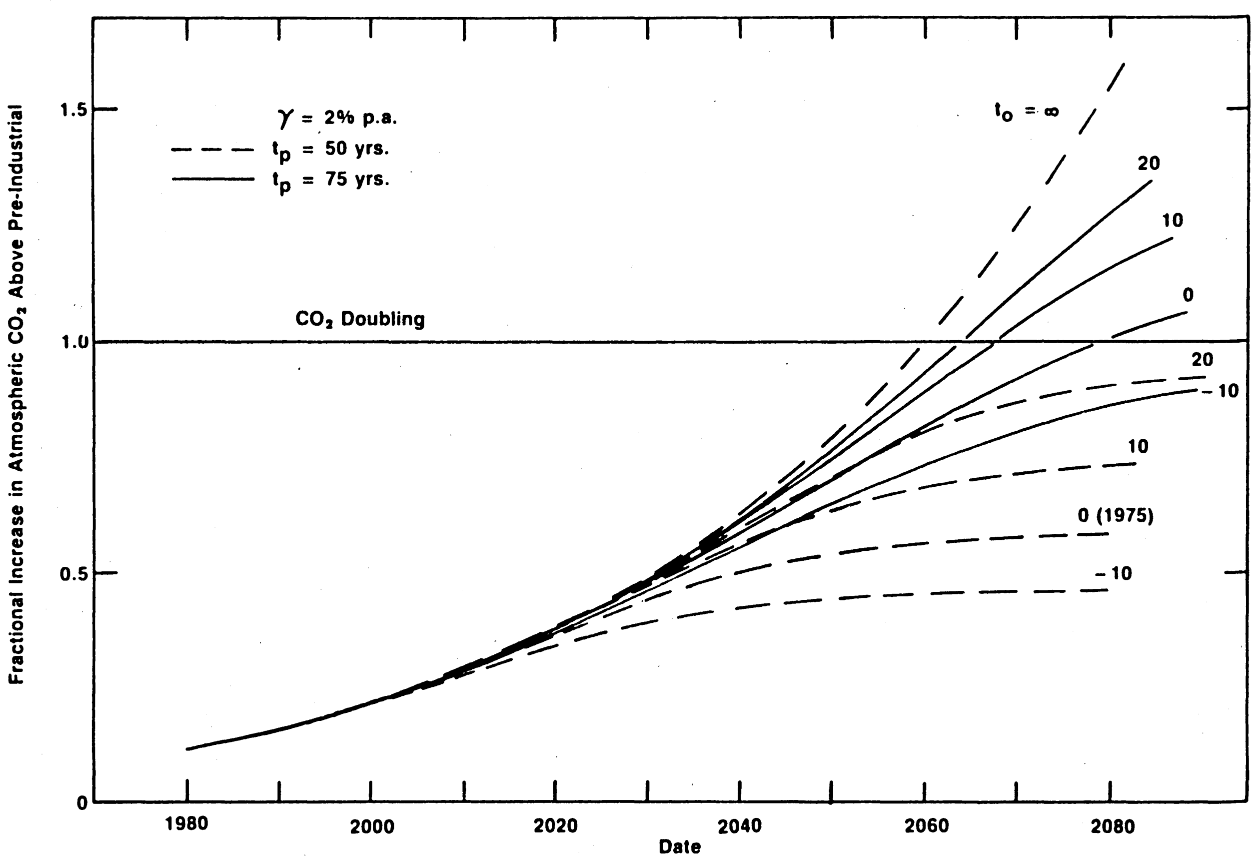
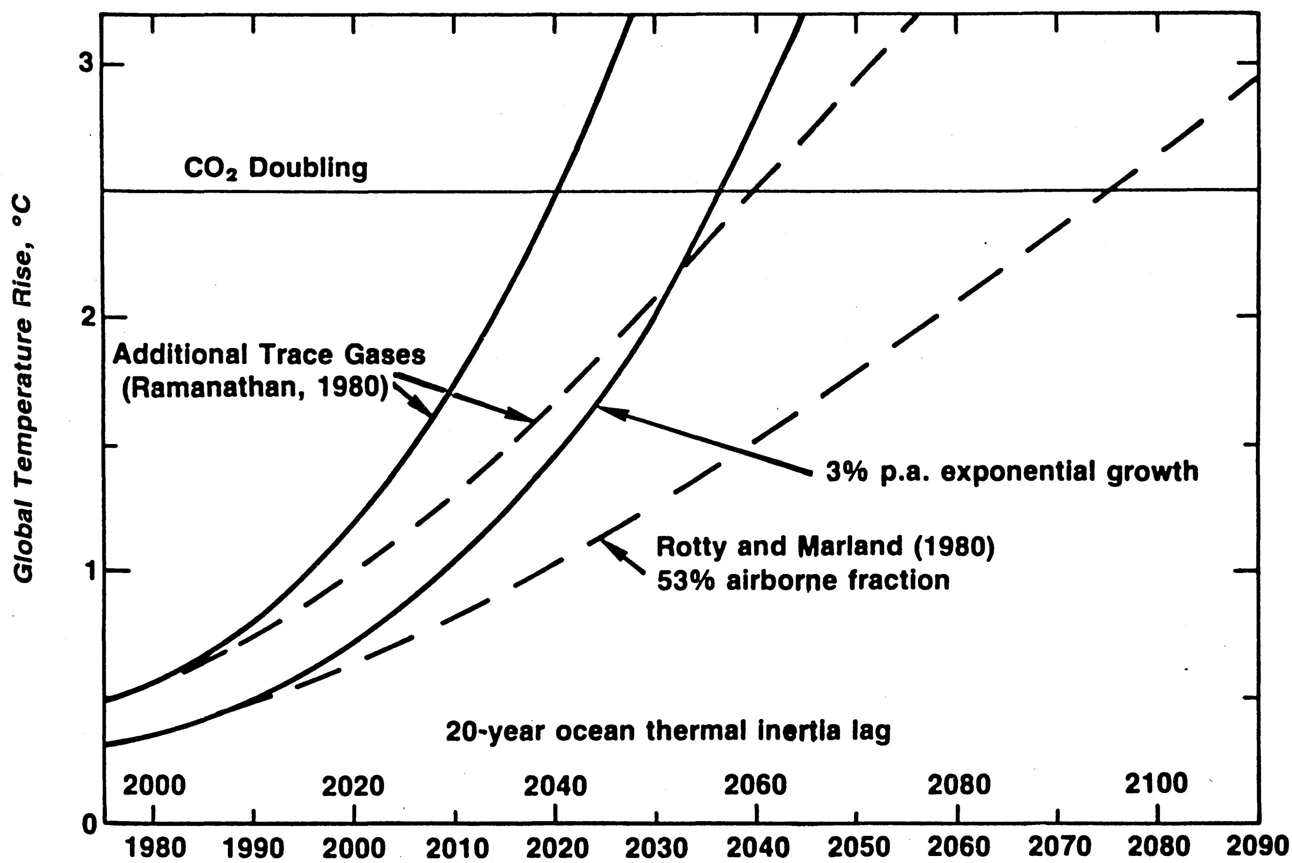


Figure 7
CLIMATIC CHANGE WITH AND WITHOUT THE PRESENCE
OF OTHER TRACE GREENHOUSE GASES



Figures 3 and 4 are plotted for a fifty-year market penetration time constant (about the lowest that could be accepted if the Marchetti proposition is believed), and for a variety of initiation dates, t_o, for the introduction of non-fossil fuel energy sources. These indicate that a 3 percent rate of growth, with a fifty-year time constant, requires immediate movement away from fossil fuel use to avoid the carbon dioxide doubling state. However, energy growth at 2 percent per annum, retaining the fifty- year t_p value, would delay the time for required action for several decades (see Figures 5 and 6). Increasing the market penetration time to seventy-five years reintroduces the difficulty (see Figure 6). These general conclusions apply to the climatic impacts of carbon dioxide emissions. The addition of the other greenhouse gases, whose effect is assumed to double the warming from carbon dioxide alone (so we consider the 0.5 level in Figures 3 through 6 as critical), changes the picture. With a fifty-year penetration time, both for reduction of carbon dioxide and the other greenhouse gases, and a 2 percent per annum energy growth rate, Figures 5 and 6 indicate that we are today already too late to avoid a serious climatic effect unless this is achieved by replacing fossil fuels with nuclear energy, which already has a sizable market share (see Figure 2). This pessimistic conclusion is somewhat relieved if allowance is made for the effect of ocean thermal inertia. A twenty-year delay from this effect would put us currently on about the t_o = -10-year curves plotted in Figure 5, and then the 50 percent carbon dioxide increase level would be asymptomatically avoided at a 2 percent per annum energy growth rate and a fifty-year penetration time. However, with t_p = 50, as we can see from Figure 6, the respite would be short, with action required in under twenty years were the 50 percent increase to be avoided.

These conclusions assume that use of resources contributing to release of the OGGs can be reduced at the same rate as carbon dioxide from fossil fuels. Since it is currently believed, though by no means certain, that the additional trace gases come from non-energy sources, such a scenario requires multiple decisions from and in many different societal sectors. The problems of such a course of action have yet to be investigated. We only note here that, were the contribution of the OGGs to climate warming to be as large as the latest estimates indicate, reduction of atmospheric carbon dioxide emissions alone would do little to relieve the anticipated climatic change.*

Before leaving the perspective on the market penetration time issue yielded by these calculations, we should point out two reservations. First, the reduction in temperature rise from ocean thermal inertia is not a permanent effect; eventually, assuming atmospheric carbon dioxide levels stabilize, the climate change will approach the steady state estimate. Hence, it is possible that the equilibrium climatic impacts will be merely delayed rather than avoided. Indeed, if Hansen et al. are right in their contention that very long (100-year) lags are in order,[20] and provided that carbon dioxide deep ocean deposition rates are not markedly increased, then a major change in our view of the policy aspects of the carbon dioxide problem is required. The implications of this for decision-making and the market penetration time problem have not yet been studied. Second, we have assumed that an overall temperature rise corresponding to a doubling of atmospheric carbon dioxide levels should be avoided. However, the curves of carbon dioxide growth that are marginally close to this state are nearly horizontal, so that a fixed criterion based on avoiding the doubling condition yields unduly high sensitivity of conclusions to, for example, the precise value of t_o. Such behavior is an artifact arising from imposition of sharply defined critical criterion (i.e., carbon dioxide doubling), and it would be more appropriate to apply a more gradually imposed condition, such as arrived at through consideration of the increasing economic costs of growing climatic impacts.[21] A revision following upon these lines remains on the future research agenda.

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*The difficulty reported in the recent Environmental Protection Agency analysis in effecting a significant reduction in climatic change through a coal taxation policy is a direct reflection of this situation.[19] The EPA projections assumed that increase in the atmospheric concentrations of the OGGs would continue unabated.

OTHER APPROACHES TO THE TRANSITION PROBLEM

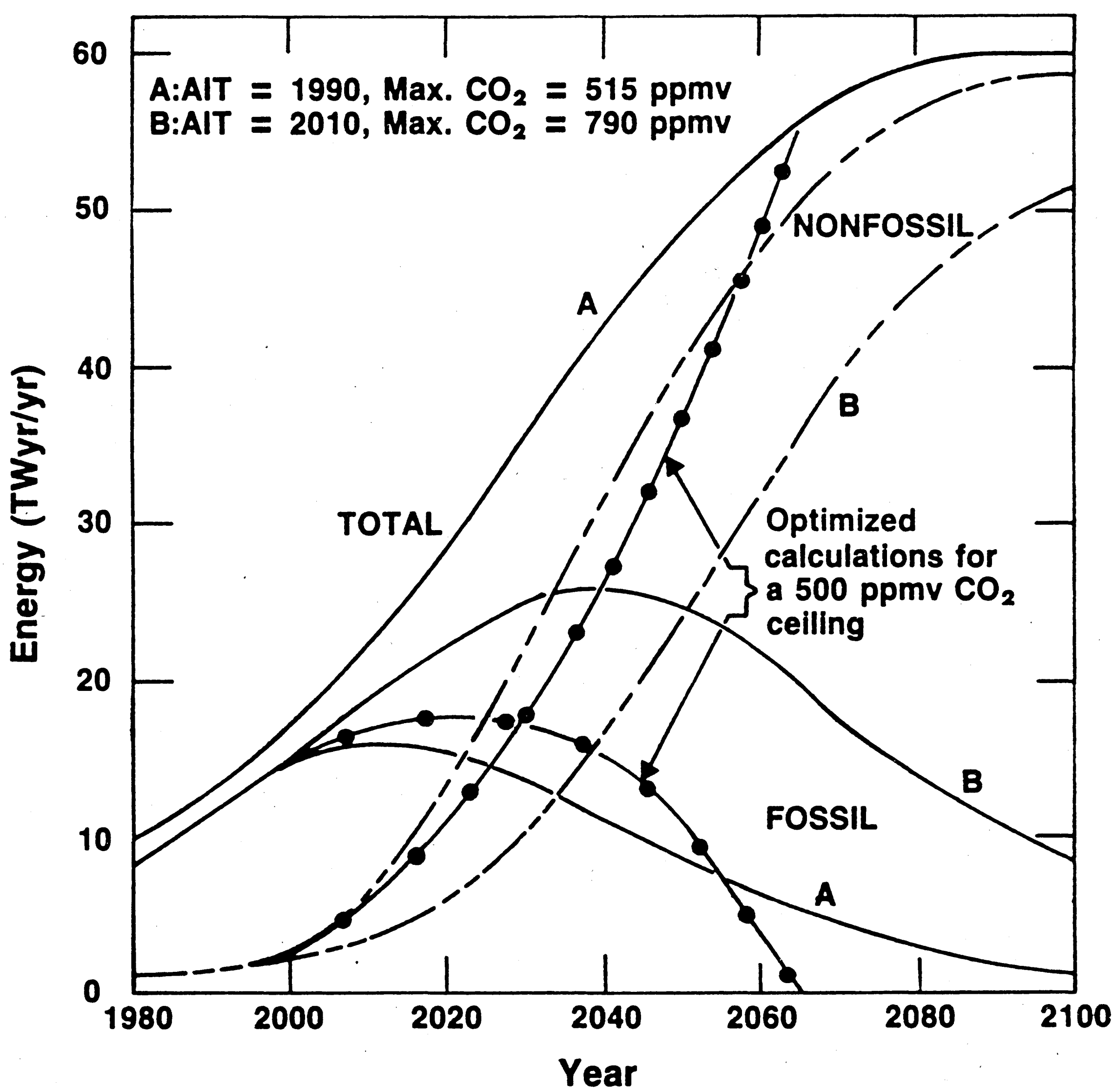
The market penetration time concept was not only the first to be applied to the question of the replacement of fossil by non-fossil energy but remains the only quantified approach. Several other views of the transition problem have been presented, but none of these have been able to come to grips with the real impediments to a rapid shift away from fossil fuel use, should this become necessary. The usual approach has been to postulate one or more future energy scenarios, appropriately divided into fossil and non-fossil portions, and then ask in what way these would have to be changed to avoid exceeding a pre-selected level of atmospheric carbon dioxide. The resultant required rates of growth of non-fossil energy forms are then studied, and qualitative arguments made as to whether these would be easy or difficult to achieve. The first widely publicized report of this nature was made by the Council of Environmental Quality (CEQ),[22] which concluded that the carbon dioxide issue needed to be incorporated as an integral part of present energy policies in order to avoid serious climatic consequences from increasing carbon dioxide emissions.

In Figure 8, we illustrate the approach used in such studies; it is taken from the extensive analysis by Perry et al.[23] In this projection, total energy use is assumed to remain unaffected as the ratio of fossil to non-fossil energy use is adjusted to asymptotically avoid exceeding a pre-selected rise in the atmospheric carbon dioxide level. The two sets of fossil and non-fossil primary energy consumption curves correspond to two values of maximum allowed atmospheric carbon dioxide concentration, with different action initiation times (AITs), which for comparative purposes can be approximately identified with the date t_o defined in the preceding section. Also shown in the figure are the results obtained through the use of an optimization technique for the transition. Perry et al. performed an extensive study on the shape of the non-fossil and fossil energy use curves for the cases shown in this figure, as well as for many other scenarios. Particular features deemed important were: the shape of the tail of the fossil fuel curve (too prompt a fall was believed to be bad) and the magnitudes of the first and second derivates of the non-fossil energy use curves. The first derivate, $\dot{E}_N$, measures the rate of installation of new non-fossil energy power plants required to meet the imposed carbon dioxide ceiling, and a simple assessment of criticality is provided here by comparison with power plant lifetime. If this is done, it is found that most transition scenarios do not make for difficulty (unless action is initiated late, well past 2000). However, the second time derivate of non-fossil energy use, $\ddot{E}_N$, can attain very large values, even with early AITs, as illustrated in Figures 9 and 10. This quantity represents the required rate of construction of new manufacturing plant that supply hardware to make the power plants; here the situation is more critical and requires further discussion.

There are various ways of investigating whether the rates plotted in Figure 10 are excessive, and these are covered by Perry et al. One method is to assume a (construction) plant lifetime of twenty years and relate this to a steady state replacement rate after population stabilization with constant per capita energy use. For the base energy scenario used in the calculations (a high 4 percent per annum initial growth in coal use, asymptoting to an annual total energy use rate of 59 terawatt-years per year), this results in an $\ddot{E}_N$

maximum value of 15 GW/yr^2, a value exceeded outright in Figure 10 for a 500 parts per million (ppmv) carbon dioxide ceiling, and--if action initiation is delayed too long--also for the 600 ppmv ceiling. In Figure 10, an optimized solution is given by systematically adjusting the transition path so as to minimize the maximum value of $\ddot{E}_N$. However, although it reduces $\ddot{E}_N$ maximum value by a half, the revised energy path does not eliminate the difficulty of transition.[24]

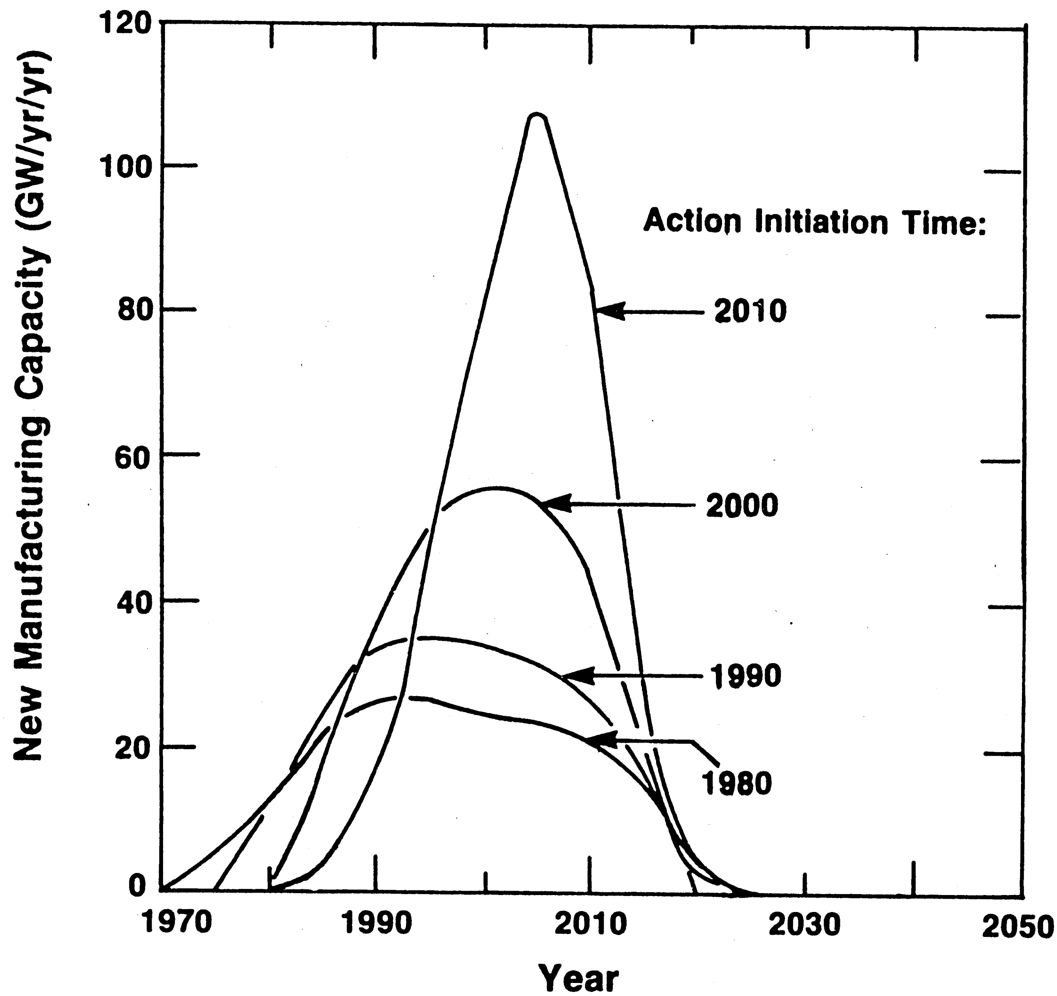
Figure 8
FOSSIL AND NON-FOSSIL ENERGY CONSUMPTION SCENARIOS WITH LIMITED MAXIMUM ATMOSPHERIC CO_2 LEVELS



Adapted from A. Perry et al., "Energy Supply and Demand Implications of CO_2," *Energy* 7 (1982): 991.

The detailed consideration in Perry et al, as well as those in the 1981 CEQ report, develop only qualitative arguments on the problems encountered in reducing, then eliminating, fossil fuel use. Clues are provided as to the nature of the potential difficulties, but it is all too easy to present arguments for or against conclusions that might be drawn, depending upon the predilections of the reviewer. Another class of methods that ostensibly would be able to treat the problem more quantitatively and with less chance of controversy devolves on the use of energy/macroeconomic models used to depict economic interactions resulting from alternative energy-use futures. These typically are used to evaluate the economic impacts of various levels of carbon dioxide increase, and associate a shadow price with these, from which a taxation rate on fossil fuel use can be calculated so as to produce the desired reduction in carbon dioxide emissions and its climatic impact.[25]

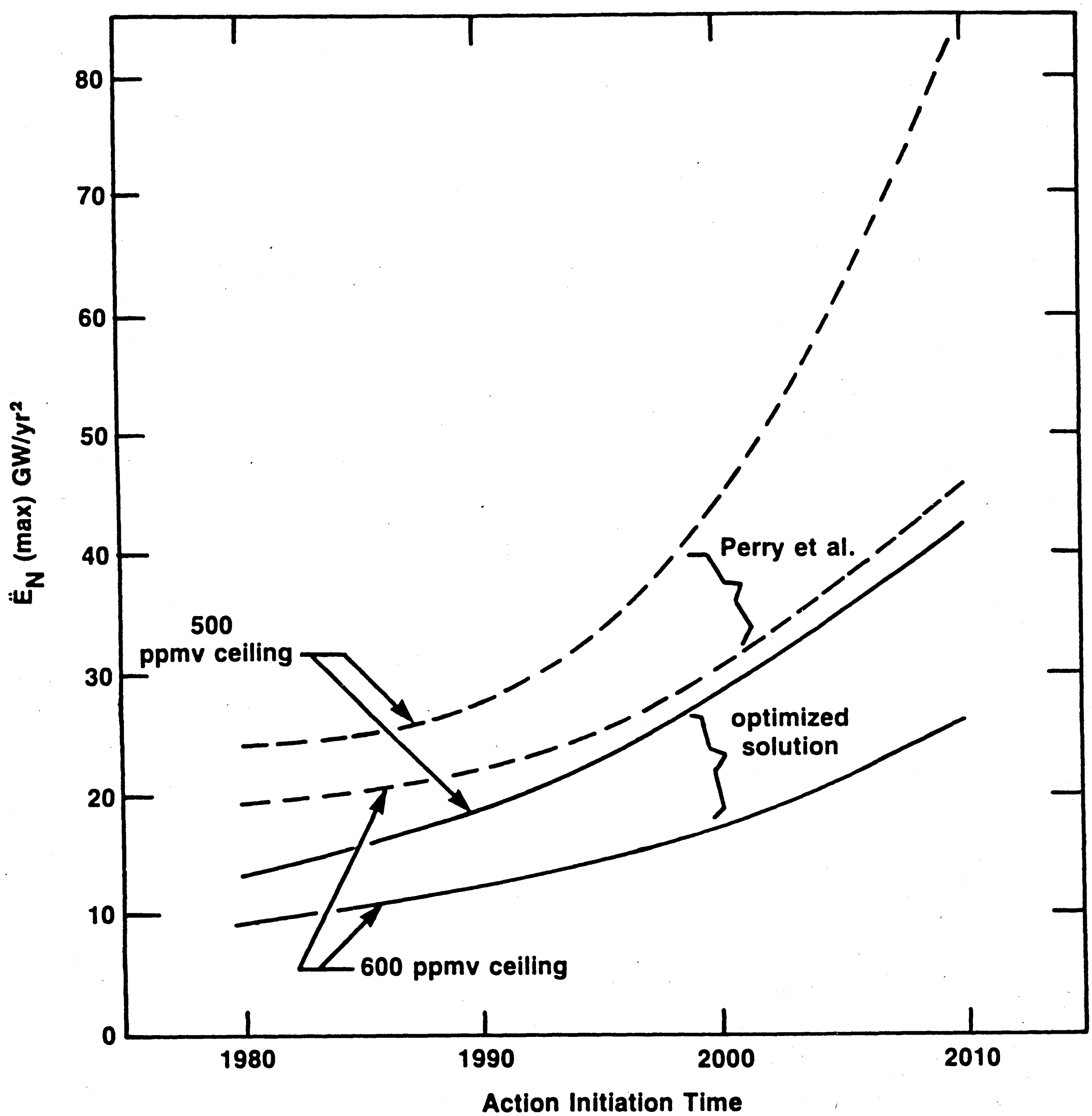
Figure 9
VALUES OF THE SECOND DERIVATE OF ANNUAL NON-FOSSIL ENERGY USE ($\ddot{E}_n$)
FOR AN ATMOSPHERIC CO_2 CEILING OF 500 PARTS PER MILLION (ppmv)



Adapted from A. Perry et al., "Energy Supply and Demand Implications of CO_2," *Energy* 7 (1982): 991.

A variety of differing conclusions have been reached by these authors, though several agree that a taxation system is not an attractive or effective route. We shall not enter into their subject matter, since all the analyses omit the principal problem with which we are concerned, i.e., the constraints of the socioeconomic system that could prevent a rapid transition to non-fossil fuel use. If included at all in these modeling efforts, these constraints are incorporated exogenously and shed no light on the real problems or possibilities of the energy transition. Other economic models do incorporate some factors that are important for our subject, such as capitalization constraints and firm profit maximization actions, though none apparently can be used to derive quantitative values of primary energy market penetration times or deal with Marchetti's claim for their irreducibility.

Figure 10
MAXIMUM VALUES OF $\ddot{E}_N$ AS A FUNCTION OF ACTION INITIATION TIME



THE VALIDITY AND POSSIBLE BASIS OF THE MARKET PENETRATION TIME CONSTANT

The examples given above show that an irreducible market penetration time for primary energy sources as low as fifty years will pose a problem for society, were it to attempt to avoid serious climatic changes--unless the nuclear alternative is accepted. Yet, is fifty years in fact an irreducible value, and, if not, what economic costs are incurred in shortening it? Unfortunately, we are not in a position to answer these questions. We have suggestions as to the nature of the forces that are at work controlling the speed of transition, but we cannot state whether these imply absolute limits on the transition rate or whether they involve marginal additional economic costs that can be sustained with relative ease under internationally enforced action. The best we can do in the following is to present a listing of a variety of social and economic factors that might influence market penetration characteristics, though we cannot say that the itemization is complete or even if it includes the most important elements.

Below we present a taxonomy of factors that could influence market penetration times, divided into three major subdivisions--economic, institutional, and physical. We can further divide these into a number of features that may potentially constrain the rate of penetration.

Economic

- Premature replacement of otherwise usable capital equipment--power plants, secondary industry plants, infrastructure needed for the delivery of energy from its origin to the final user, and end-use technologies.

- Lack of capital for financing new energy systems, including infrastructure and secondary industries.* In contrast to the item above, which introduces merely an economic disincentive for use of new energy sources, this feature implies a more severe constraint through the potential sacrifice of non-energy-sector growth and a need to shift the national emphasis to the production of new energy sources. A limiting condition is reached when total assets of the nation become insufficient to raise the needed capital resources.

- Imperfection of the markets, including the problems of market clearing, specifically the absence of adequate trading mechanisms for the new energy product, and the market inefficiency of regulatory controls (such as coal taxation), if these are envisaged.

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*The critical variable, $\ddot{E}_N$, introduced by Perry et al., and discussed above, is the first such element to have been quantitatively brought into the energy transition problem.

Institutional

- The commons problem. The international character of the carbon dioxide/climate change issue makes it particularly difficult, and time consuming, to achieve a consensus on the need for a worldwide replacement of fossil fuels. Given the heterogeneity of national constituencies, self interest many dictate many differing responses. Varying cultural attitudes can make for distinctly different ethical stances on the mitigation of the carbon dioxide threat.

- The costs of fossil fuel reduction. It is likely that the move away from fossil fuel use would involve a reduction in the standard of living, or at least a slower-than-anticipated rate of increase. It will take more time to build the required political agreement to act under such circumstances.

- Bureaucratic impediments. Even without these major impediments, most nations, whether democracies or dictatorships, have built in bureaucratic impediments to rapid major restructuring at the national level. A decision to abandon a primary energy source would constitute such a change.

- Consumer acceptance. Of less significance to our problem, but a characteristic important for smaller-scale substitutions, is consumer acceptance of a new product. In the literature, this is often cited as critical in the initial phase of introduction. If the non-fossil energy were to be radically different in form or in end-use efficiency (a decentralized energy system in the United States might be such a case), consumer acceptance could be a relevant issue.

Physical

- Material constraints. The deployment of a new energy resource could impose excessive demands on materials and products in limited supply, in addition to the new primary energy resource itself. Most important in this regard, and less obvious, are possible shortages in secondary industries and in the supporting infrastructure.

- Workforce constraints. These could occur in nearly every category--unskilled, blue collar, skilled, and professional. In some instances these shortages may reflect a population deficit; more likely, they will require training or retraining. Professional training would be the most time-consuming.

- Lack of information. The dissemination of "know-how," is potentially a major retardant to implementation. The mechanism for information diffusion has been studied but is not yet well understood; it clearly includes a social component which could have been included within the institutional category listed above.

- Capital resource limitations. This descriptor could also have been put in the economic category, though for the most part it can be ultimately associated with a material deficit. However, a shortage of financing capital could also reflect economic considerations of return on investment. To further blur the distinctions between our three main categories, we take note of the fact that, due to the very long-term nature of the carbon dioxide problem, conventional high economically-based discount rates serve as deterrents to its remediation. A socially determined discount rate may be lower, and, in this regard, arguments for present-day expenditures incurred to avoid far distant costs hinge on the ethics of intergenerationally suffered impacts, and, according to our taxonomy, capital resource limitation thus may be best listed in the institutional category.

Assuming that we have identified the factors influencing the market penetration time phenomenon, we can envisage a research program that addresses them in sufficient detail to ultimately settle our principal question concerning irreducibility of penetration times. Although we strongly advocate that this be undertaken, our needs are urgent and the research path to satisfy them is lengthy. A more expeditious route might be found by identifying the potentially most prominent mechanisms. For instance, the existing literature already makes it clear that the substitution process has distinctly different phases. In the analyses of small-scale innovative new technology, the early phase involves the pursuit of venture capital and customer acceptance. Straightforward economic competition in a fixed-size market is often thought to characterize the next phase. The last, near-saturation, phase is economically anomalous according to efficient market theory, with 100 percent share of the emergent technology rarely being obtained. Since the operant factors are of different origins in these three phases, a one-parameter logistic curve cannot allow for independent variations in them, and the simple model is clearly inadequate. Thus, in the case of replacement of global fossil fuel use, one might anticipate the initial penetration phase to be lengthened due to the need for concerted intergovernmental actions,* but shortened by non-market enforcement procedures, such as taxation, that penalizes older, competing products. In the intermediate phase, maximum non-fossil energy growth would presumably be determined by capital and resource constraints to a mandated transition or by economic competition.

In the major growth period, the potential constraints on the rate of substitution are clearly a function of scale, and the literature supports the conclusion that the larger regions and economic entities involved in the replacement process have longer time constants. We have already quoted Marchetti's results on this characteristic for energy transitions on the global, as compared to the national, scale. Other investigations on small-scale innovations support this general thesis.[26] However, there is an additional factor delimiting the range of possible energy substitution rates that has apparently been ignored to date and is also related to scale. No method for logically amending the logistic growth prescription has been devised to account for a changing underlying energy growth rate, and it is easy to see that a change in total energy growth could affect the penetration rate dif-

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*A number of scholars have, indeed, already given up on the possibility of international accord and advocate a policy of adaptation to climate change.

ferently, depending upon which of the causative factors listed above are at work. For example, a limited capacity to extract a necessary material good could be a time-limiting factor at high demand rates, whereas a high energy use rate, and with it high economic growth, could help overcome the replacement time limitations symptomatic of a low state of economic development and an associated shortage of needed technical skills.

This last possibility brings up an aspect of the carbon dioxide problem that is of special interest, particularly since it runs contrary to conventional thinking. Thus it is widely accepted that a deceleration of the rate of increase in world energy use, together with a reduction in the rate of annual increase in world gross national product (GNP), must ease the environmental problems associated with fossil fuel carbon dioxide release. From most points of view, this is a difficult proposition with which to argue. However, a reduced growth in GNP implies a slower introduction of research results and technology improvement. The importance of technology development in overall economic growth and quality of life has been emphasized in at least two recent research findings using energy/economy models.[27] Hamm has cited technological improvement as one of the prime parameters governing an optimal solution to the carbon dioxide problem. Unfortunately, this model, as well as other macroeconomic models, have to incorporate technology improvement as an exogenous parameter, the value of which is at best an educated guess. Such models, therefore, cannot prescribe the rates of growth that would best achieve a solution to the carbon dioxide problem. However, they do lead to controversial propositions, such as urging maximum short-term fossil energy growth. The latter, it is suggested, would encourage rapid economic expansion, and with it the timely improvement in carbon dioxide abatement methods or in advanced non-fossil energy, thereby limiting the rise of atmospheric carbon dioxide levels to acceptable levels at minimum cost. It is also worth noting that a reduction of energy cost through technological advance does not necessarily favor lower emissions of carbon dioxide. For example, if coal liquefaction and gasification cost were to be reduced, economic forces would encourage additional fossil fuel use growth.

We have throughout this paper made reference to early work on market penetration that was concerned with smaller-scale single-product lines or with single secondary-market penetration, and the literature is extensive on this subject. As with Marchetti's extension to the world scale, the work has been largely empirical. Identification of causal mechanisms has not been followed through with quantitative models. An itemization of the important elements in such applications, similar in spirit to the listing we have given here, has been made by Ayres and Shapanda,[28] and a recent review covering the primary literature in the field has been published by Hurter and Rubenstein.[29] The 1976 text by Linstone and Sahal states that the explanatory power of the Mansfield and Blackman work, which forms the foundation of the logistic substitution mode for new product introduction, is close to zero.[30] Neither a justification of the functional form employed, nor any quantifiable insights into the determinants of causal mechanisms, is provided by the technique. The few studies that introduce more detail have found use only in post hoc analysis. Their use for prediction beyond well-documented past experience is of doubtful value; Warren, in his review of the attempts made to apply market penetration time concepts to the prediction of the future of solar energy, notes, "Solar energy market penetration models are not science but number mysticism," and he places little faith in them as predictive tools.[31] A respectable theory of the diffusion of knowledge of a system or a process imbedded in the social system has been developed[32] and used to generate logistic or similar S-shaped curves,[33] but this sociological component can be only one of a number at work in the market-substitution process. By itself, it is not usable as a forecaster of penetration times.

Another source of information relevant to market penetration processes can be found in the literature dealing with behavior of the competitive, profit-maximizing firm in its response to changing input costs.[34] This microeconomic theory treats one of the elements determining market share in a competitive mode, but does not seem to have been applied yet to an explicit calculation of the parameters in a logistic substitution model. Aggregation to the macro level is required to bring the approach to the level of our concern, and this in turn is bound to involve many features beyond the single firm profit-maximizing response with which the theory is concerned. Peterka has constructed a model that reproduces the logistic form by assuming the growth of the firm, once initially capitalized, to be limited by the revenue available from sales.[35] The logic of the model appears sound only if other financial resources are not available to promote growth, such as external sources of financing or governmental intervention--an unlikely situation for the primary energy market substitution future with which we are dealing. The Peterka formulation has, in fact, been incorporated through an exogenously prescribed parameter into a widely used macroeconomic energy model, ETA-MACRO,[36] but including an adjustable parameter to allow for additional capital financing of the new energy form.

A full economic description will have to include a model of the firm's behavior in the competitive environment, as described through the introduction of the new emergent energy technology into the energy markets of a macro model describing overall energy and economic growth. Models of the latter variety do exist, and features that mimic energy substitution delay have been introduced. Among these is the Edmonds and Reilly model mentioned above. For macro energy/economy models, the two most prominent time-dependent features that relate to energy market penetration are increasing scarce resource costs, which depend on the resource size and on its rate of depletion, and productivity enhancement through an assumed rate of technology improvement. In all cases, however, the resultant temporal lags are determined solely by exogenous choice of parameters and tell us little about real-life limitations to the replacement process. The IIASA energy study[37] and the recent Massachusetts Institute of Technology (MIT) study by Rose et al.[38] have considered subsectors of the world's energy system in considerable detail, but we still have no means of incorporating their effects to predict market penetration time lags other than by arbitrary selection of parameter values. It is clear that help from macroeconomic/ energy modeling in the market penetration question is a long way off. Even so, such modeling might still serve a useful function by determining the sensitivity of the global-scale system to parameters representative of market penetration restraint effects once these can be identified in generic fashion. It should be remembered that it is likely that a limited ability of society to rapidly change from fossil to non-fossil energy use might arise in part from secondary constraining effects outside of the energy production sector, a complication requiring the use of macro models more comprehensive than those that concentrate on energy sector performance.[39]

None of the approaches discussed above can at present give us a mechanistic explanation of the long takeover times of primary energy forms. However, an offshoot of classical economic theory, recently expanded upon, may be able to do so. The so-called fifty-year-long-wave business cycle,[40] originally perceived as an empirically observed feature of depression and expansion in economic activity, has now been duplicated in models. Hence, it may be possible to relate the theory behind these simulations to conclusions regarding future possible energy transitions.

Until recently, the majority of the work in this field was empirical, and admittedly on a statistically insecure base; explanations, although widely discussed, were qualitative and conjectural. The very existence of the long-wave, in fact, still is in dispute. More complicated and extended statistical studies have sought other correlations, such as a connection between surges of innovative activity and economic growth,[41] though cause and effect can be argued here. Marchetti, in some later work on market penetration, has also noted the latter relationship as well as a correlation of ascendancy of the new energy forms with the Kondratieff wave itself.[42]

The modeling that has now produced a quantitative description of the long-term cycle, as well as shorter business cycles, stems from the Systems Dynamics group at MIT,[43] and by now there have been several simulations that claim to have explained the phenomenon from basic non-equilibrium features of macroeconomics.[44] As with all business cycles, the long-wave is thought to arise from a fundamental linear instability of the economic system, but with non-linear saturation effects determining its periodicity in a form of limit cycle behavior. The dominant time constants are those relating to real capital depreciation rates (twenty to thirty years are conventional numbers) and to a capital to capital-output-rate ratio (typically three years). However, although these define the response times in a linear description, they do not directly determine the non-linear behavior. The initial expansion phase involves positive feedback, termed "self-ordering" in the theory, an initial perturbation of growth in demand of capital goods, that in turn dictates a larger capital goods production capacity. This amplification is assumed to be temporally affected by a lag in ability to respond to the increased demand, and a combination of the feedback with the lag is critical in extending the ascending portion of the cycle. A lag also results when overexpansion and saturation of production capacity, a non-linear feature, combine to limit growth and eventually produce a shift to a feedback-reinforced depression phase.

In this model, the oscillations reflect the buildup and loss of total physical capital and involve labor mobility as well as capital accumulation; by contrast, short-term business cycles are controlled by employment and inventory dynamics. Hence, a considerable part of the socioeconomic system is affected during the long-wave cycle, and it is not unreasonable to assume that its large inertia is responsible for its large periodicity.

The systems dynamics modeling approach, briefly summarized here, appears to provide a means for discussing the past history of new forms of primary energy in relation to the long-wave phenomenon. If it could be included in this theory, market penetration would reflect a feature of the free market. It is not known how severe a restraint the element portrayed in the model would be in an enforced shift of primary energy use, but presumably it is researchable along the same lines of analysis used in the study of the free market situation.

THE EFFECT OF UNCERTAINTY

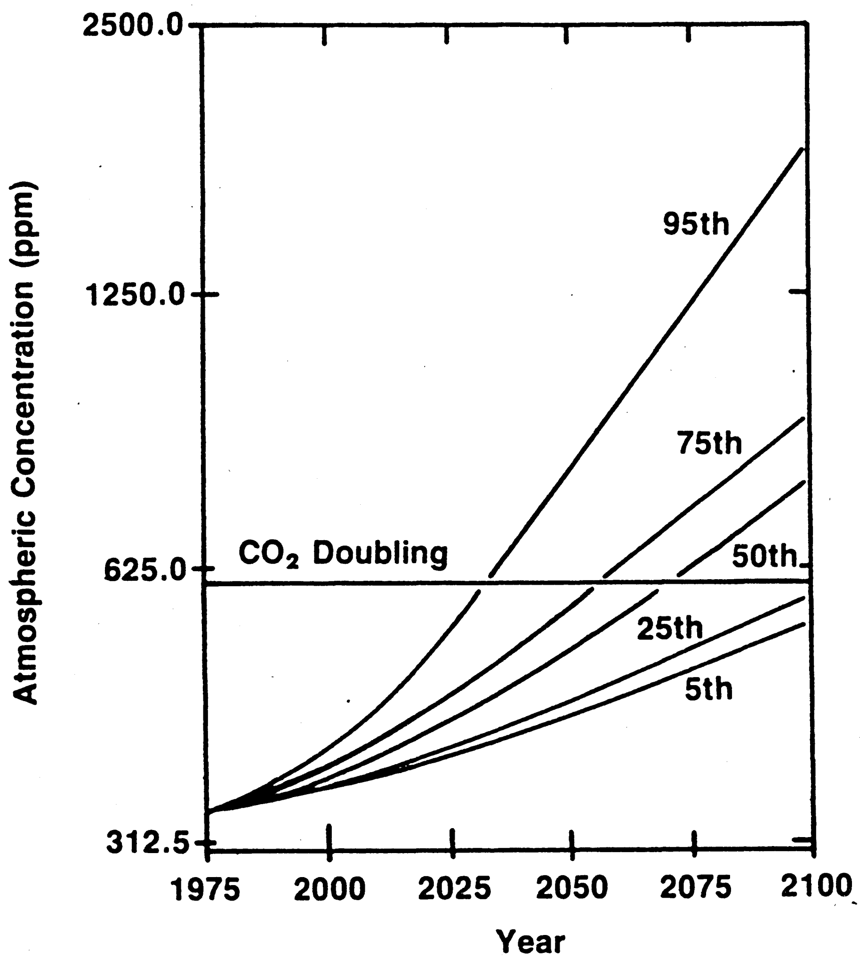
Large uncertainty, an important feature of the carbon dioxide/climate problem, makes assessment of this problem's present-day importance difficult and has resulted in widely differing opinions on the seriousness of the potential threat and its degree of urgency. Formal techniques exist for treating such a situation, based on a decision analytic approach,[45] provided probability distributions can be assigned to the uncertain variables. This subject matter goes beyond the scope of this paper, so, rather than enter into its application to market penetration time problems, we shall restrict our analysis to a less formalized discussion on the effect of uncertainty by presenting calculations for the cumulative probability of a carbon dioxide doubling event as a function of time, using probability estimates for future carbon dioxide emissions derived by Nordhaus and Yohe.[46]

Figure 11 is taken from Nordhaus and Yohe and presents the probabilities of attaining various atmospheric carbon dioxide concentrations at a number of probability levels. These were obtained from Monte Carlo runs of an optimum economic growth model, systematically varying the parameters of the model. Figure 12 transcribes these results into an evaluation of the probability of a carbon dioxide doubling condition by a given date. For a given market penetration time constant, t_p, each year in Figure 12 can be associated with a level of penetration of non-fossil energy, assuming the logistic form to apply, and using overall energy growth rates calculated by Nordhaus and Yohe (see Figure 14). Hence, we can calculate cumulative probabilities for avoiding a carbon dioxide doubling as a function of the entry date of non-fossil fuels. Figure 13 shows the results, choosing a range of market penetration time constants. We have also plotted in the figure cumulative probability curves assuming the presence of other greenhouse warming gases at a concentration that doubles the heating due to carbon dioxide alone. Note that in this case we are dealing with an effective doubling condition, i.e. one that results in a temperature rise equal to that produced by carbon dioxide in the absence of the other trace species. An increase in temperatures of 2.5 degrees Celsius is the best guess for this rise, but this figure also has a large degree of uncertainty, so that it would be incorrect for us to reinterpret Figure 13 as cumulative probabilities of avoiding a 2.5 degree Celsius rise. If this additional source of uncertainty were to be included, it would result in a wider spread of the probability curves, and hence an even earlier date for any less that fifty-fifty chance of being able to avoid a 2.5 degree Celsius temperature increase.

Figure 14 gives dates for the carbon dioxide doubling condition superimposed on Nordhaus's total energy growth estimates. It also includes a corresponding curve for an effective doubling of carbon dioxide. Both these doubling-date curves were used to produce Figure 13. From Figure 13, we can assess the risk we take through a delay in the introduction of non-fossil fuels in the absence of the other greenhouse gases. It reveals a chance of one in five that a carbon dioxide doubling will be exceeded for a fifty-year market penetration time and entry at a 1 percent market share in 1992. Entry can be delayed until 2010 if one is willing to take even bets on exceeding the doubling condition. If one can accept a high-risk situation with only a one in five chance of avoiding doubling, the 1 percent market share date can be postponed until after mid-twenty-first century. Inclusion of the other trace gases puts the first of these dates far back to 1955, and even the most probable estimate requires an entry date of 1973. The most optimistic, least risk-averse probability estimate, 20 percent, results in 1993 as the date at which 1 percent market penetration is required.

We need to repeat here that we are assuming the other greenhouse gases would be removed at the same logistic rate as is carbon dioxide. As emphasized earlier, without removal of trace gases, elimination of the use of fossil fuels can do little to delay the onset of significant climatic warming.

Figure 11
PROBABILITY LEVELS FOR THE OCCURRENCE OF A GIVEN ATMOSPHERIC CO_2 CONCENTRATION BY A CHOSEN DATE



Adapted from W. Nordhaus and G. Yohe, "Future Paths of Energy and Carbon Dioxide Emissions," in *Changing Climate: Report of the Carbon Dioxide Assessment Committee*, National Research Council (Washington, D.C.: National Academy Press, 1983).

Figure 12
CUMULATIVE PROBABILITY OF EXCEEDING ATMOSPHERIC CO_2 DOUBLING FOR THE MOST PROBABLE FUTURE ENERGY GROWTH SCENARIO

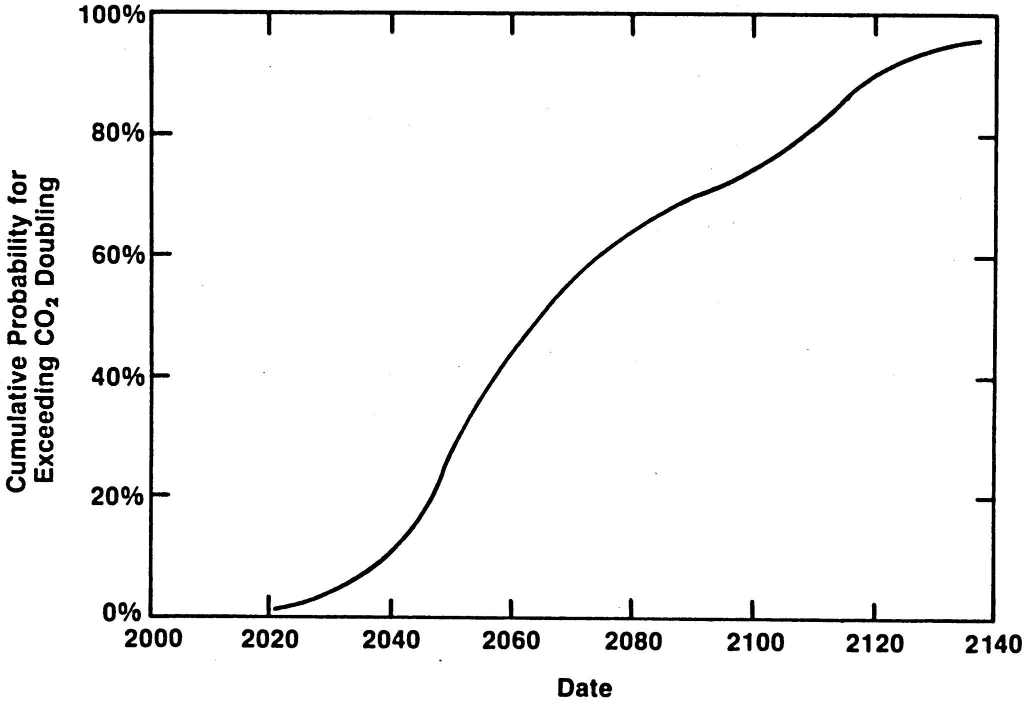


Figure 13
CUMULATIVE PROBABILITY FOR AVOIDING CO_2 DOUBLING AS A FUNCTION OF TIME OF INTRODUCTION OF FOSSIL FUEL REPLACEMENT ENERGY

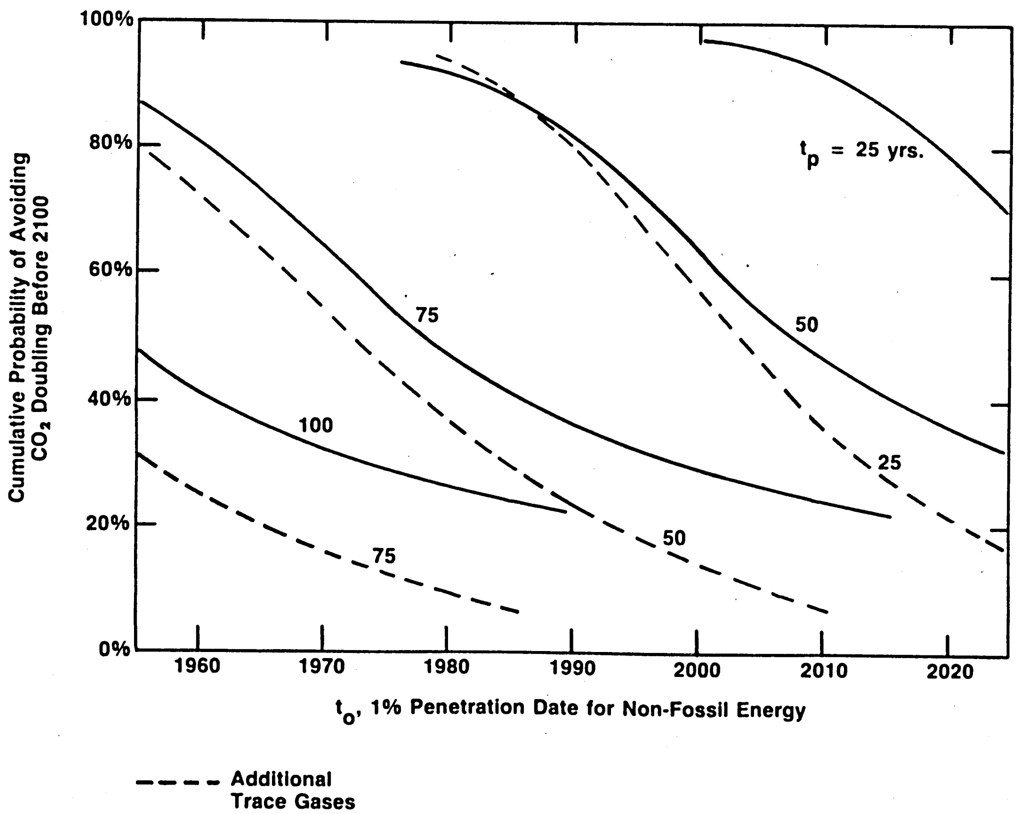
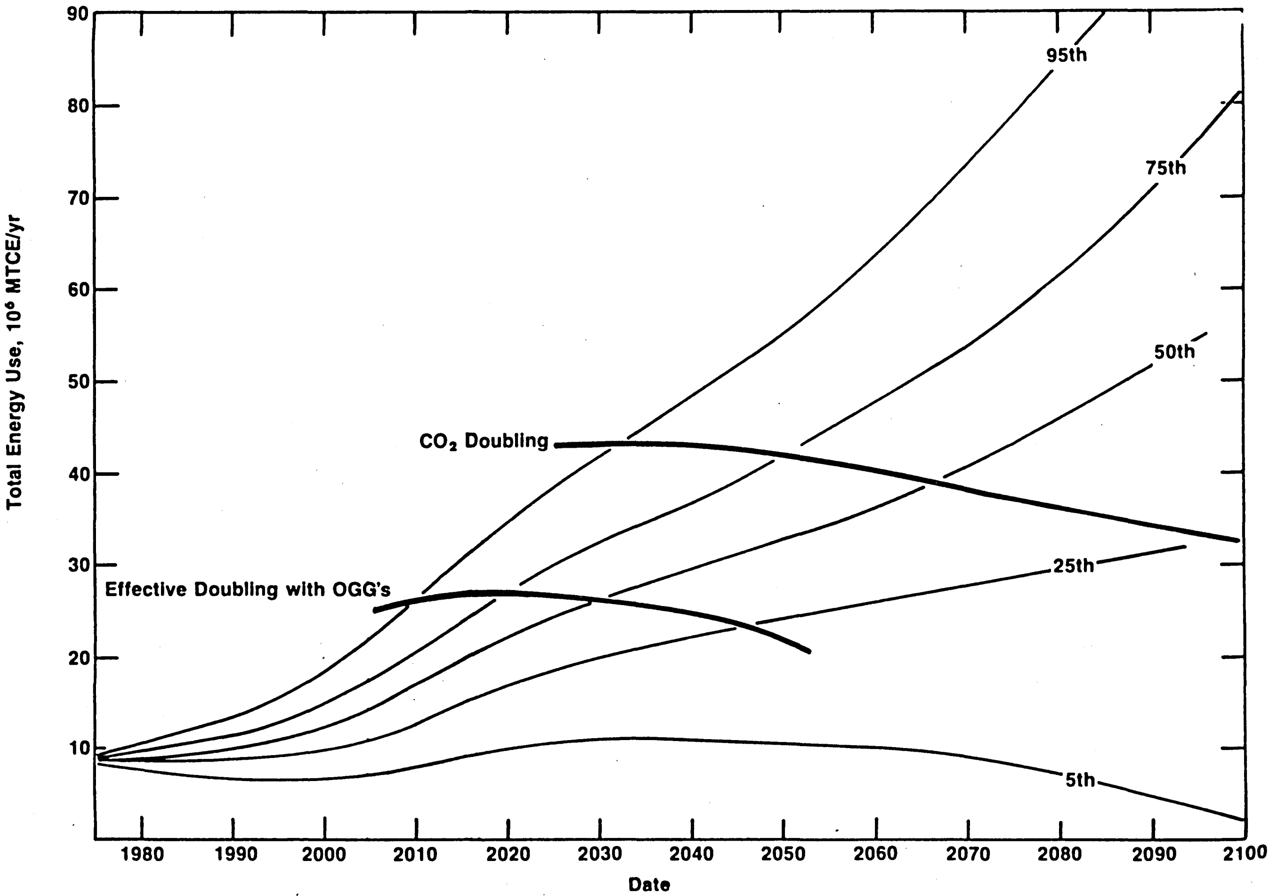


Figure 14
PROBABILITY LEVELS FOR WORLD ENERGY GROWTH



OGG = other greenhouse gases

Adapted from W. Nordhaus and G. Yohe, "Future Paths of Energy and Carbon Dioxide Emissions," in *Changing Climate: Report of the Carbon Dioxide Assessment Committee*, National Research Council (Washington, D.C.: National Academy Press, 1983).

CONCLUSIONS AND RECOMMENDATIONS

Estimated Effects of Market Penetration Time Constraints

The latest projections for global energy demand are much lower than a decade ago. Average total energy growth estimates to the mid-twenty-first century approximate 2 percent per annum. Accepting such a figure, the following conclusions on the role of primary energy market penetration time can be drawn:

- If the market penetration time constant for world energy, defined as the time taken for a new energy form to increase its market share from 1 percent to 50 percent, is fifty years or less, there is no proximate need to consider a move away from the predominant use of fossil energy as long as the effects of the other greenhouse gases are ignored.

- However, if current estimates of the energy growth rate and the climatic effects of the OGGs are accepted, immediate actions to introduce non-fossil fuels into the global energy sector are needed to avoid a significant climatic impact. The latter is defined as a mean global temperature rise of 2.5 degrees Celsius by mid-twenty-first century--our present best estimate of the climatic effect of a doubling of atmospheric carbon dioxide levels.

- If the market penetration time is seventy-five years or more, it is probably too late to avoid a 2.5 degree Celsius temperature rise, even in the absence of the OGGs, unless nuclear is the replacement energy for fossil fuels.

Irreducibility of Market Penetration Times

The only direct evidence for the irreducibility of market penetration time constants is based on an admittedly lengthy past history of the major shifts in the world's use of primary energy. No theoretical basis for the fifty-year minimum value can be abstracted from this history. Furthermore, extrapolation is suspect for a number of reasons, and prime among these are:

- The radically different nature of future as against past forces driving energy system change. Past shifts were economically or technologically preferred, whereas future changes are at least presently seen by most as a shift from more to less desirable energy forms, given limited resource availability.

- The marked past, and anticipated increased future, rate of technology development, and hence the possibility of new or more efficient means for making the transition to non-fossil energy sources.

- Preliminary evidence which indicates that the nuclear energy penetration time constant is considerably less than the historically observed minimum of fifty years. If this entry phase property is also characteristic of later phases of nuclear energy growth, the market penetration time impediment to the avoidance of an anthropogenetically induced climate change may not exist. It is unknown whether this provisional conclusion can be extended to other advanced renewable energy sources.

Belief in large inertial delays accompanying a wholesale shift away from the use of fossil fuel forms of energy appears to be ascribable to:

- The possibility that it could entail very large, overwhelmingly costly infrastructural and multi-sector revisions of socioeconomic systems. Primary evidence for the possibility of high cost is provided by the structure of total world developed assets, of which about 25 percent is accounted for by the world's investment in energy-related capital assets.[47]

- Cooperation of diverse international cultures and economies, which is required for the enforcement of a mandated move away from the most immediately attractive energy alternatives.

The Effect of Uncertainty

High uncertainty attaches to projections of future world energy needs, and this implies a probability of significant climatically induced costs at earlier dates than given by the mean values. This situation has to impact considerations. For example, allowing for the uncertainty advances by fifteen years the date at which it is necessary to introduce non-fossil fuel energy sources into the global economy (as compared with the mean, best guessed date) in order to avoid significant climatic impact at the 20 percent probability level. Such a figure applies for the fifty-year market penetration time constant. Hence, at this probability level, it is already too late to avoid the critical 2.5 degree Celsius temperature rise, even in the absence of other greenhouse gases, except perhaps if nuclear energy is seen as the replacement energy. The difficulty would be further increased were allowances to be made for additional uncertainties arising from climate modeling and errors in estimation of the costs of climatic changes.

Resolution of the Unknowns

Enough is understood about the possible factors controlling market penetration to accommodate an analysis of their roles in past energy transitions and check them against fact. Once this is done, it should be possible to establish whether these same factors are also relevant to the future. The latter study, although unlikely to lead to quantifiable predictions, should establish whether there is a chance for the successful conduct of a more detailed analysis involving a micro-level description of present and possible future energy systems.

Perhaps the single most important policy-related issue with regard to market penetration concerns the difference between free market behavior and enforced responses. It is necessary to be able to distinguish between impediments to the transition that are imposed only by free-market cost considerations and those that may be constrained by fundamental resource limitations. It would be expected that only the latter would be in effect were a compulsory shift away from fossil fuel use to be undertaken. A high priority research goal is, therefore, to determine, first, if this distinction is, in fact, real, and, second, if it is, what an ultimate resource limitation implies for a lower bound on the market penetration time constant.

Final Remarks

The meager evidence we have to date on the rapidity with which we can move into a non-fossil energy-based future suggests that market penetration rate limitations can indeed prevent amelioration of carbon dioxide and other greenhouse gas-induced climatic impacts. This conclusion is based on past evidence; we do not know if it applies to the future. Preliminary data on nuclear energy use growth rates implies that, at least for this form of advanced energy, market penetration could be much faster than in the world's past primary energy transitions.

NOTES

1. C. Marchetti, "Primary Energy Substitution Model: On the Interaction Between Energy and Society," *Chemical Economy and Engineering Review* 7, (1975): 9.

2. J. Fisher and R. Pry, *A Simple Substitution Model for Technology Change*, report 70-C-215 (Schenectady, N.Y.: General Electric Company, Research and Development Center, 1970).

3. E. Mansfield, "Technical Change and the Rate of Imitation," *Econometrica* 29 (1961): 741.

4. A. Blackman, "New Venture Planning: The Role of Technological Forecasting," *Technological Forecasting and Social Change* 5 (1973): 25.

5. C. Marchetti and N. Nakicenovic, *The Dynamics of Energy Systems and the Logistic Substitution Model*, AR-78-1B (Laxenburg, Austria: International Institute for Applied Systems Analysis, 1978).

6. C. Marchetti, "Multicompetition and the Diffusion of New Technology in the Energy System," *Chemical Economy and Engineering Review* 11 (1979): 7.

7. P. Auer, "A Model of Substitution in A Competitive Market," *Energy* 6 (1981): 561.

8. See note 5 above.

9. J. Edmonds and J. Reilly, "A Long-Term Global Energy-Economic Model of Carbon Dioxide Release from Fossil Fuel Use," *Energy Economics* 5 (1983): 74.

10. C. Marchetti, in *Energy in a Finite World: A Global Systems Analysis*, W. Haefele et al. (Cambridge, Mass.: Ballinger Publishing Co., 1981).

11. For the latest data on the changing proportion of energy use, see: R. Rotty, G. Marland, and N. Treat, "The Changing Pattern of CO_2 Emissions," ORAU/IEA-84-1(M) research memorandum, Institute for Energy Analysis, Oak Ridge, Tenn., 1984.

12. See J. Laurmann and J. Spreiter, "The Effects of Carbon Cycle Model Error in Calculating Future Atmospheric Carbon Dioxide Levels," *Climatic Change* 5 (1983): 145.

13. For instance, see the IIASA projections in W. Haefele et al., in note 10 above.

14. J. Laurmann, "Climate Change from Fossil Fuel Generated CO_2 and Energy Policy," *Environment International* 2 (1979): 461; see also Carbon Dioxide Assessment Committee, National Research Council, *Changing Climate* (Washington, D.C.: National Academy Press, 1983).

15. R. Rotty and G. Marland, "Constraints on Fossil Fuel Use," in *Interactions of Energy and Climate*, W. Bach, J. Pankrath, and J. Williams, eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1980).

16. V. Ramanathan, "Climatic Effects of Anthropogenic Trace Gases," in Bach, Pankrath and Williams, note 15 above.

17. See, for instance, J. Firor, "The Othergas Problem," this volume.

18. See Carbon Dioxide Assessment Committee, National Research Council, note 14 above.

19. Environmental Protection Agency, *Can We Delay A Greenhouse Warming?* (Washington, D.C.: U.S. Environmental Protection Agency, 1983).

20. J. Hansen et al., "Climate Sensitivity: Analysis of Feedback Mechanisms," in *Climate Processes and Climate Sensitivity*, J. Hansen and T. Takahashi, eds. (Washington D.C.: American Geophysical Union, 1984).

21. For an illustration of such an approach applied to the carbon dioxide impact cost problem, see J. Laurmann, "Assessing the Importance of CO_2-Induced Climatic Changes Using Risk-Benefit Analysis," in Bach, Pankrath, and Williams, note 16 above.

22. Council on Environmental Quality, *Global Energy Futures and the Carbon Dioxide Problem* (Washington, D.C., 1981).

23. A. Perry et al., "Energy Supply and Demand Implications of CO_2," *Energy* 7 (1982): 991.

24. J. Laurmann, "Optimizing Energy Transition Paths in CO_2 Emission Reduction Strategies," *Energy* 8 (1983): 845.

25. See notes 9 and 19 above; see also Carbon Dioxide Assessment Committee, National Research Council, note 14 above; W. Nordhaus, *Thinking About Carbon Dioxide: Theoretical and Empirical Aspects of Optimal Control Strategies*," Cowles Foundation Discussion Paper 5 (New Haven, Conn.: Yale University, 1980); R. Kosobud and T. Daly, "National CO_2 Abatement Policy Inconsistencies and Long Run Energy Technology Choices," presented for discussion at the Annual Meeting of the North American Economics and Finance Association, Dec. 18-30, 1983, San Francisco; and G. Hamm, *Analysis of Energy Sector Investment Strategies for Flexibility and Risks in Coping with Increasing CO_2 Levels in the Atmosphere*, final report EPRI TPS 81-820 (Stanford, Calif.: Engineering-Economic Systems Department, Stanford University, 1983).

26. For example, see note 2 above.

27. See Hamm, note 25 above; and H.-H. Rogner, *A Long-Term Macroeconomic Equilibrium Model for the European Community*," IIASA RR-82-13 (Laxenburg, Austria: International Institute for Applied Systems Analysis, 1982).

28. R. Ayres and A. Shapanda, "Explicit Technological Substitution Forecasts in Long-Range Input-Output Models," *Technological Forecasting and Social Change* 9 (1967): 113.

29. A. Hurter and A. Rubenstein, "Market Penetration by New Innovations: The Technological Literature," *Technological Forecasting and Social Change* 11 (1978): 197.

30. H. Linstone and D. Sahal, *Technological Substitution: Forecasting Techniques and Applications* (New York: Elsevier Publishing Co., 1976).

31. E. Warren, "Solar Energy Market Penetration Models: Science or Number Mysticism?" *Technological Forecasting and Social Change* 16 (1980): 105.

32. E. Katz, M. Levin, and H. Hamilton, "Traditions of Research on the Diffusion of Innovations," *American Sociological Review* 28 (1963): 237.

33. E. Rogers and F. Shoemaker, *Diffusion of Innovation: A Cross-Cultural Approach* (New York: Free Press of Glencoe, 1968).

34. J. Malcomson, "Replacement and the Rental Value of Capital Equipment Subject to Obsolescence," *Journal of Economic Theory* 10 (1975): 24; and L. Epstein, "Comparative Dynamics in the Adjustment Cost Model of the Firm," *Journal of Economic Theory* 27 (1982): 77.

35. V. Peterka, *Macrodynamics of Technological Change: Market Penetration by New Technologies*, RR-72-22 (Laxenburg, Austria: International Institute for Applied Systems Analysis, 1977).

36. A. Manne, *ETA-MACRO: A User's Guide*, EA-1724 (Palo Alto, Calif.: Electric Power Research Institute, 1981).

37. See note 10 above.

38. D. Rose, M. Miller, and C. Agnew, *Global Energy Futures and CO_2-Induced Climate Change*, MITEL 83-015 (Cambridge, Mass.: Massachusetts Institute of Technology Energy Laboratory, 1983).

39. For a survey of problems and possibilities along these lines, see: D. Wood, "Incorporating Technical Change in Energy/Economic Models," Studies in Energy and the American Economy, Energy Laboratory, Massachusetts Institute of Technology, Boston, 1982.

40. N. Kondratieff, "The Long Waves in Economic Life," *Review of Economic Statistics* 17 (1935): 105.

41. G. Mensch, *Stalemate in Technology* (Cambridge, Mass.: Ballinger Publishing Co., 1979); and H. Haustein and E. Neuwirth, "Long Waves in World Industrial Production, Energy Consumption, Innovations, Inventions, and Patents and Their Identification by Spectral Analysis," *Technological Forecasting and Social Change* 22 (1982): 55.

42. C. Marchetti, "Society as a Learning System: Discovery, Invention, and Innovation Cycles Revisited," *Technological Forecasting and Social Change* 18 (1980): 267.

43. N. Mass, *Economic Cycles: An Analysis of Underlying Causes* (Cambridge: Massachusetts Institute of Technology Press, 1975).

44. A. Graham and P. Senge, "A Long Wave Hypothesis for Innovation," *Technological Forecasting and Social Change* 17 (1980): 283; and J. Sterman, "A Behavioral Model of the Economic Long Wave," *Journal of Economic Behavior and Organization* 6 (1985): 17.

45. For the decision analytic approach, see Laurmann note 21 above.

46. W. Nordhaus and G. Yohe, "Future Paths of Energy and Carbon Dioxide Emissions," in Carbon Dioxide Assessment Committee, National Research Council in note 14.

47. See note 10 above.

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THE PROBLEM OF THE OTHER GASES

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INTRODUCTION

This volume is not primarily designed to discuss technical problems. However, policy discussions depend on numbers. The projected global warming resulting from increased atmospheric levels of carbon dioxide ranges from hardly anything to worry about (if we assume low energy growth and adopt those climate models with the smallest sensitivities to increased atmospheric carbon dioxide) to a large warming and serious global problems (if we assume rapid coal use and the largest model climate sensitivities). Much of the difficulty in reacting to the greenhouse problem stems from the fact that this range of possible impacts on the global climate includes very small and quite large changes.

However, there are gases other than carbon dioxide that may contribute to the warming. If these gases increase the projected carbon dioxide warming by only a few percent, they can continue to be neglected in policy discussions about greenhouse warming. But if they significantly increase the projected warming, then the likelihood of only a small effect occurring in the next century is decreased and the policy debate must necessarily shift.

This paper, then, is a brief survey of our knowledge of the other atmospheric greenhouse gases. There have been a number of previous careful discussions of this issue, and long lists of possible gases have been prepared. Possible gases are those gases with suitable infrared properties for which some reasonable speculation can be adduced regarding increased future atmospheric concentrations. The Oak Ridge National Laboratory's *Carbon Dioxide Review: 1982*, the World Meteorological Organization's *Report of the Meeting of Experts on Potential Climatic Effects of Ozone and Other Minor Trace Gases*, and the National Academy of Science's *Changing Climate* have been reviewed in assembling this paper. In addition, colleagues were consulted about more recent work. This paper will not repeat all the important points made in those publications; however, some effort will be made to indicate why the other gases need to be taken more seriously than they have been in the past.

THE OTHER GREENHOUSE GASES

A large number of non-carbon dioxide, infrared-active gases are of interest from the perspective of the climate. Three factors are important with regard to these gases:

- <u>Absorption bands</u>. If the absorption bands of the other gases fall at wavelengths that are already well occupied by carbon dioxide or water vapor, these gases will have little effect on the overall greenhouse warming. However, if the bands are in "clear windows," they can induce changes, although often minor, in the planetary energy balance.

- Strength of the absorption bands. Stronger bands can have larger effects. Since the other gases occur in much smaller concentrations and their absorptions are generally proportional to concentration, the other gases are frequently easier than carbon dioxide to include in calculations.

- Rate of increase in atmospheric concentration. Fairly long series of measurements exist for some of these gases; for some, however, serious measurements have only recently begun. Some of the other gases are emitted as a result of industrial activity. Hence, estimating future rates of increase in the concentrations of these gases can be as difficult as estimating future world coal use or future trends in certain industrial processes--for instance, the rate of replacement of old products with new products having different emission characteristics.

Another family of gases also needs to be considered. These substances are not themselves active in the infrared but react in the atmosphere to form greenhouse gases. Ozone results from such reactions, and when it is in the lower atmosphere it is a potent greenhouse gas. Even more convoluted chains of events may be important. Increases in carbon monoxide in the air, for example, consume some of the hydroxyl radical (OH) present, thereby lessening the action of hydroxyl in destroying methane, which is a greenhouse gas. Atmospheric methane concentrations tend to increase as a result.

The range of substances that must be included in the studies is broad. It includes, at one extreme, the chlorofluorocarbons (CFCs), which come only from well-known industrial sources, have long lifetimes in the atmosphere, and have atmospheric concentrations that are reasonably well monitored. At the other extreme is ozone, which is produced in the atmosphere by a complex set of reactions and has a relatively short lifetime in the air. Hence, a much denser monitoring net than now exists would be required to reliably ascertain the extent to which the average global ozone concentration in the lower atmosphere is changing. Stratospheric water vapor is an especially complex case. Water vapor, a strong greenhouse gas which increases in the atmosphere as the atmosphere warms, is, in the lower atmosphere, taken into account as a positive feedback in the carbon dioxide/climate calculations. However, the rate of flow of water to the stratosphere depends critically on the temperature of the tropopause in the tropics. If concentrations of the chlorofluorocarbons increase, they would not only warm the surface but also the tropical tropopause and so increase the amount of water in the stratosphere. This would further warm the surface.

RATE OF PRESENT AND FUTURE ATMOSPHERIC INCREASE

Table 1 lists five important trace atmospheric gases which have absorption bands in the carbon dioxide window and a direct greenhouse effect when they are present in the atmosphere. Estimates of the rapidity of increase in the concentration of each gas in the atmosphere, based on measurements made in the last few years, are shown in the second column. Projections of those rates of increase in atmospheric concentrations that might be expected in the next fifty years, as gathered from many sources, are shown in the third column. The sources of two of these gases, CFC-11 and CFC-12, the chlorofluorcarbons, are well identified; estimating future releases of these two gases is simply a matter of guessing future industrial needs, future regulations, the state of the economy, and so on. For others, which have complex and partially unknown sources, the exercise is more difficult. Present measured rates of increase can be used as indicators of the possible importance of each gas. However, all the sources of each gas will need to be delineated and detailed estimates of future source strengths made before fully satisfactory projections of future concentrations can be made.

For example, atmospheric methane is derived in part from the breakdown of organic material under anaerobic conditions, as happens in rice paddies. One might expect the area and intensity of the use of rice paddies to increase under the population pressures of the coming years and hence expect this particular source of methane also to increase. In addition, at some point in the projected global warming of the next century, releases of continental slope sediment methane clathrates could occur, accelerating atmospheric methane increases. We use such discussions to reassure ourselves that the observed rates of increase of various gases are a reasonable approximation of future rates of increase. However, these discussions need to be made much more detailed and quantitative.

Policy issues arise upon a reasonable probability that any of these gases might have a climatic impact. To estimate this probability, we need to know, in addition to the numbers in Table 1, the amount of global warming that each gas might result in so that the climatic impact of the other gases can be compared with that of increased atmospheric levels of carbon dioxide. For this purpose, we need longer-term projections of rates of increase, as well as calculations of the greenhouse effectiveness for each gas. The World Meteorological Organization group estimated the total changes in atmospheric concentrations of these gases for a one hundred-year future; for this discussion, a fifty-year time horizon might be more convenient. The future surface temperature change due to increased atmospheric concentrations of the other gases is estimated in Table 2. Since there are wide uncertainty limits on some or all of the rate estimates for the minor gases, a high and a low value is shown. Changes in surface temperature are estimated with a climate model with a sensitivity to doubled atmospheric concentrations of carbon dioxide of 1.5 to 3.0 degrees Celsius. The warming that could be produced by 2035 by this set of gases is appreciable.

Table 1
RATES OF INCREASE OF TRACE ATMOSPHERIC GASES
(In Percent per Year)

Gas	Present Rate	Long-Term Projection
Nitrous oxide	0.25	0.25 to 0.9
Methane	0.75	0.25 to 1.5
CFC-11	5.9	1 to 5
CFC-12	4.8	1 to 5
Ozone	variable	0 to 1

Table 2
SURFACE TEMPERATURE CHANGE, 1985-2035
(In Degrees Celsius)

Gas	Low Estimate	High Estimate
Ozone (tropospheric)	0.00	0.58
Nitrous oxide	0.04	0.20
Methane	0.04	0.33
CFC-11	0.03	0.24
CFC-12	0.07	0.45
Water vapor (stratospheric)	0.18	0.36
Total	0.36	2.16

The projected warming due to other gases can be compared to the expected carbon dioxide-induced warming by 2035. The National Academy of Sciences' Carbon Dioxide Assessment Committee expects atmospheric carbon dioxide concentrations to double in the third quarter of the next century, producing a global warming of 1.5 to 3.0 degrees Celsius thereafter. In the year 2035, they expect atmospheric carbon dioxide concentrations to be perhaps 420 to 460 parts per million (ppmv), producing a warming that is similar to the totals shown in Table 2.

A long list of additional gases also should be considered, including other chlorofluorocarbons, chlorocarbons, and fluorocarbons. For example, atmospheric concentrations of methylene chloride are growing by about 5 percent per year, while concentrations of methyl chloroform have been increasing 15 percent per year. Were these included, the projected warming due to other gases by 2035 would be greater than estimated above.

SUMMARY

Many reports have mentioned the problem of the other gases and make strong statements, such as, "The available studies strongly suggest that the combined climatic effects of potential future alterations in minor trace gases (including ozone) can be as large as those estimated due to a carbon dioxide increase" (World Meteorological Organization, 1982). But so far, it has not been common to combine the projected carbon dioxide effect and the effect of the other gases and discuss the resulting projected rate of climate change. This reluctance probably arises from the lack of an extensive literature on projected emissions of the other gases, such as would parallel the carbon dioxide literature. But since the early indications, as briefly reviewed here, suggest that the greenhouse effect of the other gases may equal or exceed the carbon dioxide effect in the next fifty years, it would behoove the scientific community to address these details as vigorously as possible in the coming months and years. And it would seem wise for those arranging policy discussions to include prominently among the scenarios a more rapid warming than that due to carbon dioxide alone.

SELECTED BIBLIOGRAPHY

Angell, J. and Korshover, J. "Global Variation in Total Ozone and Layer-Mean Ozone: An Update Through 1981." *Journal of Climate and Applied Meteorology* 22 1983: 1,611.

Baker-Blocker, A., Donahue, T., and Mancy, K. "Methane Flux from Wetlands Areas." *Tellus* 29 1977: 245.

Blake, D., Mayer, E., Tyler, S., Makide, Y., Montague, D., and Rowland, F. "Global Increase in Atmopheric Methane Concentrations Between 1978 and 1980." *Geophysical Research Letters* 9 1982: 477.

Chamberlain, J., Foley, H., MacDonald, G., and Ruderman, M. "Climate Effects of Minor Atmospheric Constituents." In *Carbon Dioxide Review: 1982*, Clark, W. ed. Oxford: Oxford University Press, 1982.

Chameides, W., S. Liu, and R. Cicerone, "Possible Variations in Atmospheric Methane." *Journal of Geophysical Research* 82 1977: 1,795.

Chameides, W. and Walker, J. "A Time-Dependent Photochemical Model for Ozone Near the Ground." *Journal of Geophysical Research* 81 1976: 413.

Craig, H. and Chou, P. "Methane: The Record in Polar Ice Cores." *Geophysical Research Letters* 9 1982: 1,221.

Donner, L. and Ramanathan, V. "Methane and Nitrous Oxide: Their Effects on the Terrestrial Climate." *Journal of the Atmospheric Sciences* 37 1980: 119.

Ehhalt, D. "The CH_4 Concentration Over the Ocean and Its Possible Variation With Latitude." *Tellus* 30 1978: 169.

Ehhalt, D. "The Effects of Chlorofluoromethanes on Climate." In *Interactions of Energy and Climate*, Bach, W., Pankrath, J., and Williams, J. eds. Dordrecht, Netherlands: D. Reidel Publishing Co., 1980.

Fishman, J., Ramanathan, V., Crutzen, P., and Liu, S. "Tropospheric Ozone and Climate." *Nature* 282 1979: 818.

Flohn, H. "Estimates of a Combined Greenhouse Effect as Background for a Climate Scenario During Global Warming." In *Carbon Dioxide, Climate and Society*, Williams, J. ed. New York: Pergamon Press, 1978.

Hameed, S. and Cess, R. "Impact of a Global Warming on Biospheric Sources of Methane and its Climatic Consequences." *Tellus* 35B 1983: 1.

Hameed, S., Cess, R., and Hogan, J. "Response of Global Climate to Changes in Atmospheric Chemical Composition Due to Fossil Fuel Burning." *Journal of Geophysical Research* 85 1980: 7537.

Khalil, M. and Rasmussen, R. "Increase and Seasonal Cycles of Nitrous Oxide in the Earth's Atmosphere." *Tellus* 35B 1983: 161.

Khalil, M. and Rasmussen, R. "Sources, Sinks, and Seasonal Cycles of Atmospheric Methane." *Journal of Geophysical Research* 88 1983: 5,131.

Khalil, M. and Rasmussen, R. "Carbon Monoxide in the Earth's Atmosphere: Increasing Trend." *Science* 224 1984: 54.

Lacis, A., Hansen, J., Lee, P., Mitchell, T., and Lebedeff, S. "Greenhouse Effect of Trace Gases, 1970-1980." *Geophysical Research Letters* 8 1981: 1,035.

Liu, S., Cicerone, R., and Donahue, T. "Sources and Sinks of Atmospheric N_2O and the Possible Ozone Reductions Due to Industrial Fixed Nitrogen Fertilizers." *Tellus* 29 1977: 251.

Logan, J., Prather, M., Wofsy, S., and McElroy, M. "Tropospheric Chemistry: A Global Perspective." *Journal of Geophysical Research* 86 1981: 7,210.

Logan, J., Prather, M., Wofsy, S., and McElroy, M. "Atmospheric Chemistry: Response to Human Influence." *Transactions of the Royal Society of London* 290 1978: 187.

Machta, L. "Effects of the Non-CO_2 Greenhouse Gases." In *Changing Climate*, National Academy of Sciences, Carbon Dioxide Assessment Committee. Washington, D.C.: National Academy Press, 1983.

McElroy, M., Wofsy, S., and Yung, Y. "The Nitrogen Cycle: Perturbations Due to Man and Their Impact on Atmospheric N_2O and O_3." *Philosophical Transactions of the Royal Society of London* 277 1977: 159.

Ramanathan, V. "Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications." *Science* 190 1975: 50.

Ramanathan, V. "Climatic Effects of Anthropogenic Trace Gases." In *Interactions of Energy and Climate*, Bach, W., Pankrath, J., and Williams, J., Dordrecht, Netherlands: D. Reidel Publishing Co., 1980.

Ramanathan, V., Cicerone, R., Singh, H., and Kiehl, J. "Trace Gas Trends and Their Potential Role in Climate Change." *Journal Geophysical Research* 90 1985: 5,547.

Reck, R. and Fry, D. "The Direct Effects of Chlorofluoromethanes on the Atmospheric Surface Temperature." *Atmospheric Environment* 12 1978: 2,501.

Revelle, R. "Methane Hydrates in Continental Slope Sediments and Increasing Atmospheric Carbon Dioxide." In *Changing Climate*, National Academy of Sciences, Carbon Dioxide Assessment Committee. Washington, D.C.: National Academy Press, 1983.

Seiler, W. "The Cycle of Atmospheric CO." *Tellus* 31 1974: 116.

Sze, N. "Anthropogenic CO Emissions: Implications for the Atmospheric CO-OH-CH_4 Cycle." *Science* 195 1977: 673.

Volz, A. "Climatic Impact of Trace Gases, Aerosols, Land-Use Changes, and Waste-Heat Release." In *Carbon Dioxide: Current Views and Developments in Energy/Climate Research*, Bach, W., Crane, A., Berger, A., and Longhetto, A., eds. Dordrecht, Netherlands: D. Reidel Publishing Co., 1983.

Wang, W. and Sze, N. "Coupled Effects of Atmospheric N_2O and O_3 on the Earth's Climate." *Nature* 286 1980: 589.

Wang, W., Yung, Y., Lacis, A., Moe, T., and Hansen, J. "Greenhouse Effects Due to Man-Made Perturbations of Trace Gases." *Science* 194 1976: 685.

Weiss, R. "The Temporal and Spatial Distribution of Tropospheric Nitrous Oxide." *Journal of Geophysical Research* 86 1981: 7,185.

Wofsy, S. "Interactions of CH_4 and CO in the Earth's Atmosphere." *Annual Review of Earth and Planetary Sciences* 4 1976: 441.

WMO Global Ozone Research and Monitoring Project. *Report of the Meeting of Experts on Potential Climatic Effects of Ozone and Other Minor Trace Gases*. Geneva, Switzerland: World Meteorological Organization, 1982.

SECTION 3: THE ADAPTIVE STRATEGY

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INTRODUCTION TO SECTION 3

Several responses in addition to the preventive response, are open to society. Society could opt not to act at all or to postpone any decision until some undefined time in the future, using the time to narrow the scientific uncertainties. Society could also opt for the adaptive response, and rather than limit the scope of the impending changes in the climate, seek to adapt the natural environment and the society to the effects of a changing climate. At present, the latter response is the one toward which most analysts, and many in the scientific establishment, are tending.

Generally, the adaptive response focuses upon the ability to adapt society and human activities to a changing climate. The adaptive response assumes that impacts depend as much on the structure of society and its ability or inability to adapt (or maladapt) to climate change as they do on climate change. Further, it assumes that not all climate changes have to result in unacceptable impacts, but rather that some climate changes may be beneficial and others may be sufficiently small that their effects may be lessened through compensating changes in the physical environment. The trick is to exploit the beneficial changes and minimize the effects of the adverse ones, and, in cases where the climate changes may be unacceptable to present generations, to allow room for the play of evolution and natural change in expectations. Society's expectations seem to evolve with conditions; that which is unacceptable now may, under the pressure of an adverse future, be considered part of the natural course of things.

Large-scale technological intervention into society and the physical environment constitutes the principle means by which adverse impacts, around which the case for adaptation is usually argued, can be minimized. Human activities can be altered through changed management practices and technologies. Presumably, such changes can ameliorate the impact of adverse climate changes. In cases where local resources preclude technological intervention, large-scale, regionwide interventions into the physical environment through large public works could, it is believed, significantly augment the larger regional carrying capacity. Were this not to suffice, large-scale migration of agricultural and industrial production areas as a result of drought, rising sea level, or acute water scarcity might result. To avoid disruption, these forced changes would be anticipated and patterns of economic development rationalized according to the best fit of industrial activities and settlement patterns to changed climate regimes.

The notion of the long-term acceptability of climate change is governed by the perception that society, and humanity generally, always adjusts to adverse conditions, no matter how disruptive they are. Society adjusted to the worst of the plagues and cold of the late medievel period, and it will adjust to other climate change. Climate change will be understood by future generations as a part of the natural world, and since there will be no alternative to acceptance, society will simply shoulder the effects of a hostile environment in the same way that it has always done, reconciling itself to climate constraints and moving on from there.

Overall, then, adaptive responses center on the fit of society to local environmental conditions and on the desire to optimize that fit. Society exists in equilibrium with environmental conditions. Climate change will affect local environmental conditions, and, if sufficiently large, would upset this equilibrium. The adaptive response is directed toward the impacts leading to such disequilibrium. Society can be instrumentally adjusted to climate through directed present-day application of technology and management of change in society, or it will adjust through natural evolutionary processes. It is assumed that these adjustments can successfully buffer the worst effects of a changing climate or can at least work to create acceptance on the part of the affected populations.

Of the various specific forms of adaptation that have been either explicitly advanced or obliquely or partially described, the most passive--compensation and the long-term downward adjustment of expectations--have thus far evinced little appeal. Under the first approach, climate change is treated as essentially a distributional problem. Some generations and nations benefit from climate change and the activities leading to climate change, and some suffer; climate is allowed to change and work its effects, and the only intervention that is foreseen is to ensure an equitable distribution of both among nations, and possibly generations. But as many analysts have noted, this stands in direct contradiction to historic policies with regard to the distribution of wealth both internationally and domestically. The lack of concern for future generations appears to constitute a constraint to the second of these passive strategies, which have yet to be explicitly championed, although they are implicit in the most pro-adaptation, anti-prevention analyses.

Of the remaining adaptive responses, market adaptation and anticipatory or planned adaptation receive the most attention. These differ principally in the time of action relative to impacts. Society can choose to act only upon the actual experience of impacts, allowing market forces to adjust society to impacts as they occur. This is market adaptation. Or society can choose planned or anticipatory adaptation. This is essentially a proactive response, in which society anticipates impacts and seeks to ameliorate future effects through the present-day application of technology and the present-day planned or directed management of change in society.

Market adaptation is by far the least problematic of these two types of adaptation. The notion of efficiency, and, more specifically, of efficiency in the internal allocation of resources, is central to market adaptation. Under market adaptation, impacts are experienced in the context of the market. The climate changes. Production costs and the demand for goods and services change, rising and falling with the particular form that the climate change takes regionally. Localities respond according to their own resources and position in the national economy. Some adaptations make no economic sense, but others are successful. Some are futile. The market acts to allocate resources among them based on the considerations of cost and demand, relating adaptive expenditures to the market demand for goods, and, in the process of rewarding sensible adaptations and discouraging uneconomic adaptations, presumably maximizes social welfare.

Aggregate societal adaptation is, under market adaptation, the sum of countless local adaptations. Amelioration is realized to the degree to which the reliance upon markets realizes more economically efficient outcomes than does reliance on administered systems. So long as reliance on market systems can significantly lift the background rate of growth, net impacts on society can be limited.

Anticipatory adaptation is more problematical. Adaptation is understood to involve fairly radical adjustments in the physical environment, many with particularly long time-scales for implementation. It is effected through long-range interventions in the biosphere and in water resources systems, society seeking to offset particular projected changes in the availability of moisture or any adverse changes in other climate parameters through targeted compensating changes in the terrestrial environment or, in cases where such intervention will not suffice, through long-range planning and state administration of industrial change in society. The time-scales of action are long, and action is isolated in time from the experience of climate change and its impacts. This is essentially targeted adaptation.

As such, anticipatory adaptation is dependent on reliable projections about the climate. Because large present-day investments in future amelioration often demand a high degree of certainty about the measures' effectiveness, it is often necessary to have fairly precise information regarding local climate changes, their scale and sign, and their particular placement in time. Large present-day investments will not be effected in the presence of substantial uncertainty. Precise information with regard to climate change at the local level is at least two to four decades away, and probably further, and in the case of information about impacts and chains of impacts, such information is even further removed in time.

An example of the need for precise information is evident in the case of the payback periods of investments in future amelioration. The prospects for anticipatory adaptation depend on calculations of economic feasibility, which, among other factors, are dependent on the length of the period of the usefulness of the anticipatory adaptations. Most capital intensive adaptations entail large expenses and require long periods of repayment, typically thirty years or more, during which expenses are recouped through the long-term benefits of action. But the length of the period of usefulness of any one project depends on the pattern of climate change. Above all, the latter must not manifest itself as a series of closely spaced discontinuous changes or as movement toward a climate state significantly different from that to which society is adapting. Being closely fitted to narrow ranges of conditions, anticipatory adaptations would find themselves quickly obsolete under such conditions. If closely enough spaced, climate changes can so shorten the period in which adaptations might be of benefit to society as to make large investments unworkable.

If the pattern of climate change were to result in such a situation, it would severely restrict the prospects for planned adaptation. We do not know that changes at the regional or local level will be of this nature, but at the same time, we do not know that they will not. Not knowing whether, as the planet progressively warms, climate changes at the regional level will be consistent in sign, neither the financial community nor the public decision-maker is at leisure to effect large investments in future amelioration. Faced with an uncertain future, the machinery of public decision will almost always opt for investments with certain, short-term returns. Due to the uncertainties about the returns to society, costly adaptation is presently treated as, at best, impractical, something out of step with the realities of public finance.

Based on informational considerations, the prospects for anticipatory adaptation seem rather thin. This is in direct contrast to market adaptation, which is compromised by no such internal inconsistencies. This is the principal advantage of the market, and it sets the market response above the planned response.

Beyond this difference, it is not clear how much can be said about the effectiveness or feasibility of the adaptive response. In part, this larger feasibility depends on the pace of climate change. Anticipatory adaptation assumes a fairly slow rate of change, if only because it demands some certainty that the conditions that society is restructuring itself to fit--and here the time frame is probably twenty to fifty years--will somewhat approximate the present conditions.

However, market responses are also limited to gradual changes in climate. The present, rather than the future, is dominant in the calculation of the market. The market takes its cues from existing conditions and short-term trends. Operating at the margin, it moves in new directions only haltingly, through the sum of many hesitant, often uncertain, incremental steps stretched out over long periods of time. It rarely anticipates change. The market responds after the fact of change, often only after the passage of time reveals the change to be a permanent feature of the landscape. Its long-term decisions are the sum of decisions taken to meet present-day changes, and since investment decisions carry with them a twenty- to thirty-year commitment to a certain type of economic base, it assumes a fairly slow rate of overall societal change. In a word, the response of the market is slow. It takes its leave from known conditions and generates long-term commitments to a future that is assumed to be largely like the present.

Therefore, to best fit market adaptation, global climate change would need to be stretched over a fairly long period of time. No precise estimate of the optimum rate of change has been offered, but to ensure that the future somewhat approximates the conditions of the present, the rate of planetary warming probably could be no more than one or one and one-half degrees Celsius per half-century. The alternative involves a calculus that is unworkable: a change in the mix of industrial activities at a faster rate than the rate of capital turnover in the economy.

Adaptation is usually marketed as a more feasible response than prevention. It is also frequently noted that, to the degree that some climate change is now inevitable, the adoption of an adaptive response is also inevitable. According to the analysis of Williams et al., a planetary warming of at least 0.4 to 1 degrees Celsius is now inevitable due only to carbon dioxide accumulation from fossil fuel consumption. Society will need to adapt to such a warming, regardless of the decisions it takes with respect to changes that might still be prevented. With regard to the former, the adaptive response, it is often noted, avoids the pitfalls encountered by the preventive response in the need for some type of unified international action. The adaptive response is a national response, a matter of fitting national resources to specific regional conditions. In this, it is nicely fitted to a world of zealously sovereign states.

But if it is true that adaptation is largely confined to fairly limited changes in climate, and then to market responses, then the very purpose of the adaptive response--to act as an alternative to the preventive response; to remove the constraints to mean global warmings that exceed 4 degrees Celsius--cannot be realized. Then adaptation is little more than the resolve to live through the changes, to "tough it out," regardless of the consequences. This is the dilemma of the adaptive response.

In this section, Riebsame considers broadly the nature of the adaptive response. His comments are largely confined to anticipatory adaptation, or a best-fit response. Due to the challenge climate change presents to society, purposeful, directed anticipatory action is presented as the most effective response and presumably the response of choice. It is not thought that easy laissez-faire adjustment should form the basis for societal action, if only due to failure that occasionally haunts society's efforts to adjust to slow change. The latter is often disregarded by society in its response to environmental change, and this can lead to an accumulation of impacts, some significant and negative, and to difficulty. A casual response to climate change would make this more likely. The bulk of the explicit argumentation centers on the fit of the adaptive response to the typical operation of society and to the political realities of action.

Generally speaking, the operation of society is constrained by short planning-time horizons. It responds in a post-crisis mode, acting after the fact of change. A long litany of enduring environmental problems that have thus far eluded anticipatory solutions is testimony to this fact. This is often due to political realities. Vested political interests that benefit from existing institutional arrangements and government programs often represent an insurmountable hurdle to large-scale change in governmental land-use and water-use policy. Resources often tend to flow toward regions of power rather than need. Sometimes incrementalism in the formulation of policy frustrates the purposes of long-range planning. Whatever the reason, the political realities of action weigh heavily against anticipatory action. The realities require not only definite evidence of negative impact but often the actual experience of the impacts itself; they demand a type of information we do not possess, and that, Riebsame notes, probably makes adaptation as problematic as the preventive response.

The author catalogues a long list of constraints. The time horizon of most elected officials is short, verging upon momentary. Policymakers may heavily discount the future and the importance of any impact that is distant in time. Human beings are grounded in the present, and, lacking the ability to escape the present, develop policy based on the assumption that the future will be much like the present. Many adaptations can involve significant cost, creating a conflict between present and future benefits.

Most important, Riebsame makes clear in his case studies that programs set up under the guise of long-term environmental protection are routinely captured by private interests and purposes, and their monies are diverted toward private present gain. To the degree that this is true, the oft-heard appeal for long-range planning and the talk about the long-term benefits of action are no more than a disguise for self-seeking in the present.

Taken together with the multifold uncertainties that surround anticipatory adaptation, the political constraints act to limit the prospects for adaptation. With regard to the former, it is sufficient to note the ubiquity of our ignorance in the case of even the basic workings of most impacts and the sensitivity of society to those impacts. We cannot describe the factors that explain society's past and present sensitivity to climate. We have no well-accepted concepts that are useful in the description of societal vulnerability. Little understanding is available as to the ways most impacts work their effects on society, nor is there much understanding about the ways change affects the ability of society to cope with internal and external stress. Little is known, the author suggests, and clearly much less is known than would be needed to support an adaptive response.

Crist and Reinartz consider the adaptive response operationally as they conduct a thought experiment on the nature and costs of adaptation to a drying in the Upper Midwest. Working from information available from Stockton and Boggess and others, the authors present a scenario for a change in available water resources assuming a mean global warming of several degrees Celsius. About a 50 percent drop in the available water supply is suggested. In the Red-Souris-Rainy river basin, the chosen study area, the effects of such a change in flow are largely concentrated in the summer, when demand is high and flow is lower, and are encountered in the context of a generalized increase in frequency of summer drought and low flow conditions.

These climatic changes, the authors suggest, would have a noticeable effect on the local economy. In response to these, the authors present the rudiments of an adaptive strategy, based on traditional federal responses to changes in the availability of a resource. The emphasis is on the interbasin and intrabasin transfer of water, which, the authors note, are more costly than demand-oriented responses but are also more effective. Other supply-oriented response mechanisms that the author recommend include: an expanded reservoir capacity; changes in the operating parameters of existing reservoirs; and the enhancement of supply facilities. Thirty years constitutes the historic lead time for such projects. The costs of such a program are estimated to fall in the $3 billion to $7 billion range. These estimates are uncertain, the authors conclude, but probably represent the broad magnitude of the costs associated with adaptation.

As Crist and Reinartz note, this is a speculative exercise. Local conditions could develop in any number of directions other than those the authors consider. Better information is needed. In order to account for this need, the authors suggest a delay in any action until at least the year 2000.

Titus presents the case for adaptation, arguing that a significant global warming is inevitable regardless of preventive actions that may be taken, and that, given this situation, adaptation is the one inevitable element of policy. Society will need to adapt to the inevitable, and the most appropriate form for this might be anticipatory adaptation, which, if it does nothing else, will bring home to everyone the full, and perhaps unacceptable, implications of climate change. Without the latter, prevention will not be considered viable.

The author offers these observations while addressing the impacts of sea level rise and the necessity of beginning to plan for such a rise. At Charleston, the study site, the sea level should rise about 2 feet by 2030 and 5 feet by 2075. This would inundate about 30 percent of the Charleston area by the latter date and induce economic losses equivalent to about 25 percent of the areas's projected economic activity. Anticipatory adaptation would take the form of changes in land-use planning and of hard structures like bulkheads, sea walls, breakwaters, and levees, which could hold back rising ocean levels. The projected losses in economic activity would be approximately halved by such intervention. The author points out that this kind of response is the one toward which local officials are most inclined, and, since the impact will be experienced at the local level, this will be the long-term response to a changing climate.

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SOCIAL ADAPTATION TO CLIMATE CHANGE: RESEARCH AND POLICY ISSUES

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INTRODUCTION

Schneider, in his 1980 editorial in *Climatic Change*, inquired as to whether the policy implications of the carbon dioxide/climate problem were evident yet.[1] Schneider's editorial focused on options in energy development that might lessen carbon dioxide production. However, his inquiry can be restated in terms of adaptation to the greenhouse effect and the degree to which policies designed to facilitate such adaptation are evident. I believe that such implications are evident. The potential for carbon dioxide-induced climate change, although uncertain, suggests that we should at least review the range of possible responses and assess their strengths and weaknesses. This is not to call for immediate drastic action; indeed, it would be premature to take draconian measures now to prepare for a future climate change. But the time is right to explore the broad structure of social responses, both preemptive and reactive, that might lessen the potential for adverse impacts from climate change.

This paper explores the likely societal impacts of carbon dioxide-induced climate changes and the nature of possible adaptation to such changes. It also examines the research and public policy questions that surround these two concerns. The paper is a broad discussion document, designed to help define a wide spectrum of substantive issues surrounding adaptation to carbon dioxide-induced climate change. In many instances, it also applies to climate fluctuation from any cause, natural or anthropogenic.

The outside limits on potential climate change are becoming better defined. However, our understanding is still quite limited with regard to the potential regional and local climate changes and the ways in which different societies and their different livelihood systems might react to a changing climate. But we should strive to enlarge the body of useful knowledge about the possible impacts and adjustments to carbon dioxide-induced climate change, even in the face of these uncertainties. We should not wait until the final verdict is in or until the carbon dioxide signal is evident, since most research points to a marked climate change in the next fifty years or so, even if the details are unclear. In addition, insights gleaned while exploring carbon dioxide/climate impacts should increase our understanding of the ways society copes with climate in general, with or without the greenhouse effect. Hence, we should continue to pursue lines of research that broadly investigate society's adaptive capability.

THE ADAPTATION PROBLEM

Many analyses of the carbon dioxide/climate problem conclude that policies to prevent the production of carbon dioxide or its climate effects will not be successfully implemented.[2] Schelling concludes that we must simply anticipate climatic change.[3] Scientific uncertainty, economic and social costs, political infeasibility, and outright denial of the problem by key decision-makers are some reasons given for the pessimism about preventive strategies. Others include the tendency of political systems to await crises before effecting real policy change.[4] Schneider suggests that policies designed to mitigate the impacts of climate change probably will be formulated in a post-crisis mode, leading one to envision a future in which society staggers from one climate-induced crisis to the next.[5] One also might note other slowly evolving, enduring environmental problems that have eluded anticipatory solutions. Examples of problems that have avoided solution despite increasing evidence that they will have serious future impacts include: soil erosion, acid precipitation, coastal erosion, and wildlife habitat loss. Glantz argues that such low-level, cumulative environmental problems are mismatched to the crisis management approach that characterizes policy formulation.[6]

The conventional wisdom that we will not avert a carbon dioxide-induced warming of some magnitude is rapidly becoming an article of faith in scientific and informed political circles. It also forms the basic premise of this paper. Hence, an adaptive strategy, which in its broadest sense incorporates a range of adaptive mechanisms, from systems redesign to simple acceptance of change in resource production, may be necessary to help society cope with carbon dioxide-induced climatic changes. But many of the hurdles that frustrate preventive policy also block adaptive policy. For instance, in order to be effective, some adaptive responses must be formulated well before recognized impacts occur and before the uncertainty over the effect of carbon dioxide is significantly lessened. And the costs, as well as the political infeasibility, of adaptive policies may rival those of preventive policies. Finally, adaptive policy will be formulated in the midst of continuing uncertainty about the nature of the interactions between climate and society and the complex workings of the socioeconomic systems that transform natural and human resources into life-sustaining and life-enhancing goods. Hence, adaptive policy will be imperfect and will need continual review.

The overarching policy problem, then, can be restated to include the necessity of sorting out those interactions between climate and society that will pose problems in the event of carbon dioxide-induced climate change and of prescribing responses that will lessen the negative impacts. The conjoint research problem is broader: to understand the full range of the relationships between climate and society, thus providing a guide to the most pressing problems and the most efficient solutions.

Overall, the discussion of adaptive policy is conditioned by a broader debate over the sign--the direction of the change, positive or negative--and the magnitude of potential impacts, a debate which illustrates some of the issues involved in the formulation of adaptive policy and which defines the nature and scope of the adaptive measures we should consider.

Impacts: What Sign and Magnitude?

A case for a minimal societal impact from anthropogenic climate changes is argued by those who feel that adaptation can be painless, even unconscious. Proponents of this view have turned to past agricultural adjustments to argue the point. For example, Wittwer has written:

> Fortunately, the past century provides evidence that U.S. agriculture and its research establishment can cope with and even improve during climatic change. Over the past 100 years, for example, the High Plains became the wheat belt during a moist period, then the Dust Bowl during a dry period. Agriculture, through migration and technology, was able to adapt... From 1915 to 1945, Indiana farmers experienced a +0.2 degree Celsius per year trend in temperatures and a total change in temperatures of +2 degrees Celsius during the past century. American agriculture already has demonstrated that it can adapt to a trend of +0.1 degrees Celsius per year, assuming no change in interannual fluctuations.[7]

In addition, he notes that "agriculture, through migration and technology, was able to adapt" to fluctuations like the 1930s Dust Bowl droughts. Waggoner suggests that the Okie migrations of the 1930s are examples of farmers "saving themselves while abandoning the cropland to other uses."[8] Waggoner further suggests that farmers will easily adapt to a changed climate, making current alarms appear overly pessimistic in retrospect.

These are, in some ways, powerful arguments, and the empirical approach taken should be applauded. However, the examples given are less compelling. The abandonment of Great Plains farms during the 1930s can be seen as a major human tragedy; in some areas up to 50 percent of the population emigrated during the 1930s.[9] This was a well-documented tragedy, born of the failure of a laissez-faire economy to deal with the production variability inherent to semi-arid zones and the failure to anticipate the instability of monoculture tenant farming.[10] Indeed, the long-term adaptation of which Wittwer and Waggoner speak never actually occurred. Great Plains wheat acreage did decline with the 1930s drought, but it increased dramatically during the 1940s and rose to all-time highs after 1972, when increased grain prices encouraged fence-to-fence planting. Thus, we have not effected a true agricultural adaptation in the Great Plains despite the soil bank, Payment in Kind, and other conservation measures designed to keep marginal land out of intensive crop production.[11]

It is also difficult to be as sanguine as those who argue for an easy adaptation to slow climate change if one hypothesizes that individual and collective decision-makers respond to extreme climatic events rather than mean climatic conditions. There exists great climatological uncertainty surrounding the relationships between the mean and the variance around the mean in all climatic parameters. Mean values are partly an artifact of the extrapolative methods used and partly reflective of the way climatologists tend to express their science. But some analysts argue that extreme conditions, or change in the frequency of occurrence of critical conditions--for instance spring soil moisture, maximum summer temperatures, or minimum stream flows--are more important in impacting and eliciting adjustments in agricultural, energy, and water systems.[12] It is possible that adjustment occurs in a more disjoint, step-like fashion rather than through slow, cumulative adaptation that lags slightly behind the average climate trend. This implies an ensemble of thresholds that modulate response, as illustrated in Table 1. Crises erupt as each threshold is exceeded by some extreme event.

Table 1
CLIMATE IMPACTS AND RESPONSE THRESHOLDS

Climate Impacts	Actions	Threshold
Minor	None	
		Perception threshold
	Recognize, do nothing	
		Minimal action threshold
	Adjust incrementally	
		Penultimate threshold
Severe	Change operations or location	

Modified from I. Burton, R. Kates, and G. White, *The Environment as Hazard* (New York: Oxford University Press, 1978).

On the other hand, the most concise argument that can be offered to suggest that carbon dioxide-induced climate change could be socially disruptive involves the magnitudes of the projected climate changes. Some projections indicate that the carbon dioxide-perturbed climate likely to evolve over the next fifty years resembles nothing experienced in the last thousand years or more.[13] This climate exceptionalism must surely, at least, pose a challenge to socioeconomic systems that have evolved under a different set of climatic circumstances.

The issues on which this debate centers involve the resiliency of socioeconomic systems in the face of climate change and the ability of the social support system and its managers to accommodate projected climate changes. The debate itself suggests that there is at least some possibility of a few significant negative impacts following upon climatic change. Yet, if carbon dioxide-induced climate change does indeed manifest itself as a series of crises, and if it will not be easily or unconsciously accommodated, how then do we characterize those climate impacts that might transcend the action thresholds in Table 1 and elicit a response?

THE NATURE OF POTENTIAL IMPACTS

The literature on climate impacts is growing slowly. Considerable knowledge is available on biological and societal impacts and on the response to extreme weather and climate events.[14] Some knowledge is also is available on historical climate impacts and social response.[15] Unfortunately, research on the impacts of recent climate fluctuations consists mostly of idiosyncratic case studies and is only slowly producing the knowledge needed to anticipate and perhaps mitigate the impacts of future climate fluctuations.[16] Attempts to use existing studies as a guide to the potential impacts of future climate change stumble due to the lack of rigorous approaches in previous research, especially the lack of comparable, empirical findings that have been validated across different cases and socioeconomic settings.

Efforts are underway to resolve these problems. Kates et al.[17] have edited a volume of methodologies for climate impact assessment in an attempt to systematize and broaden climate-society research. Researchers at the International Institute for Applied Systems Analysis are currently conducting impacts research based on climate-society analyses in marginal areas, where human activities, especially agriculture, are near the frontier of sustainable productivity and thus may be sensitive indicators of impacts.[18] A consortium of research centers* has recently initiated a climate impacts, perception and adjustment experiment (CLIMPAX) to study the impacts and responses associated with regional climate fluctuations identified in the recent U.S. record.[19] Such efforts signal a break with the idiosyncratic methods characterizing existing climate-society research.

Types of Impacts

The research literature on climate impacts most relevant to carbon dioxide concerns is comprised of: discussions meant to sensitize scientists and policy-makers to the climate's vulnerability,[20] idiographic (but not necessarily weak) studies of specific impacts cases,[21] and a few analyses of climate-society interaction aimed at theoretical development or the accumulation of useful lessons and ideas.[22] The work has elicited little reflective critique, although a few researchers have critically reviewed some of the methods and approaches used in the field.[23]

Impacts are the implicit and explicit focus of such research, although the term has not been well defined. Impacts have been categorized rather simply into biophysical versus socioeconomic, or first, second, ..., nth order. A simple classification of the potential negative impacts of climate change is proposed in Table 2. The most obvious negative impacts of a climate change are reductions in the flow of raw materials or decreases in the stability of resource output. The change also may increase the demand for certain resources, as happens when colder temperatures increase energy use or warmer conditions increase the need for water. This assumes, of course, that the impacted resource systems have, over time, achieved some

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*Clark University, the University of Colorado, the Illinois State Water Survey, and the National Climate Data Center.

sort of operational equilibrium with the climate; this may not be an unreasonable expectation, given the huge effort made to match resource management to the environment (e.g., in the design of water-supply systems). Finally, a climate change might lead to a long-term decrease in the productivity or carrying capacity of a resource, especially if it is not accompanied by appropriate land-use change. A decreased or more variable flow of resources, in turn, translates into socioeconomic impacts on the price of goods, returns on investments, and operating costs. Climate change might also directly affect humans through impacts on health and comfort.

Table 2
NEGATIVE IMPACTS OF CLIMATE CHANGE

Biophysical

- Decreased flow of resources (e.g., crop yields)
- More variable flow of resources (e.g., stream flow)
- Increased demand for resources (e.g., electricity)
- Loss of long-term productivity (e.g., soil erosion)

Socioeconomic

- Increased cost of resources
- Added operating costs
- Decreased return on investment
- Required new capital
- Discomfort, health effects

Measuring Impacts

Although it is relatively easy to imagine the form negative impacts might take, actually measuring or estimating the magnitude of the impacts that might accompany a climate change, say in monetary terms, is quite difficult. But great pressure exists to turn nascent ideas and initial observations on climate impacts into quantitative statements about losses and their potential mitigation by various responses, especially since the calculation of costs and benefits has become a key ingredient of modern resources management and policy-making.[24]

Measuring Direct Impacts: A simple accounting of the losses and benefits associated with climate conditions would seem to be a reasonably straightforward process. In the United States, the Assessment and Information Services Center (AISC) of the National Oceanic and Atmospheric Administration issues regular reports on the dollar value of weather and climate-induced losses or benefits. The values are distilled from reports in the news media, official estimates, and models that link atmospheric conditions to activities like agricultural production, energy use, and retail business sales. But empirical loss estimation has many weaknesses. There is no science of loss estimation, and the AISC reports and other studies that include some account of direct climate impacts rely on a grab bag of methods, including direct observation; interviews with victims and public officials; and the canvassing of secondary sources (e.g., news media reports), insurance claims, and government reports.[25] Such impact assessments are of uneven reliability and may be misleading in terms of net losses or aggregate losses across regions.

Reasoning From Extremes: Other researchers have tended to focus on loss estimation in extreme cases, arguing that impact estimates of relatively frequent, low-magnitude events are uncertain because the climate impact "signal" is often lost amidst the typical "noise" of socioeconomic activity. Some researchers turn to extreme events which, presumably, result in unambiguous impacts that are easily disentangled from the other causes of socioeconomic variability. The Assessment of Research on Natural Hazards project conducted in the early 1970s, for example, produced annual U.S. loss estimates for several climate hazards.[26] Among these were the impact of frost on agriculture, which were estimated to cause $1.1 billion in annual losses, and the cost of urban snowfall, which was about $100 million annually. These estimates included only direct effects, not the secondary effects generated as impacts rippled through socioeconomic systems. Burton, Kates and White offered a similar list of rough estimates for selected climate hazards in developed and developing countries (see Table 3).[27] More recently, Maunder and Ausubel compiled several estimates of direct annual losses due to weather and climate in various sectors of the U.S. economy.[28] But such estimates are probably unreliable. The AISC estimates that even the relatively benign year of 1982 resulted in $16.5 billion in agricultural losses, and only a 3 percent departure from normal heating and cooling requirements in 1983 resulted in an estimated $1.9 billion in additional energy use.[29]

Unfortunately, a database sufficient to provide reliable estimates of the aggregate impacts of extreme climate events does not yet exist. And we do not know if one can generalize from the impacts of a series of extreme events or climate anomalies to a permanent climate change. For example, we do not know if a contemporary, finite series of dry years on the U.S. Great Plains would have the same impacts or elicit the same responses as would a permanent change to drier conditions.

Table 3
SELECTED ESTIMATES OF NATURAL HAZARD LOSSES

					Losses and Costs per Capita at Risk (in $)			
Hazard	Country	Total Population*	Population at Risk*	Annual Death Rate per Million at Risk	Damages Losses	Costs of Loss Reduction	Total Cost	Total Costs as % of GNP
Drought	Tanzania	13	12	40	0.70	0.80	1.50	1.84
	Australia	13	1	0	24.00	19.00	43.00	0.10
Floods	Sri Lanka	13	3	5	13.40	1.60	15.00	2.13
	United States	207	25	2	40.00	8.00	48.00	0.11
Tropical cyclones	Bangladesh	72	10	3,000	40.00	0.40	3.40	0.73
	United States	207	30	2	13.30	1.20	14.50	0.04

*In millions.

Source: I. Burton, R. Kates, and G. White, *The Environment as Hazard* (New York: Oxford University Press, 1978).

Economic Analyses

Microeconomic analyses of climate impacts generally treat climate as a natural resource: a factor in the production of goods and services.[30] Unfortunately, climate, as currently conceptualized, does not readily lend itself to classical economic analyses, especially those that yield cost estimates of climate changes.[31] Economic models based on market pricing mechanisms and industrial input and output were not designed to incorporate open access or common property resources like climate. Nor are such models amenable to the long-term extrapolation necessary to estimate the impacts of future climate changes.

Yet one should be able to measure, value, and even manage climate in optimal ways that increase the net public or private benefit, if, indeed, climate is a tangible good. Along these lines, d'Arge, attempting to assess the costs and benefits associated with anthropogenic climate change, used three approaches: 1) assessment of the costs incurred in order to maintain current production levels under a changed climate; 2) appraisal of the production opportunities foreclosed or enhanced by climate change; and 3) assessment of the willingness among users of a given climate to pay in order to maintain or to change the climate.[32] Similar approaches have been applied to other natural resources, like forests and minerals. In addition, one might calculate climate-induced wage and price differentials at different locations, the value that climatic conditions add to or subtract from land, the impact of climate on crop prices and water supply costs, and even the health maintenance costs associated with different climates.[33] Often, however, economic researchers themselves note the extreme uncertainties in their calculations, which, as they also note, are often based on projections and methods ill-suited to climate impact assessment.

THE NATURE OF CLIMATE SENSITIVITY

Persistent problems encountered in economic analyses suggest that we should retreat to a more basic problem, that of identifying and comparing the climate sensitivities of various economic sectors. However, there exist no good, systematic surveys of the vulnerability of socioeconomic systems to climate impacts, although we possess anecdotal accounts of the relative or changing climate sensitivity of various human activities.[34] This is true in part because we lack widely accepted concepts for describing social vulnerability or resiliency. In addition, we have not systematically monitored parameters of vulnerability as systems change. Finally, the theoretical base for understanding systemic vulnerability has been pauperized by inappropiate use of ecological concepts, especially where those concepts do not allow for innovative human behavior. There is no easy way to hurdle these barriers. However, some researchers have attempted to make sense of societal vulnerability to impacts.[35] A few general principles can be distilled from this literature.

The tendency of activities or sectors to incur losses from climate fluctuation derives from the relative importance of climate as a input to economic and ecological systems. Many activities with a strong seasonal cycle are, de facto, sensitive to climate but not necessarily sensitive to nonregular climate fluctuations. This holds for agriculture, construction, water transportation, recreation, etc. The seasonality rule does not hold as strongly for many business cycles, such as those observed in retail sales, which are affected by nonclimate seasonalities like holidays.[36]

It is a well-accepted axiom of ecology that ecological parameters (e.g., throughputs, outputs, storages, populations, energy cascades) are relatively stable where system diversity is large. This diversity rule appears to hold in most natural resource systems as well: systems of diverse composition are less vulnerable to disruption by environmental fluctuation. Cultivation of multiple crop varieties, reliance on several different sources of energy, and other strategies which diversify holdings or activities all impart a certain resilience to climatic fluctuation, although perhaps at the cost of reduced average yields or increased capital investments.

Systems with a wide margin between average operating conditions and failure parameters also tend to be more resilient in the face of climate fluctuations. Flood buffers, excess generating capacity, large food reserves, and water storage capability are mechanisms through which such a margin is maintained. But here again, the costs can be great, and the relative benefits of over-designing systems to perform even under rare conditions are difficult to assess and may lie largely in the unquantifiable realm of public confidence and safety.

Finally, a system's vulnerability to disruption also derives from its management by humans, and management or political constraints might drastically affect its reliability in the face of climatic fluctuation.[37]

What are the Sensitive Sectors and Regions?

Logic, experience, and conventional wisdom, at first glance, ease the process of differentiating a region's climate-sensitive activities from its more climate-immune sectors. Rain-fed agriculture; hydroelectric generation; the provision of domestic, industrial, and irrigation water; the demand for space heating and cooling; and certain manufacturing and recreational activities are climate-sensitive sectors that have received the greatest attention from climate impact assessors and society's risk managers. Less obvious are climate sensitivities in inland fish and game management, pollution control, forest fire control, natural rangeland grazing, waste disposal, urban design, public services, and human health. These areas have received much less research attention than agriculture, water resources, and energy use, which might be called the big three climate-sensitive sectors.

Regional differences in climate vulnerabilities make analysis of sensitivity to climate fluctuation more difficult. Maunder has developed a complete set of regional climate sensitivity indicators for New Zealand, several of which have been used in policy formulation and implementation.[38] Unfortunately, although rough outlines for assessing national climate sensitivities have been proposed, the development of climate sensitivity indicators is difficult, and the data-intensive, analytical task has not been seriously attempted for the United States.[39] An empirical description of U.S. climate sensitivities requires a reliable, consistent impacts data base, which does not exist. Maunder and Ausubel compiled a rough list of the sensitivity to weather and climate anomalies of various components of the U.S. gross national product (GNP) (see Table 4).[40] However, they consider anomalies lasting up to a season or two; different sensitivities might emerge with multiyear climate fluctuations.

Table 4
ANNUAL LOSSES DUE TO ADVERSE WEATHER AND CLIMATE
(In Millions of Dollars)

Economic Sector	Losses	Pecent of Gross Revenue
Agriculture	8,240.4	15.5
Construction	998.0	1.0
Manufacturing	507.7	0.2
Nonair transportation	96.3	0.3
Commercial aviation	92.4	1.1
Communications	77.4	0.3
Electric power use	45.7	0.2
Fossil fuel use	5.1	0.1
Other[a]	2,531.8	2.0
Total	12,594.8	

(a) Governmental, retail, etc.

Source: W. Maunder and J. Ausubel, "Identifying Climate Sensitivity," in *Climate Assessment: Studies of the Interaction of Climate and Society*, R. Kates, J. Ausubel and M. Berberian, eds. (New York: John Wiley and Sons, 1985).

What are the Trends in Sensitivity?

Argumentation exists on both sides of this issue. Bowden and his colleagues postulate that in the long run societies tend to adapt to recurrent climate fluctuations in a way that lessens biophysical and socioeconomic impacts.[41] This adaptation is achieved through altered social organization, infrastructural improvements in agriculture transportation, communication, and through development of more resilient technologies, like supplemental irrigation. Bowden et al. support this lessening hypothesis with case studies of recurrent droughts in the African Sahel and on the U.S. Great Plains, but their analysis does not address the question of changing vulnerability in the face of a permanently changed climate. However, a wide set of other trends that could increase biophysical sensitivities to climate impacts act against the mechanisms of lessening. For example, soil erosion over time can reduce the drought resistance of crops produced on impoverished soil, and decreased genetic diversity can increase the sensitivity of ecosystems to climatic perturbation.[42]

Alternatively, other scientists argue that societal vulnerability to climate fluctuation is growing.[43] Lamb argues that climate variability itself is increasing, concurrent with an increase in society's vulnerability to climate disruption. This view has been opposed by those who cite, for example, crop yield and food stock statistics showing no imminent crash, just a chronic food distribution problem. Unfortunately, we do not fully understand the past or present changes in societal climate sensitivity. We lack the baseline information that would provide clues to changes in the climate sensitivity of the various economic sectors.

THE ADAPTIVE STRATEGY

Adaptation, as broadly defined earlier, is the only policy alternative to prevention, but not all policies aimed at solving climate impact problems will be purely adaptive. Crisis decision-making or incrementally adjusted policy may be socially maladaptive, given a major climate change. Adaptive policies, even if effective, will probably result in losses to some segments of society. Generally, we should strive to avoid economic injury to any party while seeking efficient solutions to our problems; no stakeholder should be handed a windfall loss because of adaptive policy decisions.[44] We might, then, in theory, apply a social welfare test to proposed adaptive policies, especially since any policy will surely favor some specific strategies above others and will probably entail unequally distributed costs.

Randall offers two concepts that are useful in the evaluation of the welfare efficiency of policy: (1) constant proportional shares, which demands that any improvement in one interest's utility be accompanied by proportional improvements in all other interests' utility, and (2) Pareto-safety, which demands that improvement for one interest be accompanied by no finite loss to other interests, but which does allow relative economic loss.[45] Pareto-safety seems to be a reasonable minimum base against which to compare carbon dioxide-adaptive policy alternatives. But we will find Pareto-safety a harsh task master, given the persistent tendency of macroeconomic policy to reduce utility for at least one interest.

The distributive effects of policy may be a major problem in carbon dioxide-climate adaptation. Large-scale environmental problems seem, ipso facto, regionally divisive in the United States. For example, regional tensions surround the issue of federal land ownership and management, as is evident in the so-called Sagebrush Rebellion,[46] and federal resource policy often entails very different consequences for different parts of the country, resulting in economic and social deficit areas.[47] Thus, appropriate policy must be sensitive to regional differences in vulnerability and capability.

Climate, like other open-access resources, will not bound by political frontiers, and only regionally based planning will adequately address the problems associated with climate impacts. It might be useful to draw from air-pollution policy concepts like airsheds or attainment areas, or to define logical climate impact mitigation units like those used in water development. Climate-sheds or strategic climate planning units might be defined on the basis of both physical characteristics and potentially affected human activities. State and regional policy affecting especially agriculture, water, and energy might be coordinated as background climate information aggregates and as specific carbon dioxide/climate projections improve. Possible carbon dioxide/climate problems demand that we avoid the parochialism that has hindered integrative resource management, as has happened in, for instance, western water issues.

Maladaptive Policy

It is possible that we will worsen environmental or social conditions through decisions taken in the heat of climate-induced crises. If a crisis mentality prevails, we might engage in decision-making processes whose impacts are worse than those of a do-nothing policy. For example, it is possible that decreased crop yields may lead to efforts to intensify agriculture in situ through more intensive inputs of capital, energy, and materials. However, it is also possible that this may only worsen some ultimate system breakdown in terms of farm failure and land degradation, given continued environmental worsening.

The Clark University Climate and Society Research Group explored this possibility in their catastrophe hypothesis.[48] They argued that as societies adapt to recurrent climate fluctuations, they may become more vulnerable to very rare extremes. Warrick and Bowden argued this point with regard to Great Plains drought and dryland small grains production, the continued drought vulnerability of which is exported to a large, often poor, segment of global society through increased mean yields, constant relative yield variability, and aggressively developed foreign markets.[49] Droughts, then, do inevitably lessen yields, and the increased prices they cause are often too high for Third World markets. The people who have come to depend on cheap surplus grain then face food shortage. In terms of global food stability, a policy of foreign export of variable supplies may be a maladaptive adjustment to surplus production, especially in an era of carbon dioxide-induced climate change, which may shift the frequency of climate extremes, thus heightening the probability of catastrophe.

The Nature of Adaptive Policy

Four general types of adaptive strategies might be imagined. These are shown in Table 5. They include a null policy, which might now be seen as the safest response given the scientific uncertainty surrounding the carbon dioxide/climate question. Research on social response to natural hazards suggests that the denial of a hazard, or no action if it is recognized, are among the most frequent adjustments to an environmental threat.[50] Such a wait-and-see policy appears to prevail at present with regard to the carbon dioxide issue. Also included is a best-fit strategy, which will ostensibly be our national adaptive strategy. The best-fit approach seeks to adjust support systems to changed conditions and relies heavily on technical knowledge developed by the scientific community. Inadequate knowledge, political realities, and unanticipated complications, however, tend to act against full implementation of best-fit strategies.

Least-regret strategies seek to minimize the potential for climate-induced catastrophe. These strategies are based on simple prudence, are relatively easily implemented, and may be less costly than the best-fit alternative. Least-regret policies designed to avoid total system collapse should accompany all best-fit proposals. Finally, strategies that seek to maintain maximum flexibility in support systems have a large appeal now due to the scientific uncertainties surrounding the carbon dioxide/climate problem. However, because they rely on large operational buffers and over-engineering, they can be very expensive. Schneider's *Genesis Strategy* is an example of such a conservative approach: keep options open by maintaining large reserves that buffer society from environmental shocks.[51] This reduces the chance of being forced into decision-making in extremis, when maladaptive choices are more likely to be made.

Table 5
GENERAL TYPES OF ADAPTIVE POLICY

Do nothing; deny the problem (**null policy**)

Attempt to find a **best fit** to the new climate

Aim at a policy of "**least-regret**"

Aim at a policy of **maximum flexibility**

These strategies can be variously characterized. For instance, they can be described in terms of the degree to which they involve significant social intervention. Some strategies tend more toward maintenance of the status quo than others, seeking to adjust support systems to the new climate while leaving them otherwise unchanged. Others tend to be more interventionary, utilizing the opportunity either to fine-tune support systems into a better fit with environmental and economic realities or to rethink and perhaps reshape socioeconomic policy. The former, considered in light of agricultural adaptation to climatic change, might involve a northward shift of corn production but little alteration in agricultural support programs and policies. The latter might attach new programs to such a northward shift, for instance efforts to fix the most glaring market imperfections surrounding corn production or to centralize agricultural planning and thereby provide greater leverage in effecting adjustment.

In addition, adaptive policies could be characterized according to the degree to which they seek to anticipate climate changes and alter the structure or operation of support systems in advance.

Potential Adaptive Responses: The Substance of Policy

A taxonomy of responses is presented in Table 6 in the form of various generic adaptations that might be made in any resource system--for instance, agricultural, energy supply, or transportation systems. The first four types of response, spatial, temporal, operational, and infrastructural, involve physical changes that would show up in the landscape or be evident in types or scheduling of human activities. The last category, institutional/organizational, involves less obvious responses like those relating to the flow and use of political power, decision-making ladders, and group and individual interrelationships. The generic physical adaptations are listed in order of increasing economic and social costs, with temporal adjustments probably the least disruptive and operational and locational changes probably involving the greatest costs. Relationships exist between these adaptations and the types of impacts shown in Table 2. The more obvious involve an increased variability of resource flows and increased flexibility in support systems, or an increase in extreme climatic events and a "hardening" of the systems. Such hardening might entail efforts to avoid system failures triggered by various climate thresholds--for example, the use of frost protection devices for crops at the northern limit of their cultivation, or supplemental irrigation projects. Biased extension or contraction of the allowable operating parameters seems to be a probable response to a unidirectional carbon dioxide-induced climate change and is probably cheaper than the symmetrical enlargement of operating ranges. Unfortunately, this might prove an inadequate response if a climate trend is accompanied by greater variability.

Table 6
A TAXONOMY OF ADAPTIVE RESPONSES

Temporal changes	Seasonal shifts in activities Shifts in temporal spacing
Infrastructural changes	Hardening (e.g., coastal levees) Softening (subtract expensive capability/strength) Capacity (symmetric and asymmetric)
Operational changes	Flexibility Asymmetric extension or contraction of limits Mix of operations Switch to new activities
Spatial changes	Location Concentration Linkages, nodes
Institutional/ organizational	Decision-making structure Group relationships

Constraints to Policy Formulation

Warrick and Riebsame identified two critical factors in social response to climate fluctuation: the information cascade and cognitive aspects of policy formulation, and the various constraints and incentives to actual policy implementation.[52] Special attention has been given to the policy effects of decision-makers' cognitive limitations.[53] Important constraints include: uncertainty; poor imageability of impacts; policy incrementalism; short planning horizons; poor grasp of statistics; and simple denial.

The various political constraints to adaptive policy formulation and implementation have received less attention, but a sense of pessimism reigns. Mann notes that:

> There exists a profound skepticism of existing political and economic institutions and their capability of resolving major public problems, whether concerned with the environment or other issues. Government, it is argued, tends to regulate where it should not, and spends more than it should, thus constituting a dual burden on all of society. Politicians and bureaucrats are viewed as lacking the appropriate incentives for problem solving; indeed, their incentive structure is viewed as leading them in the direction of perpetuation and aggravation of social problems.
>
> ...The constitutional and electoral systems with relatively brief terms of office and the necessity for incumbents to satisfy pressing and current public demands lend themselves to emphasis on meeting present demands with little concern for the future environment.[54]

Others have offered evidence for a broad lack of resolve among policy-makers faced with cumulative, long-term problems whose negative effects will accrue mostly in the future.[55] Unfortunately, we have no formalized methods of assessing the validity of such assertions, only rough guidelines for conducting general analyses of proposed policies.[56]

A lack of imagination may constitute the largest constraint to efforts to conceptualize new climate defensive and adaptive policies. Policy analysts,[57] psychologists,[58] and natural and technological hazards researchers[59] find the human ability to imagine new events and responses to be quite limited, or, as they describe it, boundedly rational. We tend to anchor our assessments of future possibilities on our perceptions of past events. Unfortunately, few past environmental changes are similar to the predicted carbon dioxide-induced climate change. Thus we may have trouble formulating even slightly novel adaptive strategies as climate change unfolds. However, various heuristic aids might help to expand the recognized range of possible adjustments. Several such aids seem appropriate: case studies of related problems; analogues; and scenarios.

Policy Case Studies, Analogies and Scenarios

The following case studies were chosen to illustrate some of the problems likely to be associated with a policy aimed at ameliorating the impact of carbon dioxide on the climate.

National Water Management: Issues surrounding water supply, irrigation, flood control, and inland navigation may have been the most enduring constellation of natural resource problems dealt with in the public policy arena. National water policy development has generally been aimed at a narrow best fit between supply and potential demand, with scant recognition of market forces, ecological effects, systemic flexibility, or alternative management options such as non-structural adjustments.[60] For instance, flood control policy has traditionally been constrained to a narrow set of policy alternatives, with communities enticed to choose from a narrow range of engineering works, including dams, levees, and channelization, in lieu of non-structural responses to flood hazards, like flood-plain regulation or warning systems.[61] This, however, has failed to reduce flood losses.

Similarly, the history of the federal flood insurance program also illustrates an enduring crisis orientation. The program was initiated as a response to the 1965 floods associated with Hurricane Betsy but was not given adequate support from Congress until after the 1972 floods of Hurricane Agnes. Hence, it took two major disasters to get the program underway, even though flood losses, especially those related to flood-plain encroachment, as encouraged by flood "control" projects, had been growing steadily since at least 1900.

Water development generally has not followed a program of prudent flexibility. Developers have continually defined water availability in terms of the regulated mean flow for some period of record in irrigation, navigation, and domestic supply calculations. This approach fails to account for longer-term fluctuations and has caused water allocation problems--for example, overappropriation in the Colorado River basin.[62] Of course, operating margins are built into most systems, with a standard ratio of water use to safe yield calculated into the design of most new projects. Unfortunately, this safe yield is not always updated with growing demand; the ratio has dropped below values that are considered safe in many mid-Atlantic urban water systems.[63]

<u>Great Plains Small Grains Production</u>: Policies designed to rescue Great Plains wheat, corn, and sorghum agriculture from persistent overproduction have failed dismally. The 1983 Payment-in-Kind program, the latest installment in a fifty-year effort to reduce crop acreages, foundered on the rocks of a short, sharp drought, a sense of unfairness stemming from the poor quality of in-kind grain, and various negative impacts of the program on the agricultural services and supply sector. A lack of consistency and commitment in federal implementation and a failure to recognize the year-to-year financial needs of farm firms appear to be key weaknesses in acreage reduction policy on the Plains.[64]

The Great Plains Conservation Program (GPCP), for example, encouraged farmers to permanently convert erosion-susceptible cropland to grazing land, or other conservation use.[65] Unfortunately, 60 percent of the program's funds have been used to increase agricultural water supplies rather than to reseed or decommission marginal cropland. This has resulted in part from economic pressures, since per-acre income continues to be lower for livestock grazing and other noncrop uses. Perhaps most critically, the GPCP has relied on long-term contracts with farmers, locking them into conservation commitments at a time (e.g. the 1970s) when interannual grain production controls, an important determinant in production decisions, varied widely. Thus the policy's effectiveness has been reduced by the interactive effects of other policies. Finally, the GPCP has actually encouraged more intensive agriculture and, perhaps, the conversion of marginal land not to grass but to irrigation, in essence converting a wind erosion problem into a water erosion, supply, and salinization problem. The participants in the GPCP have increased irrigated acreage much faster than nonparticipants. In short, the program may actually have been and still may be maladaptive.

Soil Erosion: Agricultural soil loss as an environmental concern has many parallels to carbon dioxide-induced climate change: it is a slow, anthropogenic, cumulative problem that often operates below typical perceptual thresholds. In addition, its chief costs in intensely farmed parts of the United States will not become manifest until some future time, and it interacts with other environmental fluctuations, for instance climate change. Soil erosion is currently a serious problem on 296.6 million acres of nonfederal land.[66] About 23 percent of U.S. cropland is losing more than 5 tons of soil per acre, the generally recognized threshold of damaging erosion, including 23 percent of corn-belt acreage and 40 percent of the cropland in the Southeast. Selective erosion of critical nutrients, as opposed to total top soil, is a less recognized but probably equally important problem. The U.S. Department of Agriculuture predicts that the continuation of 1977's erosion rates would decrease corn and soybean yields 15 to 30 percent by 2030.[67] But there is little direct evidence for depressed productivity due to soil erosion, the erosion signal in yields has not generally overcome the signal of intensive inputs of material and energy.

Soil erosion presents a policy problem mismatched to traditional economic and resource management solutions. It has been suggested that soil mismanagement illustrates the degree to which our institutions and economy are ill-adapted to the existing environment.[68] Our inability to recognize slow, cumulative environmental trends, conflicting economic incentives and disincentives for conservative soil management, and continuing scientific uncertainty all conspire to block solutions to the soil loss problem. Current political and economic decision-making systems are inadequate to the task, since social mechanisms for the allocation of resources engender conflicts between short-term economies and long-term realities. Hence, it may be necessary to deal with soil loss, the carbon dioxide/climate problem, and similar environmental problems, as ethical questions tied up in broader social issues such as the distribution of wealth, optimal food production and allocation systems, and even the size and structure of energy, transportation, and settlement systems.[69]

Colorado River Management: Rhodes et al. present a pertinent case study of Colorado River management with special emphasis on the floods in the spring of 1983.[70] They argue that the flooding resulted from two long-term management changes in the basin, and, of course, the remarkably wet conditions of 1982-83. Two reservoirs, Lake Powell and Lake Mead, are especially important in flood control in the basin. Lake Powell has been below full storage parameters for seventeen years. This provided an extraordinary flood buffer, allowing the reservoir to absorb even extremely high spring runoff without extra downstream releases. But the required minimum flood storage in Lake Mead, the next downstream reservoir, was not increased after Lake Powell's filling ended in 1982, with the result that the system's characteristics had changed but the overall operational parameters had not. In addition, marked flood-plain encroachment occurred during the "flood-safe" Lake Powell filling period. Hence, stream flows that in earlier years would have inflicted minimal damage caused serious loss in 1983. This encroachment was probably encouraged by perceptions that the river had been flood-proofed and was allowed by lax local zoning enforcement, over which the Bureau of Reclamation, the agency with flood control responsibility in the basin, has little control.

Rhodes et al. also argue that the seventeen-year "flood-proof" period was, in essence, an anthropogenic environmental change involving less variable streamflows and a markedly reduced probability of damaging extremes. They conclude that "two decades are more than sufficient" to change perceptions of climate constraints; the encroachment was a logical appropriation of apparently flood-proofed land and could have been avoided only by basin-wide land-use enforcement.

The irony of recent Colorado River flooding is heightened by the hypothesized carbon dioxide/climate impacts in the basin, which some suggest might include streamflow reductions of 20 percent or more.[71] However, the management and legal implications of such a carbon dioxide-induced reduction of Colorado River discharge are not different from the problems arising from the current supply/demand imbalance. Some observors argue that inflexibility, particularly with regard to the current allocative mechanisms, constitutes the key constraint to rational basin management.[72] Obstacles to changed management are embedded in institutional structures and the law, which through the Colorado River Compact requires the upper basin states to deliver a fixed quantity of water to the lower basin states even in drought years. Climate change-induced shortages will surely intensify the demand for better, perhaps market-oriented, allocative mechanisms.

<u>Lessons From the Case Studies</u>: The case studies cited here illustrate several common problems with long-term environmental management policy. These can be distilled into five key weakness:

(1) the policy does not do what it was designed to do;

(2) the policy is improperly applied;

(3) the policy is misused;

(4) the policy interacts in negative and/or counter-intuitive ways with other policies; and

(5) the policy is not flexible in the face of changing conditions.

<u>Analogies</u>: Society regularly, though often poorly, adjusts to environmental changes that are similar to carbon dioxide-induced climate change. Glantz and Ausubel created an analogue to the carbon dioxide/climate problem through an analysis of the perception of, and response to, the ongoing, slow, cumulative depletion of the Ogallala Aquifer in the U.S. Great Plains. They note that:

> Because studies of possible responses to the Ogallala depletion are more advanced, they may shed light on responses to hypotheti-

cal CO_2-induced climate change. Portions of the congressionally mandated $6 million High Plains Study that analyzed the Ogallala depletion for its impacts on the national, regional, state, and local economies could provide useful first approximations of how farmers and other decision-makers might respond to a CO_2-induced change in the regional water balance.[73]

The analogue approach is thus efficient, economical, and capable of making more concrete our first generation carbon dioxide/climate impact speculations. A first step in this approach might be the development of criteria for, and a list of, appropriate analogues. Case studies of climate policy analogues might be selected to mimic the carbon dioxide/climate problem, suggesting that they include at least these characteristics:

- long-term, cumulative environment change
- scientific uncertainty
- intergenerational issues
- political/economic complexity

Knowledge of policy failures and successes in similar environmental problems should aid in the formulation of carbon dioxide/climate adaptive policy. Of the policy case studies presented earlier, the issues surrounding water management, soil erosion, and agricultural policy seem most related to carbon dioxide/climate policy problems. More careful reviews of these areas should give us a better idea of the constraints and incentives to successful policy with regard to carbon dioxide/climate change.

Scenarios: Realistic, carefully constructed scenarios of climate impacts and adaptive strategies may be a useful tool in conceptualizing adaptive carbon dioxide policy. The carbon dioxide/climate problem, surrounded by uncertainty, and lacking current real-world manifestation, lends itself to scenario construction that is aimed at stretching our imagination of potential impacts and adaptations. Lave and Epple discuss three reasonable goals with regard to the use of scenarios: (1) changing mindsets; (2) formal modeling of impacts and adjustments; and (3) integrating disparate facts and hypotheses from different disciplines.[74]

The greatest immediate utility of scenarios with regard to the carbon dioxide/climate problem may reside in efforts to "stoke the imagination" and possibly change preceptions. However, the scenario is not a well-developed tool in environmental hazard analysis. There exist no generally accepted "rules of the game," and too many scenarios end up as unbelievable "future shock" nightmares. Hence, they may stir some public concern, but hold little credibility among political decision-makers. Lave argues that, at the least, scenarios must be based on "disciplined imagination," realistic assumptions, and informed judgment. A scenario that one is willing to present to political decision-makers must be widely reviewed and fine-tuned in several iterations among groups of experts. However, the point in the process at which review and revision becomes self-defeating, leading to bland, watered-down "scenarios-by-committee," cannot be specified in advance. Such an effect may have detracted from the value of the *Climate to the Year 2000* studies.[75]

Implementing Adaptive Policy

An adaptive carbon dioxide/climate policy will not be self-executing. Federal mission agencies, for instance the Departments of Agriculture or Commerce or the Environmental Protection Agency, will probably deal individually with subsets of the carbon dioxide/climate problem as they arise. It seems unlikely that a new agency will be created to deal specifically with climate problems, although an interagency program, like the U.S. National Climate Program, might emerge to coordinate the response. The existing structures and political orientations of the responsible agencies will affect how well the country responds to carbon dioxide/climate impacts.

Mechanisms for Implementation: The strategic responses listed in Table 6 might be effected incidentally as socioeconomic systems adjust to changing conditions. Experience, however, suggests that specific mechanisms will be needed to realize societal adaptation in most sectors. Table 7 lists four basic mechanisms for encouraging or coercing adaptation.

The relative efficacy of these mechanisms with regard to the carbon dioxide/climate problem remains speculative. They have been listed roughly in order of increasing governmental intervention, and, presumably, increasing costs and problems encountered in implementation. Incentives for adaptation will probably be used and be relatively cheap but will be only partially successful. Outright mandate, including court battles and enforcement, may get the job done, but will be more costly and painful to society and is less likely to be implemented widely.

Table 7
MECHANISMS OF POLICY IMPLEMENTATION

Incentives (e.g., tax breaks)
Compensation (sharing between affected interests)
Aid (outright grants)
Mandate (legal)

The Key Implementation Constraint: A problem must be perceived as serious by the people who will be affected by it, as well as by its solution, if a solution is ever to be implemented. This is founded on some basic axioms about public sector decision-making: 1) any solution to a real, complex problem will adversely affect some individuals or groups; and 2) potentially affected interests may be able to block policy implementation if they are sufficiently unhappy with it.[76] Thus, the first and most fundamental constraint to the development and implementation of adaptive carbon dioxide policy is found in the rather vague public image of carbon dioxide-induced climate change. Climate itself is a vague public concept, poorly recognized even by people who regularly use climate resources; its change may not readily be recognized as a serious threat.

It will not be easy to maneuver around this constraint. However, a mixture of simple and more complex mechanisms for increasing believability are available. The simplest approach might involve compelling statements of the problem. The Environmental Protection Agency used this approach in press releases on its *Can We Delay a Greenhouse Warming* report.[77] It is important, however, to avoid overstatement or sensationalism. Alternatively, one might link the carbon dioxide problem to tangible impacts, for instance a doubling of food prices, mandatory growth controls in western cities, or increased coastal erosion. Another approach might involve the development of well-articulated scenarios of what might happen were no adaptive policy action taken. Such scenarios must be understandable and realistic, and must speak to real-world problems that affect people's lives, for instance, farm foreclosures, food and energy, and water shortages.

Serious problems are placed on the national political agenda once there is widespread agreement both that a serious situation exists and that significant negative impacts will occur if nothing is done to forestall them. However, interest group pressure, particularly from environmental groups, governmental agencies, and publics adversely impacted by an adaptation, forms the last, though still formidable, constraint to policy implementation. This need not prove an insurmountable obstacle as long as these interests can be convinced that the adaptive mechanisms in question are fair, workable, and efficacious, and, above all, that the mechanisms address a serious problem.

BRIDGING THE CLIMATE-SOCIETY KNOWLEDGE GAP

Research is steadily eliminating uncertainties surrounding the climate's response to increasing atmospheric concentrations of carbon dioxide. Unfortunately, similar progress is not taking place with regard to the connection between climate and society. Three lines of research, proposed in this final section, may help bridge the climate-society knowledge gap relatively quickly and cheaply. The first involves various theoretical efforts in the human ecology of climate fluctuation. The others involve a broad-brush effort to canvass societal climate sensitivities, as well as efforts to develop a simple methodology for measuring the climate signal in human activities.

Needed Theoretical Development

The study of climate-society interaction falls under the aegis of the multidisciplinary field of human ecology. Our understanding of human-environment relationships improved in the 1960s and 1970s with the development of ideas about cultural adaptation, social systems, and, especially, the role of perception in modulating environmental behavior. The next step might involve the development of better methodologies for exploring the relationship between social structure and the environment.[78] Behavioral studies have focused on the individual, progressing up the scale of aggregation by summing individual perceptions and behavior. But experience and intuition suggest that human aggregates interact with the environment in different ways than do individuals, and that institutional structure imparts constraints and incentives to adjustive behavior.[79]

The nature of this theoretical work cannot be detailed in advance. However, one possible focus would be particularly relevant to the carbon dioxide/climate problem: research on the interaction of social structure with slow, cumulative environmental change. Human ecology, despite its attention to adjustment choice, takes a rather static view of human-environment relationships.[80] We have some broad ideas about how sociocultural change occurs,[81] but we have not managed to incorporate change per se into an explanatory framework of environmental interaction. We lack an understanding of how slow cumulative change affects society's ability to cope with internal and external stress. But we harbor a disturbing intuition that slow, imperceptible change tends to sneak up on us until it threatens the functioning of society's support systems.

Our ideas of societal adaptation to changing environmental conditions seem to be anchored by two extremes: either we adapt slowly, through countless incremental trial-and-error outcomes, or we adjust in a step-like fashion as crises erupt. The long history of animal and plant domestication would appear to be an example of slow adaptation, and the causes of, and responses to, the recent oil shortages exemplify the latter type. Both incremental and momentous change appear to include sociotechnical adaptation, though the relative importance of each--the costs and benefits and the predictability or controllability of certain modes of change--remain obscure.

Studies of the interaction of slow environmental change and social structure are desperately needed. We need to know why, for example, causal relationships between overgrazing and range deterioration are so easily demonstrated within the framework of range science, but so stubbornly disavowed by the ranching community.[82] We need to know more about how people and their collectives view themselves as actors in environmental change. The lack of attention to matters of slow social and environmental change limits our ability to visualize the impacts of, and adaptations to, environmental threats. If, as it appears, we tend to ignore slow change in the environment, then we will certainly not devise effective preemptive strategies to mitigate the impacts of carbon dioxide-induced climate change. But this is speculative, based on little validated empirical evidence of the causes and role of change in interactions between humans and nature. Even the most widely cited models of change in social and resource systems, for instance Marx's historical materialism, are short on empirical validation.[83] Thus, the problem does not derive solely from theoretical oversight, but stems also from inattention to empirical methodology and case study.

Sensitivity Analysis

A two-pronged effort to identify sectoral climate sensitivities can improve our decisions about what to look for in empirical data. First, we should canvass the methods used in previous research, seeking to identify sensitivity indices. Especially important are indices that provide first-cut indications of climate vulnerabilities and point to the non-climate data needed to develop a picture of the magnitude and seasonal and spatial distributions of climate sensitivities in the United States. Next, a rough sensitivity analysis of the sectors listed in Table 8 should be conducted to identify the areas that are most vulnerable to climate change. Some approaches to such studies are suggested by Maunder and Ausubel, and they have produced a rough sensitivities list (see Table 9).[84]

Table 8
PROVISIONAL LIST OF CLIMATE-SENSITIVE SECTORS

Agriculture
1. Small grains*
2. Vegetable*
3. Citrus
4. Irrigated*
5. Ranching*
6. Poultry*
7. International markets*

Communications
1. Microwave
2. Equipment maintenance

Construction
1. Major projects
2. Housing

Energy
1. Electricity
   a. Thermal
   b. Hydro*
2. Gas*
3. Petroleum
4. International markets

Fisheries
1. Ocean
2. Inland

Industrial and Commercial
1. Industrial operations
2. Retail sales

Recreation and Tourism
1. Resorts and tourism
2. Winter sports*
3. Hunting
4. Special events

Resource Management
1. Fish and game
2. Forestry and fire control
3. Environmental quality

Social Services
1. Health*
2. Rural and municipal services
   a. Snow removal*
   b. Low income
   c. Unemployment
   d. Education

Transportation
1. Highway
2. Air
3. Rail
4. Oceanic shipping
5. Inland barge

Water Resources
1. Supply*
2. Quality*
3. Flood control

*Activities that might be especially sensitive to changes in precipitation and temperature.

Table 9
SENSITIVITY OF GROSS NATIONAL PRODUCT ELEMENTS
TO WIDESPREAD ANOMALOUS WEATHER

	Weather: Unusually					
GNP Elements	Hot Summer	Cold Winter	Dry Summer	Stormy/ Wet	Snowy	Mild
1. Personal consumption expenditures						
a. Gasoline and oil	-	-	-	-	-	++
b. Electricity	++	+	?	++	?	-
Natural gas, fuel oil, coal	?	++	?	++	+	-
c. Furniture and appliances	-	-	-	?	-	++
d. Food at home	++	+	++	+	++	--
Food away	--	--	?	?	--	++
e. Apparel	-	+	?	?	-	+
f. New and used cars	-	-	-	-	-	++
g. Housing	-	--	?	?	-	++
h. Transporation	-	-	?	-	-	++
i. Other	?	?	?	?	?	?
2. Non-residential fixed investment	?	?	?	?	?	?
3. Residential	-	-	-	?	-	++
4. Change in business inventories	+	+	+	+	+	--
5. Net imports	+	++	+	+	+	--
6. Government purchases						
a. Federal	+	+	+	+	+	-
b. State and local	+	+	+	+	+	-

Note: Double pluses and minuses indicate the greatest sensitivities.

Source: W. Maunder and J. Ausubel, "Identifying Climate Sensitivity," in *Climate Impact Assessment: Studies of the Interaction of Climate and Society*, R. Kates, J. Ausubel, and M. Berberian, eds. (New York: John Wiley and Sons, 1985).

A sensitivities assessment should help us prioritize our concerns with regard to carbon dioxide/climate change. This prioritized concern might then be fused with other approaches to help set a research and policy agenda. For instance, we might wish to weight our priorities according to the proportion of national or regional GNP contributed by each sensitive activity. This might be a modest effort, probably involving "quick-and-dirty" approaches designed to result in an ordered worry list, rather than sophisticated economic and statistical analysis. This list of sensitivities could then be used to inform the development of appropriate impact and adjustment case studies, anologues and scenarios.

Appropriate Empiricism: Harvesting Natural Experiments

Empirical evidence to guide theoretical development may be best gathered through field trials, in which one observes, reconstructs, and interprets the social response to actual climate fluctuations. But we must carefully design the research to collect the type of evidence that makes results from the experimental sciences so compelling. The following ideas stem from an emerging program called CLIMPAX, which was designed to harvest recent (1931 to present) "natural experiments" in parts of the country that experienced marked, persistent climate changes of ten- to twenty-year duration.[85] These experiments are designed to extract climate impact signals from the typical noise of socioeconomic time series through longitudinal and case-control analytical methods; the lack of any clear signal would allow us to conclude that fluctuations of the magnitudes and characteristics in question have no discernable effect on critical systems like agriculture, energy, and water resources. Studies of a range of climate fluctuations might allow us to determine thresholds of detectable impacts for different sectors in different climate settings.

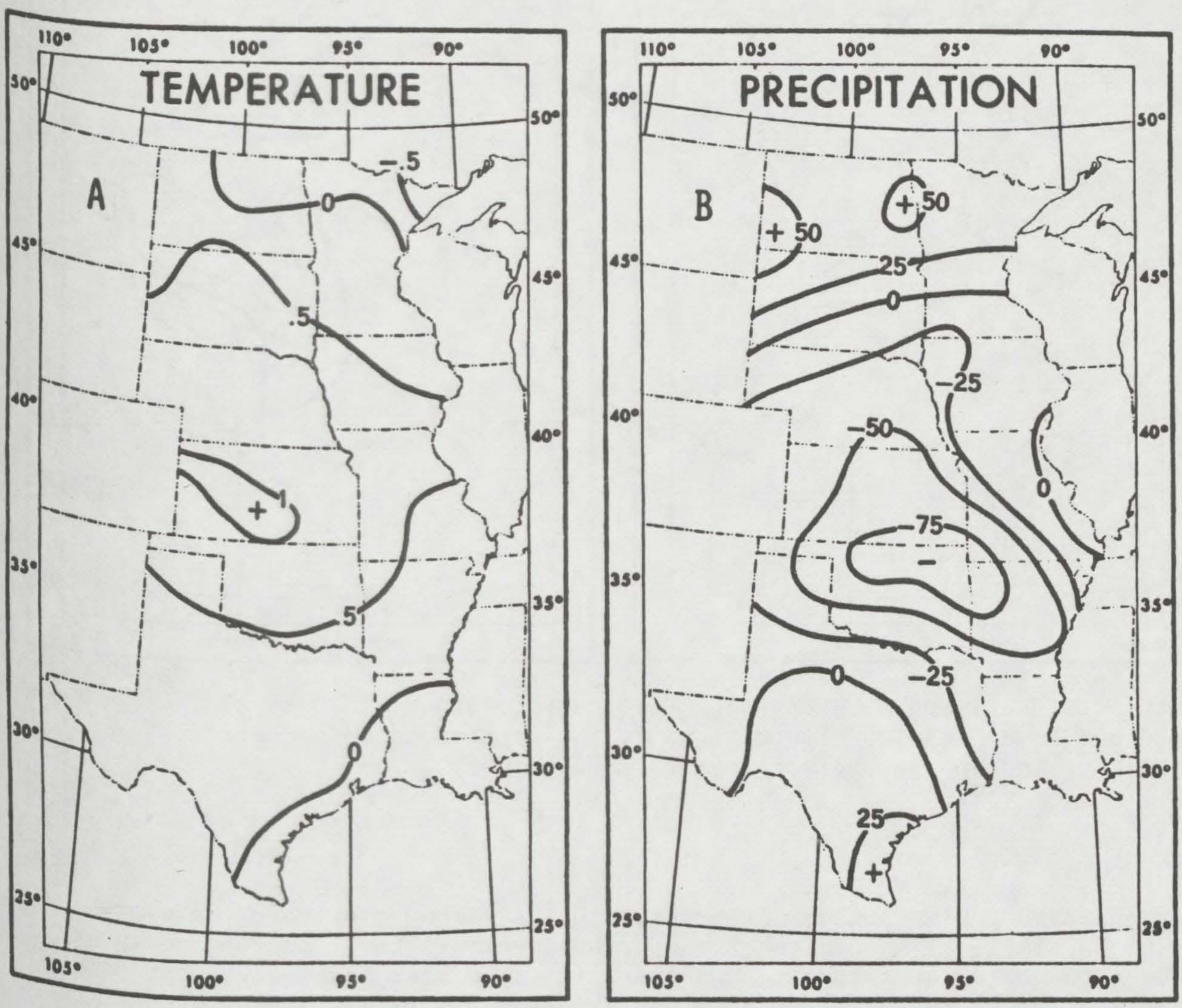
To identify a set of potential impact case studies, Karl and Riebsame[86] searched all coterminus U.S. climate divisions for marked, step-like changes in temperature and/or precipitation, comparing all possible adjacent non-overlapping ten- to twenty-year epochs. A few midcontinental cases exhibiting a change to warmer, drier conditions were selected from among the hundreds of areas assessed. For example, up to a 1 degree Celsius increase in spring (March through May) temperature and a 75 millimeter (approximately 25 percent) precipitation decrease was found in climate conditions of the south-central Great Plains between the epochs 1951-61 and 1962-72 (see Figure 1). A northern Great Plains case is shown in Figure 2. Parts of the Dakotas experienced a small, persistent increase in temperature with a 25 to 50 millimeter (11 to 23 percent) decrease in summer precipitation between 1939-57 and 1958-76.

The next steps, then, involve collecting appropriate biophysical and socioeconomic data series for these cases, establishing longitudinal profiles (e.g., across the 1957-58 Dakota break in climate), perhaps with some sort of adaptational lag built in, and selecting case-control sites--nearby areas that did not experience the change or at least did so to a much lesser degree. Before and after and case-control comparisons should then allow one to identify a climate impacts signal, if it exists.

Of course, an empirical approach cannot totally emulate a carbon dioxide-induced climate change. Regionally constrained fluctuations will, theoretically, have different impacts than national-scale climate change. Additional analysis is needed to identify cases that might emulate carbon dioxide-forced changes in other climate characteristics, particularly variability. The criteria used by Karl and Riebsame do not mimic the current projections of carbon dioxide/climate change and should be reanalyzed for fluctuations that look more like the projections. For example, areas should be chosen that have experienced relatively consistent trends toward warmer, drier conditions for as long as possible. Such a case would be more meaningful if we could also find a nearby, and presumably geographically similar, area whose climate remained relatively constant during the same period. Case-control comparisons could then be attempted. The computational routines are simple, and the necessary impacts data could probably be collected relatively quickly, perhaps in one field season.

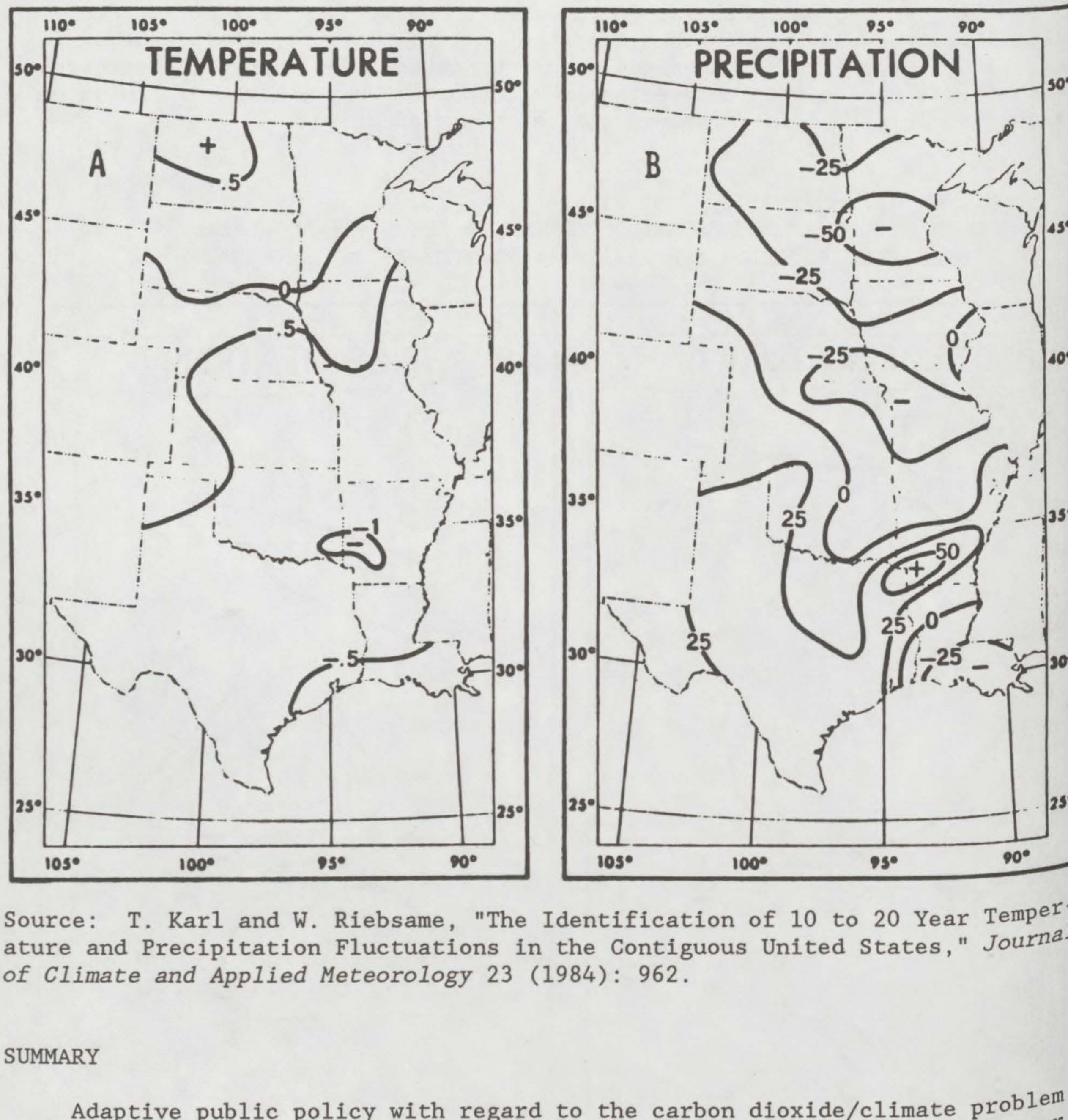
Finally, we need a small set of cases that bracket the range of carbon dioxide/climate change predictions from the best to the worst cases. Some modest efforts along these lines could put our carbon dioxide/climate concerns on much firmer ground and improve the likelihood that any policies formulated to adjust society to climate change will be truly adaptive.

Figure 1
CHANGE IN SPRINGTIME AVERAGE TEMPERATURE (in degrees Celsius) AND TOTAL PRECIPITATION (in millimeters) FROM 1951-61 TO 1962-72



Source: T. Karl and W. Riebsame, "The Identification of 10 to 20 Year Temperature and Precipitation Fluctuations in the Contiguous United States," *Journal of Climate and Applied Meteorology* 23 (1984): 960.

Figure 2
CHANGE IN SUMMERTIME AVERAGE TEMPERATURE (in degrees Celsius) AND TOTAL PRECIPITATION (in millimeters) FROM 1939-57 to 1958-76



Source: T. Karl and W. Riebsame, "The Identification of 10 to 20 Year Temperature and Precipitation Fluctuations in the Contiguous United States," *Journal of Climate and Applied Meteorology* 23 (1984): 962.

SUMMARY

Adaptive public policy with regard to the carbon dioxide/climate problem may be as simple as a commitment to further monitor the situation and sponsor thought-provoking conferences. However, it might also involve greater substance, as in the development of alternative tax or land-use laws designed to alter the types and locations of certain agricultural practices or change the capacities of regional energy and water systems. Recognizing the cognitive constraints that prevail in the solution of novel problems, we should at least explore the range of mechanisms that might be employed to improve our formulation of adaptive carbon dioxide/climate policy, while simultaneously taking an introspective look at the policy process with regard to long-term environmental change. If the carbon dioxide/climate problem is real and becomes recognized as a serious public policy issue, then even absent a climate crisis, we may well evolve, for example, a farm policy that encourages adaptive flexibility in agricultural systems, an antediluvial policy to minimize the negative effects of sea level rise, or even policies designed to help society benefit from climate change.

NOTES

1. S. Schneider, "The CO_2 Problem: Are There Policy Implications--Yet?" *Climatic Change* 2 (1980): 203.

2. R. Ridker, "Social Responses to the CO_2 Problem," in *Proceedings of the Carbon Dioxide and Climate Research Conference*, L. Schmitt, ed. (Washington, D.C.: U.S. Department of Energy, 1980); Carbon Dioxide Assessment Committee, National Research Council, *Changing Climate* (Washington, D.C.: National Academy Press, 1983); and S. Seidel and D. Keyes, *Can We Delay a Greenhouse Warming?* (Washington, D.C.: U.S. Environmental Protection Agency, 1983).

3. T. Schelling, "Anticipating Climate Change," *Environment* 26, no. 8 (1984): 6. Schelling offers a detailed breakdown of preventive options but gives little attention to adaptive policies.

4. M. Glantz, "A Political View of CO_2," *Nature* 280 (1979) 189.

5. S. Schneider, "CO_2, Climate and Society: A Brief Overview," in *Social Science Research and Climate Change*, R. Chen, E. Boulding, and S. Schneider eds. (Dordrecht, Netherlands: D. Reidel Publishing Company, 1983).

6. See note 4 above.

7. S. Wittwer, "Carbon Dioxide and Climatic Change: An Agricultural Perspective," *Journal Soil and Water Conservation* 35 (1980): 116.

8. P. Waggoner, "Agriculture and a Climate Changed by More Carbon Dioxide," in Carbon Dioxide Assessment Committee in note 2 above.

9. M. Bowden et al., "The Effects of Climatic Fluctuations on Human Populations: Two Hypotheses," in *Climate and History*, T. Wigley, M. Ingram, and G. Farmer, eds. (Cambridge: Cambridge University Press, 1981).

10. Great Plains Committee, *The Future of the Great Plains*, 75th Congress, First Session, 1937, Document 114; and D. Worster, *Dust Bowl: The Southern Great Plains in the 1930s* (New York: Oxford University Press, 1979).

11. W. Riebsame, "Managing Agricultural Drought: The Great Plains Experience," In *Beyond the Urban Fringe*, R. Platt and G. Maeinko, eds. (Minneapolis: University of Minnesota Press, 1983).

12. M. Parry, "Climatic Change and the Agricultural Frontier: A Research Strategy," in Wigley, Ingram, and Farmer in note 9 above; see also L. Mearns, R. Katz, and S. Schnieder, "Changes in the Probabilities of Extreme High-Temperature Events: Changes in Their Probabilities With Changes in Mean Temperature," *Journal of Climate and Applied Meteorology* 23 (1984): 1,601.

13. W. Kellogg and R. Schware, *Climate Change and Society: Consequences of Increasing Atmospheric Carbon Dioxide* (Boulder, Colo.: Westview Press, 1981).

14. G. White, ed., *Natural Hazards: Local, National, Global* (New York: Oxford University Press, 1974); and I. Burton, R. Kates, and G. White, *The Environment as Hazard* (New York: Oxford University Press, 1978).

15. Wigley, Ingram, and Farmer in note 9 above; and T. Rabb, "Climate and Society in History: A Research Agenda," in Chen, Boulding, and Schneider in note 5 above.

16. See F. Hare, "Changing Climate and Human Response: The Impact of Recent Events in Climatology," *Geoforum* 15 (1984): 383.

17. R. Kates, J. Ausubel, and M. Berberian, eds., *Climate Impact Assessment: Studies of the Interaction of Climate and Society* (New York: John Wiley and Sons, 1985).

18. M. Parry and T. Carter, *Assessing the Impacts of Climate Change in Marginal Areas: The Search for an Appropriate Methodology* (Laxenburg, Austria: International Institute for Applied Systems Analysis, 1983).

19. R. Kates et al., *The Climate Impact, Perception, and Adjustment Experiment (CLIMPAX): A Proposal for Collaborative Research*, Center for Technology, Environment and Development (Worcester, Mass.: Clark University, 1984); and T. Karl and W. Riebsame, "The Identification of 10 to 20 Year Temperature and Precipitation Fluctuations in the Contiguous United States," *Journal of Climate and Applied Meteorology* 23 (1984): 950.

20. See, for example, W. Roberts and H. Lansford, *The Climate Mandate* (San Francisco: Freeman, 1979); and H. Lamb, *Climate, History and the Modern World* (London: Methuen, 1982).

21. See, for example: W. Maunder, *The Value of the Weather* (London: Methuen, 1970); R. Garcia, *Drought and Man: The 1972 Case History*, vol. 1: *Nature Pleads Not Guilty* (New York: Pergamon Press, 1981); S. Changnon, "How a Severe Winter Impacts Individuals," *Bulletin American Meteorological Society* 60 (1979): 110; Assessment and Information Services Center, *U.S. Impacts of the Great 1980 Heat Wave and Drought* (Washington, D.C.: National Oceanic and Atmospheric Administration, 1980); and Assessment and Information Services Center, *The Economic and Social Impacts of the Winter of 1976-77* (Washington, D.C.: National Oceanic and Atmospheric Administration, 1981).

22. See, for example, M. Parry, *Climatic Change Agriculture and Settlement* (Kent, U.K.: Dawson, 1978); and Kates, Ausubel, and Berberian in note 17 above.

23. For example, M. Glantz, J. Robinson, and M. Krenz, "Climate-Related Impact Studies: A Review of Past Experiences," in *Carbon Dioxide Review: 1982*, W. Clark, ed. (New York: Oxford University Press, 1982).

24. For example, for a discussion of the policy implications of quantifying costs and benefits in environmental decision-making, see A. Prest and R. Turvey, "Cost-Benefit Analysis: A Survey," *The Economic Journal* 75 (1965): 683; and R. Andrews, "Will Benefit-Cost Analysis Reform Regulations?" *Environmental Science and Technology* 15 (1981): 1,016.

25. For example, Comptroller General of the United States, *California Drought of 1976 and 1977: Extent, Damage, and Governmental Response* (Washington, D.C.: General Accounting Office, 1977); and W. Dando, R. Mower, and D. Munski, *The 1980 North Dakota Drought: Economic Effects* (Grand Forks, N. Dak.: University of North Dakota, Department of Geography, 1981).

26. G. White and J. Haas, *Assessment of Research on Natural Hazards*, (Cambridge, Mass.: Massachusetts Institute of Technology Press, 1974).

27. Barton, Kates, and White in note 14 above.

28. W. Maunder and J. Ausubel, "Identifying Climate Sensitivity," in Kates, Ausubel, and Berberian, note 17 above.

29. Assessment and Information Services Center, *Climate Impact Assessment Annual Summary: 1982 and 1983* (Washington, D.C.: National Oceanic and Atmospheric Administration, 1983 and 1984).

30. J. Ausubel, "Economics in the Air--An Introduction to Economic Issues of the Atmosphere and Climate," in *Climatic Constraints and Human Activities*, J. Ausubel and A. Biswas, eds. (Oxford, U.K.: Pergamon Press, 1980).

31. A. Freeman, "The Hedonic Price Technique and the Value of Climate as a Resource," paper presented at the Climate and Economics Workshop, April 24-25, Ft. Lauderdale, Resources for the Future, Washington, D.C.

32. R. D'Arge, "Climate and Economic Activity," in *World Climate Conference*, report 537 (Geneva, Switzerland: World Meteorological Organization, 1979).

33. For example, Climatic Impact Assessment Project, *Economic and Social Measures of Biological and Climatic Change*, Monograph 6, (Washington, D.C.: U.S. Department of Transportation, 1975); D. Haurin, "The Regional Distribution of Population, Migration, and Climate," *Quarterly Journal of Economics* 95 (1980): 293; and C.A.K. Lovell and V.K. Smith, "Microeconomic Analysis," in Kates, Ausubel, and Berberian in note 17 above.

34. See note 20 above.

35. P. Timmerman, *Vulnerability, Resilience and the Collapse of Society*, Environmental Monograph 1 (Toronto: Institute for Environmental Studies, University of Toronto, 1981); C. Hollings, "Resilience and Stability in Ecological Systems," *Annual Review of Ecology and Systematics* 4 (1973): 1; and M. Glantz, *Man, State and Fisheries: An Inquiry into Some Societal Constraints that Affect Fisheries Management* (Boulder, Colo.: National Center for Atmospheric Research, 1984).

36. See note 28 above.

37. See Glantz in note 35 above.

38. J. Maunder, "The Formulation of Weather Indices for Use in Climate-Economic Studies: A New Zealand Example," *New Zealand Geographer* 28 (1972): 130.

39. A. Eddy, ed., *The Economic Impacts of Climate*, vols. 1, 2 (Norman, Okla.: Department of Meteorology, University of Oklahoma, 1980).

40. See note 28 above.

41. See note 9 above.

42. National Academy of Sciences, *Genetic Vulnerability of Major Crops* (Washington, D.C., 1972).

43. See note 20 above.

44. A. Randall, *Resource Economics* (New York: John Wiley and Sons, 1981).

45. Ibid.

46. See S. Brubaker, ed., *Rethinking the Federal Lands* (Washington, D.C.: Resources for the Future, 1984).

47. T. Arrandale, "The Battle for Natural Resources," *Congressional Quarterly* (1983).

48. See note 9 above.

49. R. Warrick and M. Bowden, "The Changing Impacts of Drought in the Great Plains," in *The Great Plains: Perspectives and Prospects*, M. Lawson and M. Baker, eds. (Lincoln, Nebr.: Center for Great Plains Studies, University of Nebraska, 1981).

50. See Burton, Kates, and White in note 14 above.

51. S. Schneider with L. Mesirow, *The Genesis Strategy* (New York: Plenum Press, 1976).

52. R. Warrick and W. Riebsame, "Societal Response to CO_2-Induced Climate Change," *Climatic Change* 3 (1981): 387.

53. B. Fischhoff and L. Furby, "Psychological Dimensions of Climatic Change," in Chen, Boulding, and Schneider, note 5 above.

54. D. Mann, "Research on Political Institutions and Their Response to the Problem of Increasing CO_2 in the Atmosphere," in Chen, Boulding, and Schneider, note 5 above, p. 118.

55. T. O'Riordan, *Environmentalism* (London: Pion, 1976).

56. For example, J. Anderson, *Public Policy-making* (New York: Praeger, 1975).

57. See, for example, C. Lindblom, "The Science of 'Muddling Through'," *Public Administration Review* 19 (1959): 78; and E. Brooks, "Governmental Decision-faking," *Transactions of the Institute of British Geographers* 63 (1974): 29.

58. See note 53 above.

59. R. Kates, *Hazard and Choice Perception in Flood Plain Management*, research paper 78, Department of Geography (University of Chicago, 1962); P. Slovic, H. Kunreuther, and G. White, "Decision Processes, Rationality, and Adjustment to Natural Hazards," in *Natural Hazards: Local, National and Global*, G. White, ed. (New York: Oxford University Press, 1974); and D. Mileti, "Human Adjustment to the Risk of Environmental Extreme," *Sociology and Social Research* 64 (1980): 327; and Burton, Kates, and White in note 14 above.

60. Detailed by G. White, *Strategies of American Water Management* (Ann Arbor, Mich.: University of Michigan Press, 1969); for an update, see United States Water Resources Council, *A Unified Program for Flood Plain Management* (Washington, D.C., 1979); and S. Changnon et al., *A Plan for Research on Floods and Their Mitigation in the United States* (Champagne, Ill.: Illinois State Water Survey, 1983).

61. G. White, *Flood Hazard in the United States: A Research Assessment*, monograph 6 (Boulder, Colo.: Natural Hazards Research And Applications Center, University of Colorado, 1975).

62. C. Howe and A. Murphy, "The Utilization and Impacts of Climate Information on the Development and Operation of the Colorado River System," in *Managing Climatic Resources and Risks*, Climate Board, National Research Council (Washington, D.C.: National Academy Press, 1981).

63. See note 17 above; and C. Russell, D. Arey and R. Kates, *Drought and Water Supply: Implications of the Massachusetts Experience for Municipal Planning* (Baltimore: Johns Hopkins University Press, 1970).

64. L. Tweeten, *Foundations of Farm Policy* (Lincoln, Nebr.: University of Nebraska Press, 1979).

65. J. Kasal and W. Buck, *An Economic Evaluation of the Great Plains Conservation Program* (Washington, D.C.: U.S. Department of Agriculture, 1970).

66. United States Department of Agriculture, *Soil, Water, and Related Resources in the United States: Status, Condition, and Trends* (Washington, D.C.: U.S. Department of Agriculture, 1980).

67. Ibid.

68. J. Wade and E. Heady, "Controlling Nonpoint Sediment Sources With Cropland Management: A National Economic Assessment," *American Journal of Agricultural Economics* 59 (1977): 13; and J. Weiner, "Agricultural Soil Erosion: Adaptational Problems and Ethics," manuscript, Department of Geography (Boulder, Colo.: University of Colorado, 1984).

69. See also Glantz in note 4 above for a discussion of the need for different policy-making approaches.

70. S. Rhodes, D. Ely, and J. Dracup, "Climate and the Colorado River: The Limits of Management," *Bulletin American Meteorological Society* (1984).

71. R. Revelle and P. Waggoner, "Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States," in Carbon Dioxide Assessment Committee, National Research Council, note 2 above; and Environmental Protection Agency, *Potential Climate Impacts of Increasing Atmospheric* CO_2 *with Emphasis on Water Availability and Hydrology in the United States*, EPA 230-04-84-006 (Washington, D.C.: U.S. Environmental Protection Agency, 1981).

72. For example, see R. Coats, "The Colorado River: River of Controversy," *Environment* 26 (1984): 7.

73. M. Glantz and J. Ausubel, "The Ogallala Aquifer and Carbon Dioxide: Comparison and Divergence," *Environmental Conservation* 11, no. 2 (1984): 123.

74. L. Lave and D. Epple, "Scenario Analysis," in Kates, Ausubel, and Berberian, note 17 above.

75. National Defense University, *Climate Change to the Year 2000: A Survey of Expert Opinion* (Washington, D.C., 1978); see also Glantz et al., note 23 above, for a review of the operational problems found in this and other climate impact studies.

76. See O'Riordan in note 55 above.

77. Seidel and Keys in note 2 above.

78. J. Bennett, *Northern Plainsmen: Adaptive Strategy and Agrarian Life* (Chicago: Aldine Publishing Co., 1969); and J. Bennett, *Of Time and Enterprise* (Minneapolis: University of Minnesota Press, 1982).

79. See, for example, K. Hewitt, ed., *Interpretations of Calamity: From the Viewpoint of Humany Ecology* (Boston: Allen and Unwin, Inc., 1983).

80. H. Sprout and M. Sprout, *The Ecological Perspective on Human Affairs* (Princeton, N.J.: Princeton University Press, 1965).

81. R. Lauer, *Perspectives on Social Change* (Boston: Allyn and Bacon, 1973).

82. N. Rosetta, "Herds, Herds on the Range," *Sierra* 70 (1985): 43.

83. M. Harris, *Cultural Materialism* (New York: Vantage Books, 1979); see especially pp. 141-257.

84. See note 28 above.

85. See Kates et al. in note 19 above.

86. See Karl and Riebsame in note 19 above.

A WATER RESOURCE MANAGEMENT RESPONSE TO THE GREENHOUSE EFFECT IN THE RED RIVER BASIN

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INTRODUCTION

Reconstructions of climatic history provide sufficient data to document the nonstationary nature of climate. Over long periods of time, climate changes significantly, varying, for instance, from glacial to nonglacial conditions over the last 15,000 years. Catastrophic climate changes are unlikely to occur in the future. However, significant variations in climate are expected to occur because of natural solar energy variations and human-induced variations in the chemistry of the atmosphere.

A direct link exists between climate change and the water levels of our lakes, streams, and prairie potholes. Hence, we must begin thinking now in terms of probabilistic futures. In fact, this is imperative given our current engineering and political processes. The planning, design, funding, and construction of water resource developments can take several decades, which means that the major water projects being conceived for today's needs will probably not be implemented until sometime in the twenty-first century. Therefore, where it can be shown that the present climate is anomalous compared to past conditions or probable future conditions, today's water resource manager must deal with probabilistic future scenarios in planning.

The relevance of future climate conditions to water resource planning is apparent in three reservoir projects that were constructed in the 1950s in the Red River of the North basin in northwestern Minnesota and eastern North Dakota. These reservoirs were planned in response to the 1930s drought, using limited historic records. Their primary purpose is water supply, and they have functioned well for that purpose. However, they have also more than recovered their initial economic investment cost in terms of flood control. This is due to the relatively wet period of the last thirty years. Currently, one of the reservoir projects has been recommended for modification so that it will be more effective in flood control. Similarly, other projects are being planned now for flood control with little consideration given to the water shortages that existed in the 1930s. But water supply could be as much of a problem or concern in the next decade as flooding is now.

The U.S. Corps of Engineers has had much experience in responding to short-term climate variations like floods, droughts, and hurricanes through emergency programs. However, its response to changed long-term climate conditions has been one of reaction rather than of anticipation.

Although this approach has been effective and is likely to continue, the problems with existing projects in the Red River basin make it worthwhile to speculate on a water resource management response to a probable future climate scenario--one that is significantly different from that suggested by statistical extrapolations from the immediate past. This paper is a thought exercise in one such probable climate scenario. It identifies a specific reaction and adjustment to the climate scenario used in the 1983 National Academy of Sciences report, "Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States."[1]

BASE CONDITION

The National Academy of Sciences study predicts that atmospheric concentrations of carbon dioxide will double to 600 parts per million by the middle of the next century, resulting in an increase in mean global temperature. It assumes that this projected greenhouse effect would result in a 10 percent reduction in mean annual precipitation and a 2 degree Celsius increase in mean annual temperature. Although a different climate change may very well occur, this scenario appears probable based upon many studies to date.[2]

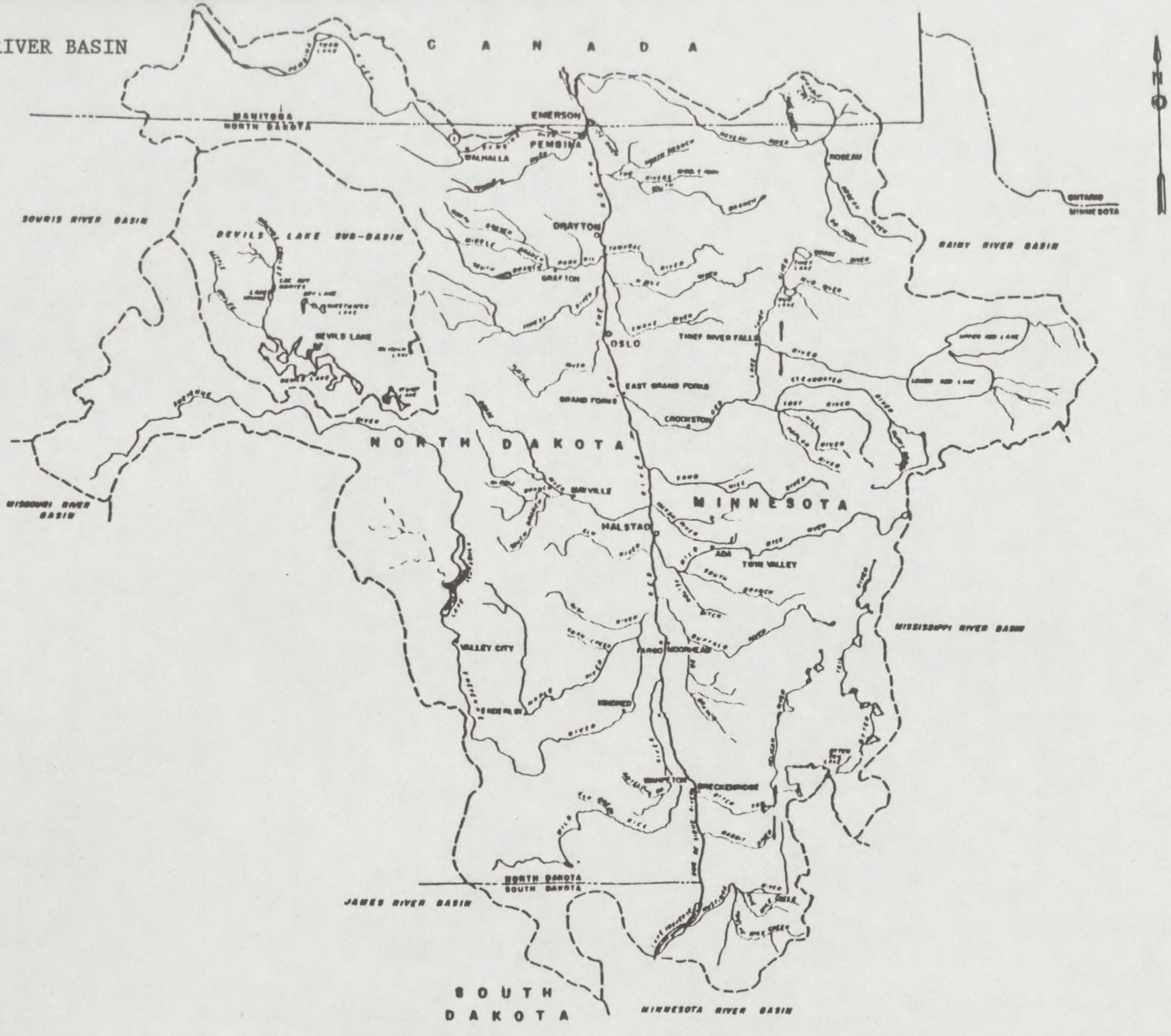
It is safe to assume that the overall impact of such a climate change will vary geographically, given the physiographic differences that exist within the United States. Some regions of the country will benefit and some will be adversely affected. However, all regions will have to readjust. To better analyze and properly define the magnitude and extent of the adjustments, one water resource region was selected for attention in this paper. This region, the Red River basin, is an important agricultural region that is very much dependent on normal precipitation for crop production. Past reductions in precipitation have upset the hydrological balance, requiring adjustments in water resource management. A similar change is assumed for the future and is assumed to be likely to occur within a time frame that affects the planning of numerous large-scale water resource systems.

BASIN DESCRIPTION

Figure 1 shows the Red River basin. It is a roughly triangular area. The basin includes the eastern portion of North Dakota in the west and the northwestern edge of Minnesota in the east. The southern tip of the basin reaches as far as South Dakota along the North Dakota-Minnesota border. Sixteen counties in North Dakota and sixteen counties in Minnesota are included in the basin. Nineteen major sub-basins make up the approximately 40,000 square miles of the basin's U.S. portion. The Red River of the North, which is formed by the confluence of the Bois de Sioux and Ottertail rivers at Wahpeton, North Dakota, and Breckenridge, Minnesota, bisects the valley. The basin eventually drains into Lake Winnipeg and the Hudson Bay in Canada.

The topography of the region is diverse. In the east is an area of lakes, ridges, and hills. The central portion includes the very flat Red River Valley, and the western part is rolling drift prairie, dotted with prairie potholes. The annual precipitation varies from about 24 inches in the southeast to 17 inches in the northwest. About 75 percent of the precipitation falls between April and September. This is adequate for crop production in normal years. However, periods of drought are frequent, especially in the western part of the region. Potential evapotranspiration

Figure 1. RED RIVER BASIN



Red River of the North (Minnesota, North Dakota and South Dakota) Basin Map, U.S. Department of Agriculture, Soil Conservation Service, RR-200/1.

losses generally exceed precipitation and average 30 inches. This region has a continental climate with a mean annual temperature of 40 degrees Fahrenheit. Extreme temperatures have been known to vary from -54 degrees Fahrenheit to 118 degrees Fahrenheit.

The average runoff at the outlet of the U.S. portion of the basin at Emerson, Manitoba, is about 2,387,000 acre-feet or 1.1 inches. The monthly distribution of streamflow is highly variable. Maximum runoff generally occurs in April and May, due to snowmelt. August through March are low flow months, when little or no flow may be evident.

Agriculture is the basic industry of the region. The importance of the basin to domestic and foreign food production is well documented. The Red River basin produces three-fourths of the nation's sunflower harvest, one-third of it's barley, one-fourth of its sugar beets, one-fifth of it's flax, and one-tenth of it's wheat, oats, and potatoes. The annual value of these products is currently about $4 billion. The population of the basin is approximately 570,000, according to the 1980 census. About 46 percent lives in urban areas, and 54 percent lives in rural areas. The population should be over 600,000 by the year 2000, according to state projections. The only standard metropolitan statistical area is the Fargo-Moorhead urban area. Only one other community, Grank Forks, North Dakota, has a population greater than 25,000.

The development opportunities of the basin are limited by a variety of water resource problems. Flooding has been a significant problem over the last thirty years, occurring primarily as a result of spring snowmelt often aggravated by rains. The worst flooding is in the central third of the region. In this area, the water can be spread out for miles on the flat landscape. Regional average annual flood damages to rural areas are almost twice those of urban areas. In addition, water supplies are not adequate to meet the needs in the basin. This problem became most evident during the 1976 drought, when many communities were forced to undertake voluntary conservation and rationing. Rural residents were compelled to haul water for domestic use and livestock. In conjunction with reduced crop yields, this greatly increased interest in irrigation. Finally, to a much lesser extent, the basin also has problems with water quality, erosion, fish and wildlife losses, and recreation.

IMPACT OF POSTULATED EFFECT

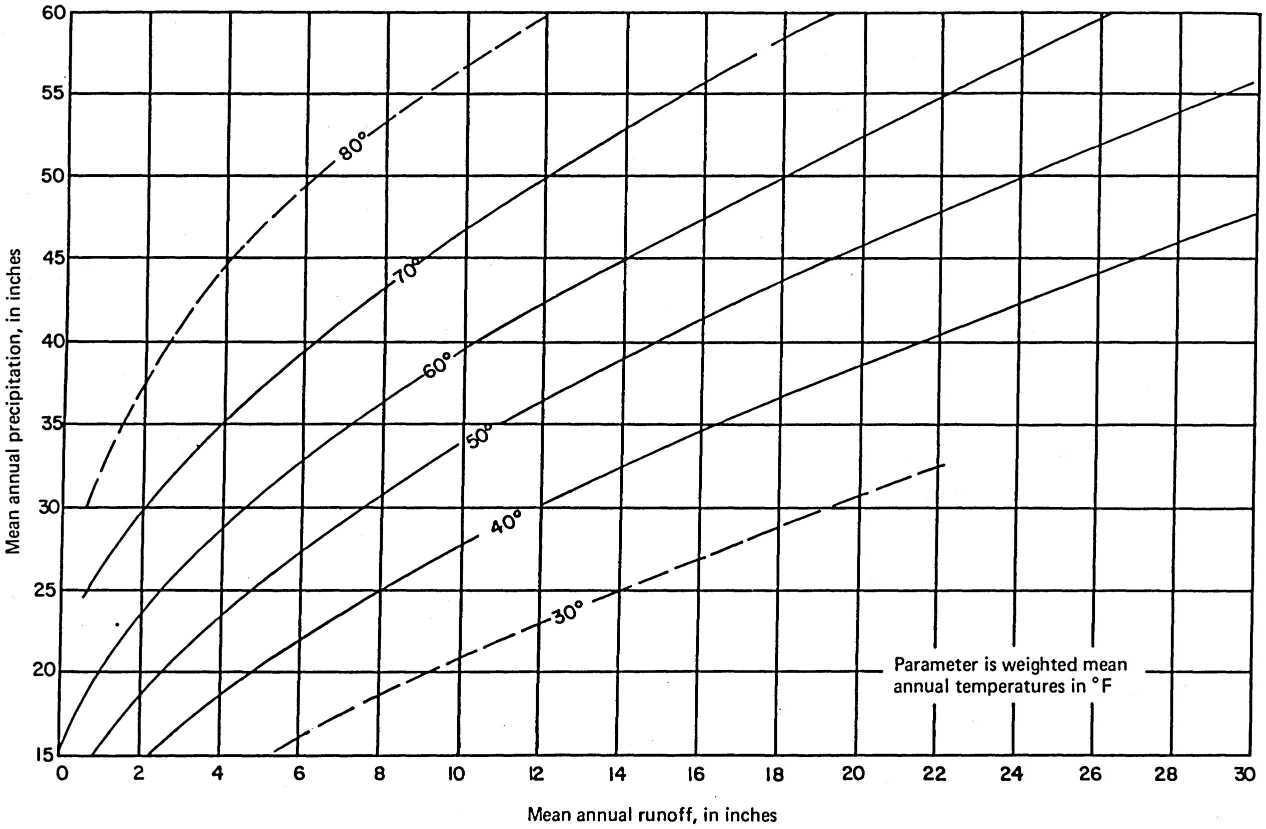
The postulated climate change would affect water resource management in two ways.[3] First, it would affect water supply through effects on lake levels, streamflow, and groundwater recharge. Second, it would affect the regional demand for water, including agricultural irrigation, municipal and industrial water requirements, livestock needs, and lawn watering. In the Red River basin, potential evapotranspiration losses generally exceed precipitation. Therefore, further changes in these variables may have an important and even synergistic effect on runoff by increasing water requirements and reducing the supply.

Effect on Supply

A carbon dioxide-induced climate change can have a significant effect on runoff in the Red River basin. This is largely because small changes in precipitation and temperature have a considerable amplification effect on runoff. For example, Nemec and Schaake, using the deterministic Sacramento soil moisture accounting model, superimposed a small climate change on two basins: one arid and one humid.[4] Both the dry basin in that study and the Red River basin receive approximately 21 inches of average annual precipitation. The dry basin, the Pease River basin at Vernon, Texas, has a drainage area of 3,490 square miles, a mean annual precipitation of 21 inches, and a mean annual runoff of 0.43 inches. They found that a 50 percent reduction in annual runoff would result from a 10 percent decrease in precipitation and a 4 percent increase in potential evapotranspiration (an approximately 2 degree Celsius increase in temperature), a significant reduction caused by a relatively moderate change in precipitation and temperature.

Langbein et al. developed an empirical relationship between average annual precipitation and average runoff as a function of weighted annual temperature, as shown in Figure 2.[5] This relationship was based on representative data from twenty catchments throughout the contiguous United States. The curves show average runoff reductions for a given decrease in average annual precipitation or an increase in average annual temperature. These curves can be used to superimpose a carbon dioxide-induced change in these climate variables on almost any basin to get a generalized evaluation. Stockton and Boggess used this relationship to assess the effects in the Souris-Red-Rainy region.[6] Their work assumes a uniform distribution of climate changes throughout the year. They found that average annual runoff would decrease by 45 percent with a 10 percent decrease in precipitation and a 2 degree Celsius increase in temperature, which agrees well with Nemec and Schaake for a dry basin. Table 1 shows the impact on annual flows at selected stations on the Red River. The reductions are very significant. The projected flow at Emerson could be as much as 500,000 acre-feet less than what presently occurs at Grand Forks, North Dakota.

Figure 2
RELATIONSHIP OF ANNUAL RUNOFF TO PRECIPITATION AND TEMPERATURE



After W. Langbein et al., *Annual Runoff in the United States*, U.S. Geological Survey Circular 52 (Washington, D.C.: Department of Interior, 1949).

Table 1
AVERAGE ANNUAL FLOWS IN THE RED RIVER BASIN UNDER PRESENT AND PROJECTED CONDITIONS
(In Acre-Feet)

	Present Average Annual Discharge	Scenario Average Annual Discharge
Fargo, North Dakota	401,400	220,800
Grand Forks, North Dakota	1,845,000	1,014,800
Emerson, Manitoba	2,387,000	1,312,800

Reservoirs are useful for mitigating the effects of climate variability. Nemec and Schaake investigated the impact on the reservoir storage-yield relation for the same arid and humid basins discussed previously.[7] The storage-yield relation is the amount of water that can be reliably released for a given storage capacity. The simulated streamflow data from the deterministic model were used as input to a large hypothetical reservoir. The reservoir was assumed to be full at the start of the period of record. Storage deficits were then observed. The hypothetical reservoir of concern, on the Pease River, would yield 10 percent of the mean annual flow with 90 percent reliability and a storage capacity equal to 10 percent of the mean annual historic flow. This study shows that a 10 percent reduction in precipitation and a 4 percent increase in potential evapotranspiration would result in a 25 percent reduction in reservoir yield.

In terms of water reserve, Stockton and Boggess, in their study of the Souris-Red-Rainy basin, found the ratio of total available storage to average annual flow for the present condition and for the scenario condition to be 1.7 and 3.1 respectively.[8] Hence, it would take approximately 1.7 years to refill the reservoirs to their capacity today were they to be drained, and 3.1 years to refill them to full capacity under a carbon dioxide-induced climate regime.

The real impacts of any reduction in flow should be evaluated in comparison to required demand. Stockton and Boggess have determined this for the Souris-Red-Rainy basin (see Table 2). This table suggests that the supply would be more than that required for water supply needs in the basin. However, it must be noted that the basin would be affected by a climate change not so much through changes in the average conditions as through changes in the frequency of extreme conditions. Drought incidence and the duration and intensity of drought would increase. Furthermore, variations in the requirement-supply ratio do not necessarily reflect the most relevant impacts, which are experienced during those times of the year when demand is high and supply is low. And it does not consider sequential variations in streamflow and demand. This may be important, considering that 75 percent of the average annual precipitation occurs between April and September.

In addition, the study by Nemec and Schaake further corroborates the serious impact of such a climate scenario on reservoirs in the Red River basin. Future projects would be required to compensate for this change and meet the projected increase in demand for the next planning period. Furthermore, the projected demand under the present climate would increase under the hypothesized climate due to increased evaporation and the need for additional agricultural irrigation.

Table 2
COMPARISON OF REQUIREMENT-SUPPLY RATIOS FOR
THE PRESENT CLIMATE AND FOR A WARMER, DRIER CLIMATE

Climate	Supply or Demand (in billion gallons per day)
Present	
Estimated mean annual supply[a]	6.1
Estimated mean annual requirement[b]	0.47
Warm/dry scenario	
Estimated mean annual supply[c]	3.4

Requirement-supply ratio, present: 0.07
Requirement-supply ratio, warm/dry scenario: 0.14

(a) Assumes zero groundwater overdraft.

(b) Projection through the year 2000.

(c) Assumes no increase in evaporation rate from the present climatic state.

Source: C. Stockton and W. Boggess, *Geohydrological Implications of Climate Change on Water Resource Development* (Fort Belvoir, Vir.: U.S. Army Coastal Engineers Research Center, 1979).

Effect on Demand

The overall impact of a warm, dry future would be significant in terms of water supplies, agricultural production, and corresponding water demands in the basin. The basin's water supply is used primarily for irrigation and municipal and industrial supply. Consumption in the Souris-Red-Rainy region is now about 120,000 acre-feet and is expected to increase to 500,000 acre-feet by the year 2000, due mostly to irrigation. Irrigation use is expected to increase from the present 15 percent to 74 percent, with withdrawals of 340,000 acre-feet in 1975 increasing to 600,000 acre-feet in the year 2000. Irrigated farmland now covers about 36,000 acres and is projected to expand to 311,000 acres by the year 2000.

The regional economy, however, could change depending on the magnitude and severity of the climate impact. For instance, impacts on agriculture would be widespread, although not all are undesirable. A longer growing season would be associated with the warmer temperatures and would favor a northward shift of the leading edge of wheat, corn, and soybean production. Such a shift would be economically desirable, even though it would be at the expense of existing crops. Soils in the area are suitable for corn and soybeans, although, in the absence of irrigation, moisture stress would limit the northward shift. Irrigation demands for surface waters are projected to remain at 50 percent of the permitted allocation, given constant climate conditions. However, a warm, dry future might conceivably double the present irrigation withdrawals were farmers to make full use of their permits to replace lost precipitation. And shifts in crop production to more water-dependent crops, such as corn and soybeans, would further exacerbate this problem.

A warm, dry future would exert the greatest water-related stress on the urban residents and businesses in the Red River basin, because most local potable water sources for the cities are already overexploited. Farmers would compound this problem were they to continue to tap deep aquifers for domestic supplies and double their present irrigation withdrawals with full use of existing permits. And the degree to which they would do so would depend on climate impacts elswhere. For instance, although the United States is improving its production of most agricultural products, Karl Butzer of the University of Chicago suggests that the net effect of decreased precipitation and increasing temperature would be decidedly negative, and that increased production in areas with improved climate conditions could not balance the losses in the high productivity zones.[9] The Red River Valley, then, would become even more important than it already is as a crop-producing region, with corresponding pressures on its water resources.

Inter-regional demographic change represents one important unknown in the larger climate change problem. For instance, if the agricultural base of the area expands, then the agriculture-related businesses that provide the economic stimulus in the region will likewise grow. Total population figures, then, would exceed current projections, and water demands would increase, imposing additional strains on water resources and the supply systems. Demand could seriously overtax supplies under these conditions and require that federal, state, and local interests coordinate and plan on a scale not now exercised in order to avert major crises and conflicts regarding the allocation and use of limited water resources. This latter action is made likely by joint control of these waters with Canada, and by local interests, which are very conscious of possible water shortages and which already compete with one another for the available water.

REACTION AND ADJUSTMENT

The likelihood of climate change must be acknowledged by water resource managers and the public if a corresponding reaction and adjustment in water resource management is to occur and be implemented in a timely and logical manner. A wait-and-see attitude is not warranted, as is shown by the Red River of the North reservoir experience mentioned above. Hence, in order to effectively ameliorate the impact of the predicted climate change, water resource managers must guide the public in a phased implementation strategy, one that systematically addresses the problem by revealing rational priorities for action through time. Such a strategy would result in a program through which society could achieve the most efficient water use by the most practical and available methods that are within economic reason.

The steps involved in the development of a strategy might include:

- Step 1 Identify the magnitude and severity of the water problem and establsh an overall water resource management goal or goals.
- Step 2 Inventory potential supply- and demand-oriented water resource measures.
- Step 3 Evaluate those measures by analyzing their cost effectiveness and the impacts of their implementation.
- Step 4 Identify actions to minimize any adverse impacts.
- Step 5 Design the specifics of a response and implementation program.
- Step 6 Prioritize and phase in an implementation strategy.

These steps need to be accomplished within the context of the larger public forum. Private individuals and organizations with an interest and authority need to be involved. The components of the response program need to be supported by an analysis in which costs, benefits, impacts, and institutional and legal implications are evaluated and the constraints to implementation identified. And, to be effective, the strategy must be an integral part of a regional effort involving federal, state, and local interests. The evaluation and development of a long-range program is a major portion of the strategy, although a separate element might be devoted to developing emergency actions to deal with floods and other short-term water crises not presently anticipated in the base condition.

Each of the strategy steps will be discussed; however, additional emphasis will be placed on steps 3, 4, and 5 in order to better define the types of response that are available, the magnitude of the economics and impacts, and the actions required to minimize those impacts. Finally, we provide general guidance as to the most effective Red River basin response.

Step 1: Identify the Problem and Establish Goals

Initial investigations should elaborate on current state, national, and international goals, particularly with regard to significant hydrological conditions, apparent water issues, the relative responsibilities of public and private water agencies, and the people to be involved. A reliable estimate of current and projected water inventories and demands would form an important basis for this effort.

Step 2: Supply- and Demand-Oriented Measures

Given the base condition in the Red River basin, a number of alternative measures could be components of a phased implementation strategy. An inventory of these measures is presented in Table 3. Attention is focused on an inventory of both the supply- and demand-oriented measures specific for the Red River basin. The list is certainly not all-inclusive; however, it does include the kinds of measures that might work in the Red River basin. Measures with the greatest potential for success are starred (*).

Step 3: Evaluate Measures

Impact evaluation involves the assessment of the economic, environmental, or social effects of particular measures, whether positive, as in the case of the economic benefits of additional water supply, or negative, as in the case of the environmental damage that might result from water transport. Precise estimates of the economic benefits of the measures identified in Table 3 are difficult to produce. This is because the effectiveness of each measure cannot be readily established and because changing interest rates, inflation, and strict regulations have resulted in rapidly increasing developmental costs. The lengthy period of time between the initial planning and the completion of a water project further complicates the estimate. For simplicity of discussion, the benefits of any measure will be assumed to be at least equal to its costs. Preliminary cost estimates for the supply-oriented measures are offered by category in Table 4. These estimates are very approximate. However, they are valid for discussion purposes, since they probably represent the overall magnitude of expense in 2030 associated with the identified measures. Demand-oriented measures are much less costly to develop; however, their overall beneficial impact is also less.

The estimated costs of such measures are large. However, the resulting economic impacts from inaction may be worse. Future business and economic activities, employment, public services, and the entire economic base may be seriously affected. For instance, rural communities and local farming operations would suffer increased transportation costs, less competitively priced products, and foregone profits were agricultural processors to become unwilling to locate in the basin.

Adaptive responses can adversely affect streamflows. Supply measures that utilize additional groundwater can be expected to result in increased streamflow caused indirectly by municipal and irrigation return flows. Storage measures, on the other hand, may reduce streamflows due to evaporation, seepage, and transmission losses. The overall impact of the above measures would be best determined on the basis of minimum in-stream flow requirement.

The social impacts of the adaptive measures include those impacts directly attributable to the measures themselves. These include the displacement of people, businesses, and farms; effects on life, health, and safety; and impacts on the quality of life. However, demographic impacts would also occur indirectly, as a result of economic change. The unavailability of water for irrigation would severely limit rural economic and demographic growth, as would the inability of small communities to exploit the economies of scale typical of those required for water facilities. Patterns of regional growth might be affected, depending on the location of available water facilities. Growth in urban areas probably would be limited by potential water shortages.

Table 3
POSSIBLE MEASURES FOR ADAPTING TO CLIMATE CHANGE

SUPPLY ORIENTED

Surface Reservoirs
1. Estimate the response of the five existing major reservoirs and revise their operation and management to best accommodate demand.*
2. Expand storage at Lake Ashtabula as a supplement.*
3. Develop new reservoirs on the Pembina, Red Lake, Sheyenne, and Wild Rice rivers, basing the design of storage on the largest historical drought conditions.

Groundwater Reservoirs
1. Use groundwater reservoirs for emergencies only.
2. Increase infiltration for groundwater recharge.
3. Identify new sources.

Interbasin and Intrabasin Transfers
1. Operate the Garrison Diversion project for water supply needs in the Red River basin.*
2. Develop an interbasin transfer system from Rainy Lake to the Red River basin.*
3. Use pipelines to transfer water from beach ridges on the east and hills on the west to the areas of need in the Red River Valley.*
4. Expand the rural water distribution system.*
5. Develop a water supply source from Devils Lake.*

Supply Facilities
1. Construct more off-channel storage facilities (utilize oxbows areas wherever possible).*
2. Enlarge existing supply facilities.*
3. Decrease water losses along conveyance structures.

Runoff Control
1. Increase water yield through soil conservation measures.
2. Improve snow retention in upland areas to increase infiltration and water storage.

Evaporation Control
1. Control evaporation through the timing and type of irrigation.
2. Use evaporation suppressants for the major bodies of water.

Other
1. Develop a weather modification program such as cloud seeding.
2. Protect prairie potholes, wetlands, and other natural areas from drainage.
3. Reestablish the windbreak program.

DEMAND ORIENTED

Use*
1. Introduce rationing.
2. Eliminate nonessential outdoor uses.

Recycling*
1. Implement conjunctive water use.

Economic Incentives
1. Use pricing mechanisms.
2. Introduce metering.

Technology*
1. Improve crop varieties, fertilizers, and pesticides.
2. Introduce more efficient equipment.
3. Modify facilities.
4. Adjust on-farm management.

Education Program*
1. Utilize newspaper articles and ads, bill inserts, and pamphlets.
2. Develop flyers, posters, and displays.
3. Implement customer assistance and school programs.

* Measures with the greatest potential for success.

Table 4
ESTIMATED COSTS OF SUPPLY-ORIENTED MEASURES

Measure	Estimated Cost Range
Surface reservoirs	$1.0-1.5 billion
Groundwater reservoirs	150-200 million
Interbasin and intrabasin transfers	2-5 billion
Supply facilities	40-50 million
Runoff control	5-10 million
Evaporation control	50-100 million
Other	10-25 million

Finally, increased groundwater withdrawals may cause the soil moisture zone to recede, causing plant and animal communities to suffer drought and leading to a breakup of ground cover. If significant, this could result in an increase in surface erosion from wind and runoff and in the loss of wildlife habitat. Silt and sediment loads in surface waters could also increase. On the other hand, wildlife would benefit from a more permanent source of water for habitat adjacent to storage facilities. Such surface waters would also provide nesting and feeding areas for waterfowl.

Step 4. Minimizing Measures

The adverse impacts of particular adaptive measures can be minimized through careful, measured development. Certain impact-minimizing measures might be considered to assure that the overall management program is most effective and has the greatest chance of success. These might include measures to:

- Establish critical plateaus as early-warning indices.
- Reevaluate forecasts on a periodic basis to ensure that no additional or unanticipated changes occur.
- Strengthen federal, state, and local response capabilities.
- Establish a disaster program with insurance options.
- Identify and utilize strategic irrigation scheduling.
- Use crop residue management for the control of soil erosion and dust storms.
- Prioritize measures in terms of their effectiveness, considering all impacts and costs.

Step 5: Design Response Program

It would be useful to consider the full range of options open to society, their advantages, disadvantages, and their potential impacts before adopting a program of response and implementation. The selection and implementation of a response might best occur in conjunction with studies designed to reduce any uncertainties surrounding impacts. Such studies might: (1) integrate the effects of climate change and their solutions into a broader, basinwide context, including all those infrastructure problems confronting the agricultural economy; (2) inventory and better identify the water needs on a case-by-case basis; and (3) adjust and provide midcourse corrections to any measures that are implemented.

Criteria that might help society to formulate the desired response include completeness, effectiveness, efficiency, and acceptability. Completeness is the extent to which a given measure provides for all the investments or other actions necessary to ensure the realization of the planned effects. Effectiveness is the capability of the measures to alleviate specified problems. Efficiency is cost effectiveness. Finally, adaptive measures are acceptable to the degree that they are compatible with existing laws, regulations, and public policies and are acceptable to state and local entities and the public.

Step 6: Prioritizing and Phase Response

The development of a strategy for effective implementation might be the final step in a water resource response to climate change. In the short-term, it might be useful to concentrate on study and selective research in order to develop a long-term response and complete this by the year 2000. A cooperative approach of all interested publics would best ensure that the water management strategy identified best represents what is needed to satisfy the needs of the basin.

Primary research and further studies that might be emphasized in the short-term include studies to:

- Refine the decision data and firmly establish the goals and objectives of the basin.
- Establish economic and technical criteria for measuring development.
- Define the effects a response will have on existing water systems.
- Improve the financing of a specific response.
- Identify guidelines for selecting and prioritizing the strategy's components.

Large-scale demonstration projects might be established as a key aspect of the research. Such demonstration projects could be undertaken in order to determine the desirability and effectiveness of various large-scale measures. It would be useful to mesh this with other basin programs, thereby minimizing any redundancy of effort.

Once developed the long-term portion of the program might constitute the final action and implementation effort in the basin. A number of changes might be necessary in the present approach to water management in the basin if such a long-term program was to become a reality. These changes might include modifications to existing practices and regulations, institutional adjustments, different authorities and/or responsibilities, updated methods for financing, etc. Whatever changes are necessary, water resource managers will have to redirect thier focus in order to help arrive at a unified, cooperative, and acceptable strategy to the future water resource conditions in the Red River basin.

SUMMARY

This paper has examined a water resource management approach for the Red River basin in the event of a carbon dioxide-induced climate change. The impacts on the water resources of the Red River basin from such a climate change would be relatively moderate on a scale of negligible, minor, moderate, and major. An additional water supply would be required to compensate for these impacts, which involve both reduced water resources and increased water demand. This additional supply would translate into a large dollar investment. Generally, lead times of up to thirty years would be required for the most ambitious of these projects; however, this schedule can be accelerated under emergency conditions.

The foregoing approach for reaction and adjustment does not involve a call for massive action in new directions. However, it does focus on the importance of efforts to ensure public and governmental awareness of the possibility of changed future environmental conditions. In this regard, strong leadership is required from government and the public if water resource systems are to respond to any such change.

Efforts to evaluate adaptive responses to possible climate change are very useful, especially efforts to identify where our knowledge is certain and complete and where it is weak. For example, it is clear that more research and observation needs to be done, not only to define with more certainty the direction and magnitude of carbon dioxide-induced climatic change, but also to better define the most likely hydrological response to it. The lesson of this paper, however, is that one must not assume unchanging climate conditions. Water resource managers must anticipate such changes, not merely react to them.

NOTES

1. R. Revelle and P. Waggoner, "Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States," in *Changing Climate*, Carbon Dioxide Assessment Committee, National Research Council (Washington, D.C.: National Academy Press, 1983).

2. See Carbon Dioxide Assessment Committee in note 1 above; and S. Seidel and D. Keyes, *Can We Delay a Greenhouse Warming?* (Washington, D.C.,: U.S. Environmental Protection Agency, 1983).

3 H. Schwarz, "Climatic Change and Water Supply: How Sensitive is the Northeast?" in *Climate, Climatic Change and Water Supply*, Geophysical Research Board, National Academy of Sciences (Washington, D.C.: National Academy of Sciences, 1977).

4. J. Nemec and J. Schaake, "Sensitivity of Water Resource Systems to Climate Variation," *Journal of Hydrological Sciences* 27 (1982): 327.

5. W. Langbein, et al., *Annual Runoff in the United States*, U.S. Geological Survey Circular 52 (Washington, D.C.: Department of Interior, 1949).

6. C. Stockton and W. Boggess, *Geohydrological Implications of Climate Change on Water Resource Development* (Fort Belvoir, Vir.: U.S. Army Coastal Engineers Research Center, 1979).

7. See note 4 above.

8. See note 6 above.

9. K. Butzer, "Adaptation to Global Environmental Change," *Professional Geographer* 32 (1980): 269; see also H. Frazer, "Making the Most of Climate Change," paper presented to Futurescan 83, Saskatoon, Saskatchewan, June 8-10, 1983.

CAN COASTAL COMMUNITIES ADAPT TO A RISE IN SEA LEVEL?

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INTRODUCTION

The greenhouse effect poses a fundamental question: will its adverse consequences unfold more rapidly than our ability to address them? Although the authors of this book disagree on how we should address the challenge, we are united by a common committment to ensure that our ability to address the consequences prevails. The possible solutions fall broadly into two categories: (1) slow or prevent global warming; and (2) accelerate the process by which humanity learns to live on a warmer planet. Both of these efforts require considerable research and policy implementation. Williams et al., and Johansson and Williams examine technical solutions by which we might shift away from fossil fuel combustion. Mintzer and Miller and Ciborowski and Abrahamson discuss policy options through which such a shift could be encouraged. Crist and Reinartz, Riebsame and this paper examine options through which society could prepare for the consequence of a global warming.

Until now, most policy-oriented discussions of the greenhouse effect have centered on efforts to stop or slow the warming. Such an emphasis has been warranted by the growing consensus that the greenhouse effect is the most serious environmental threat that confronts mankind, short of nuclear war. As Roger Revelle suggested decades ago, mankind is conducting a dramatic, uncontrolled experiment on the planet. The momentum behind this experiment is very great and is almost synonomous with industrial society. By contrast, the constituency that would like to slow or stop this experiment is very small. Unfortunately, discussions of a global warming appeal to a very limited audience; most people are not interested in the greenhouse effect, energy policy, or environmental policy, despite their importance. History may show that the smaller constituency, which includes most of the authors of this volume, was right.

However, academic foresight alone will not solve this problem unless we can draw others into the constituency. Thus, the actions that are necessary to prevent a greenhouse warming from proceeding past the danger point include many of the actions that are necessary for society to adapt to the more moderate consequences that may occur in the meantime. Most important is the need for public awareness. Groups affected by the greenhouse effect must understand its implications before they can work to stop the warming or prepare to live with it.

This paper examines the impacts of sea level rise on particular communities and the measures that can be taken to avert the more serious consequences. We focus on sea level rise not because it is the most important consequence of global warming but because it is the consequence for which our understanding of the impacts, constituencies, and possible responses is greatest. We describe the probable impact of the greenhouse effect on sea level; the physical and economic impacts of sea level rise on

Charleston, South Carolina, and possible responses; the impacts on wetlands loss in Louisiana; and the relationship between efforts to adapt to a global warming and efforts to prevent it. We conclude with three recommendations.

THE EMERGING IMPORTANCE OF RISING SEA LEVEL

Since the beginning of recorded history, sea level has risen so slowly that, for most practical purposes, it has been constant. This slow rate of rise has allowed plants and animals to thrive along coasts. At the mouth of the Mississippi River, for example, it has permitted the sediments washing down the river to form a great delta with thousands of square miles of salt marshes and cyprus swamps supporting alligators, eagles, fur-bearing animals, water fowl, and half of the nation's shellfish catch. Civilization has prospered along the water. Although society has long recognized the dangers of Neptune's occasional outbursts, it could always be confident that the waters would recede to their original level after each storm passed.

Recently, however, the assumption that sea level changes are unimportant to today's activities has been called into question. Along much of the Atlantic and Gulf coasts of the United States, relative sea level rise, which accounts for subsidence, has been about 1 foot in the last century. Coastal geologists have estimated that significant erosion, such as has been experienced along most recreational beaches, would be expected from such a sea level trend. The problem has been most severe in Louisiana, which has been losing over 40 square miles of wetlands each year, largely due to a relative sea level rise estimated at 3 feet per century. Furthermore, reports by the National Academy of Sciences and the U.S. Environmental Protection Agency have estimated that the global sea level could rise 1.5 to 5 feet in response to the expected greenhouse warming. By contrast, it has risen only 4 to 6 inches in the last century.

Local governments are beginning to formulate strategies in response to current sea level trends. The decisions they make could involve millions of dollars per mile of shoreline and may involve controversy regarding individual and community rights. These officials view the prospect of accelerated sea level rise from greenhouse warming as a sword that could cut either way. It may provide them with the momentum necessary to enact measures that are necessary anyway; but it could also overwhelm their efforts, or, if subsequently proven to be a false alarm, make their foresight look foolish. They want to know more about sea level rise but fear that they may have to act before they know enough.

THE IMPACT OF THE GREENHOUSE EFFECT ON SEA LEVEL

The earth's temperature is primarily determined by the amount of sunlight the earth receives, the amount of sunlight it reflects, and the amount of heat retained by its atmosphere. Visible light from the sun penetrates the atmosphere and warms the surface, which radiates heat back to space. Carbon dioxide, water vapor, oxygen, and a few trace gases absorb some of this outgoing radiation, keeping the earth about 30 degrees Celsius warmer than it would otherwise be. Because the atmosphere allows light to penetrate but retains heat, much like the glass panels of a greenhouse, this phenomenon is known as the greenhouse effect.

Our understanding of the greenhouse effect has become more important as we have come to realize that humanity is increasing the atmospheric concentrations of the greenhouse gases. Atmospheric concentrations of carbon dioxide are expected to double in the next century. The National Academy of Sciences has concluded that such a doubling will raise the earth's average temperature by 1.5 to 4.5 degrees Celsius (3 to 8 degrees Fahrenheit).[1] The World Meteorological Organization and others estimate that emissions of methane, nitrous oxide, chlorofluorocarbons, and other trace gases will further warm the planet an amount equal to 50 to 100 percent of the expected carbon dioxide-induced warming.[2]

The expected global warming could raise the sea level by three mechanisms: thermal expansion, melting, and deglaciation. First, the upper layers of the oceans would expand with additional atmospheric heating. Second, the warmer temperatures would melt mountain glaciers and polar ice, with melt water running off into the oceans. Finally, the West Antarctic, East Antarctic, and Greenland ice sheets could begin to melt or even collapse into the oceans as the atmosphere warms, raising sea level by displacing ocean water. For example, glaciologists have suggested that the West Antarctic Ice Sheet could completely disintegrate over a period of several centuries, raising sea level about 20 feet.

Two recent reports have estimated the possible rise in sea level in the next century. In the recent National Academy of Sciences report, Revelle estimated a worldwide rise of 2.3 feet by 2080 from thermal expansion and the melting of Greenland and mountain glaciers.[3] While noting that the deglaciation of Antarctica could add 6 feet per century, on an average, beginning in the middle of the next century, he declined to add any Antarctica contribution to his sea level projection.

In a recent report by the U.S. Environmental Protection Agency, Hoffman et al. developed a variety of scenarios which take into account each of the major sea level rise determinants and the uncertainties that attach to each.[4] Although they covered a much wider variety of possibilities than Revelle to predict the rise from thermal expansion, their methods for projecting the contributions of glaciers were extremely crude. They did, however, consider the possibility that an increase in snowfall in Antarctica would offset melting and deglaciation. They concluded that the existing evidence indicates that increased melting in Antarctica would overwhelm additional snowfall, and they projected that the most likely rise in sea level would be 0.9 to 1.3 feet by 2025 and 3.0 to 4.4 feet by 2075. However, they did emphasize the necessity of additional model runs, and stated that a rise as low as 1.8 feet or as high as 11.3 feet by 2100 cannot be ruled out.

CHARLESTON CASE STUDY

This section summarizes the results of a study directed by the Environmental Protection Agency. The study considered the physical and economic impacts of sea level rise, the actions that people could take in response to these effects, and the value of policies that anticipate them. Timothy Kana and others with the Research Planning Institute estimated the physical impacts; Michael Gibbs of ICF Incorporated estimated the economic impacts; and Robert Sorenson of Lehigh Unversity, formerly of the U.S. Army Corps of Engineers, defined various engineering responses.[5]

The case study of Charleston used four scenarios of sea level rise, shown in Table 1. The trend scenario assumes a continuation of Charleston's historical rate of change in relative sea level. The low, medium, and high scenarios are consisten with the estimates of Revelle and of Hoffman et al.[6] The high and trend scenarios are both extremely unlikely but cannot be ruled out.

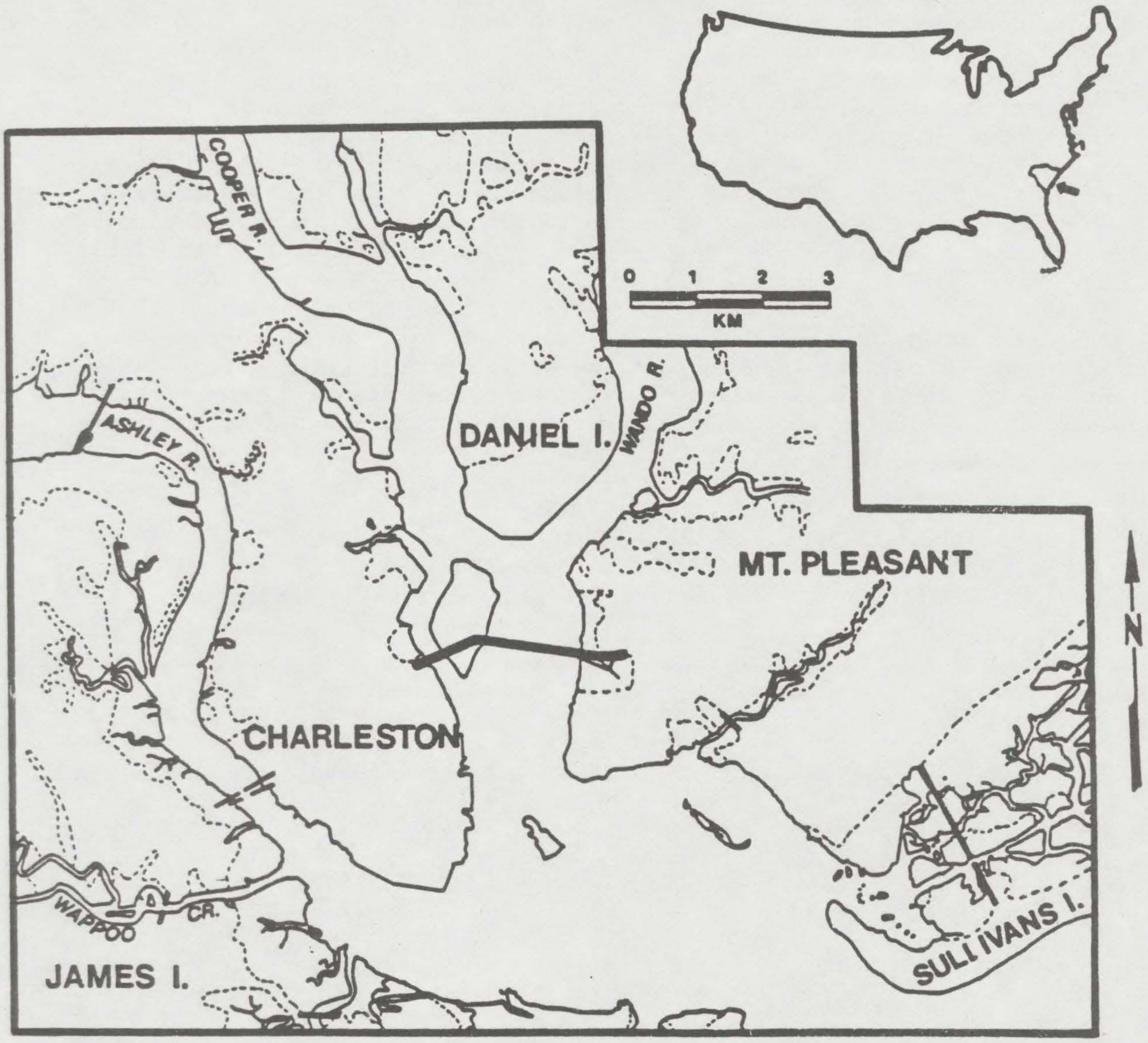
Table 1
SEA LEVEL RISE SCENARIOS FOR CHARLESTON
1980 TO 2075
(in centimeters [feet])

Scenario	1980	2025	2075
Trend	0	11.2 [0.4]	23.8 [0.8]
Low	0	28.2 [0.9]	87.6 [2.9]
Medium	0	46.0 [1.5]	159.2 [5.2]
High	0	63.8 [2.1]	231.6 [7.6]

The Charleston study area consists of the land around Charleston Harbor, which is formed by the confluence of the Cooper, Ashley, and Wando rivers (see Figure 1). It includes all of Charleston and parts of North Charleston, Mount Pleasant, Sullivans Island, and James Island. Lower Charleston Peninsula, in the center of the study area, has a maximum elevation of only 20 feet above sea level and includes several low-lying areas that have been reclaimed from the harbor. North Charleston, on the upper part of the peninsula, has elevations up to 30 feet. West Ashley, to the west of the peninsula, has elevations of 10 feet or less, and Mount Pleasant has elevations between 10 and 30 feet. Sullivans Island is a narrow barrier island with an average elevation of less than 8 feet.

Although the Charleston area does not have a history of extensive hurricane damage, its 6-foot tidal range exposes parts of the area to periodic flooding. The only major flood protection structure in Charleston is the Battery, located at the tip of the Lower Charleston Peninsula. This sea wall provides protection from a ten-year, but not a one hundred-year, storm.

Figure 1
CHARLESTON STUDY AREA



Reprinted with permission from T. Kana et al. in M. Barth and J. Titus, eds., *Greenhouse Effect and Sea Level Rise: A Challenge for this Generation* (New York: Van Nostrand Reinhold, 1985), page 107.

The Impacts of Sea Level Rise if Charleston Fails to Prepare

The physical consequences of sea level rise can be broadly classified into four categories: shoreline retreat caused by erosion and inundation; increased flooding from storms; higher water tables; and salt intrusion into surface and fresh water. A rise in sea level would cause shorelines to retreat for two reasons. First, low-lying land would be inundated. Second, some areas with elevation sufficient to avoid inundation could be lost to erosion. Higher water levels would allow storm waves to erode beaches further inland than present levels allow, and they would reduce the efficiency of calm waves that normally dredge material off the bottom and push sand back onto the beach. Coastal geologists have shown that a rise in sea level of one foot can erode beaches from one hundred to several hundred feet.

Since the water levels evident during storms could increase in elevation by the amount of sea level rise, sea level rise also would increase storm damage. This would increase the area of land vulnerable to storm damage and increase flooding in areas that are already in flood plains. Furthermore, beach erosion from sea level rise could leave some areas much more vulnerable to damaging storm waves. The case study did not focus on salt intrusion.[7]

Kana et al. estimated shoreline retreat and flooding, assuming that no additional protective measures, for instance sea walls or bulkheads, would be implemented. They also assumed that the existing protective structures would withstand the increased stresses of sea level rise. Table 2 summarizes the impacts of sea level rise on shoreline retreat and on the ten- and one

Table 2
CHARLESTON STUDY AREA: SUMMARY OF DIRECT PHYSICAL IMPACTS BY SCENARIO
(In Square Kilometers [Percent of Total Area])

Scenario	Year	Area Lost to Shoreline Movement	Area in 10-Year Flood Zone[a]	Area in 100-Year Flood Zone[a]
No change	1980	--[b]	30.8 [32.9]	59.2 [63.2]
Trend	2025	1.8 [1.9]	32.9 [35.1]	61.1 [65.2]
	2075	3.9 [4.2]	34.9 [37.2]	62.9 [67.1]
Low	2025	4.9 [5.2]	35.7 [38.1]	63.7 [68.0]
	2075	14.2 [15.1]	45.0 [48.0]	71.2 [76.0]
Medium	2025	7.8 [8.3]	38.6 [41.2]	66.0 [70.4]
	2075	28.7 [30.6]	58.5 [62.4]	78.7 [84.0]
High	2025	13.0 [13.9]	41.4 [44.2]	68.4 [73.0]
	2075	43.0 [45.9]	69.4 [74.1]	83.9 [89.5]

Note: One square kilometer equals 0.38 square miles.

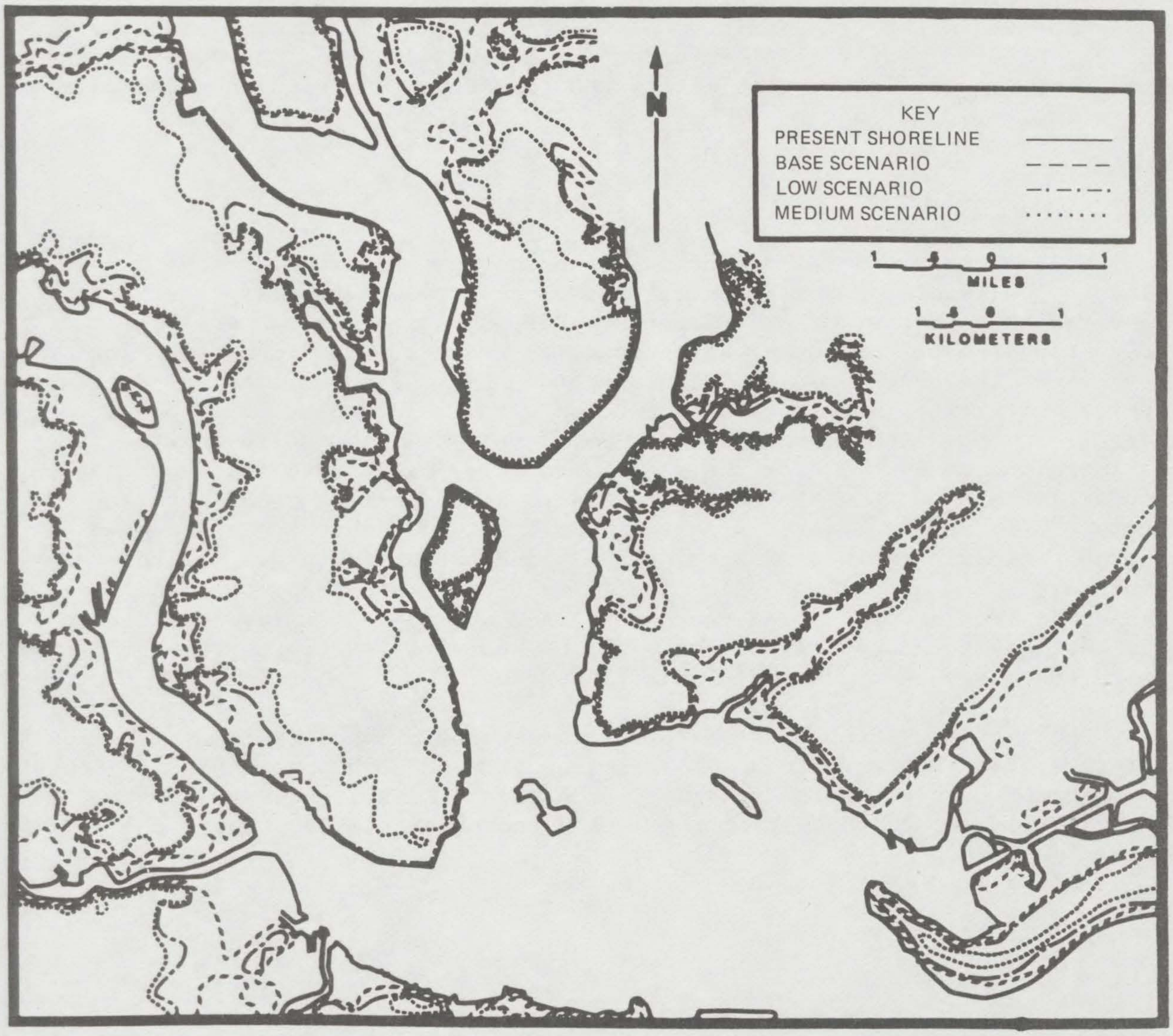
(a) Includes area lost due to shoreline movement.

(b) Total area in 1980 is 275 square kilometers.

hundred-year flood zones for the years 2025 and 2075 under the four scenarios. The study area would lose 4.2 percent of its land by 2075 were current trends to continue. Under the low scenario, it would lose 5.2 percent of its land by 2025 and 15.1 percent by 2075; under the medium scenario, it would lose 8.3 percent by 2025 and 30.6 percent by 2075. The impacts of the high scenario in 2025 are slightly less than those in 2075 for the low scenario.

Figure 2 illustrates the projected locations of mean spring high water (the area flooded once every two weeks), the seaward limit for development in the area under the low and medium scenarios for 2075.

Figure 2
SHORELINE RETREAT UNDER THE LOW AND MEDIUM SCENARIOS FOR 2075



Reprinted with permission from T. Kana et al. in M. Barth and J. Titus, eds., *Greenhouse Effect and Sea Level Rise: A Challenge for this Generation* (New York: Van Nostrand Reinhold, 1985), p. 133.

The developed portions of the Charleston Peninsula protected by The Battery would not be threatened by shoreline movement under the low scenario. However, this structure would not prevent the inundation of a significant portion of the peninsula by 2075 under the medium scenario. Although a substantial sediment supply makes it less vulnerable to erosion than the typical East Coast barrier island, Sullivans Island could lose the first one or two rows of houses along the ocean by 2025 in the medium scenario, and it would migrate landward by its own width by 2075, destroying virtually all existing development.

About one-third of the study area is currently in the ten-year floodplain, and about two-thirds is within the one hundred-year floodplain. Almost half of the study area would be in the ten-year floodplain, and three-quarters in the one hundred-year floodplain by 2075 under the low scenario, even though the projected effects on flood-zone boundaries are small for both the low and medium scenarios in 2025. Over 60 percent of the study area would be within the ten-year floodplain by 2075, and 84 percent would be in the one hundred-year floodplain under the medium scenario. By 2075, a ten-year storm would flood approximately the same area that a one hundred-year storm would flood today.

Economic Impacts

No one can predict how individuals and communities would respond to a rise in sea level. However, certain assumptions about the response are required to estimate economic impacts. Responses include sea walls, levees, beach nourishment, and other engineering approaches, as well as planning responses like changes in the developmental mix, the curtailment of developmental activities, and the abandonment of vulnerable areas. In the low scenario, Gibbs assumed that actions would only be taken to reduce the rate of shoreline movement. For the medium scenario, he assumed that more actions would be taken because the physical impacts would be larger and apparent sooner: (1) in 2020, structures would be built to reduce shoreline movement in the peninsula and West Ashley-James Island areas; (2) a sea wall on the peninsula would be built to stop shoreline retreat and to protect the peninsula from a one hundred-year storm in 2060; (3) a low levee system in the West Ashley-James Island area would be built to reduce the rate of shoreline movement by an additional 75 percent.

Table 3 shows Gibbs' estimates of the economic impacts. Under the low scenario, the impact would be $1.2 billion through 2075, more than 17 percent of the projected economic activity in the area. This figure would exceed $1.9 billion, or 27 percent of the area's economic activity, under the medium scenario.

Table 3
ECONOMIC IMPACTS OF THREE SEA LEVEL RISE SCENARIOS
ON THE CHARLESTON STUDY AREA
(In Millions of 1980 Dollars)

Scenario	1980-2025	1980-2075
Low	280 (4.9)*	1,250 (17.3)
Medium	685 (12.0)	1,910 (26.5)
High	1,065 (18.7)	2,510 (34.8)

Note: Evaluated at a 3 percent discount rate.

*Impact as a percentage of total economic activity in the study area.

Planning for Sea Level Rise

The adverse impacts of sea level rise can be reduced if communities and individuals prepare for them. Various engineering and planning options are open to society in anticipation of sea level rise. Engineering responses to the physical impacts of sea level rise concentrate on holding back the sea. The "hard options" include bulkheads, sea walls, levees, revetments, and off-shore breakwaters. Soft engineering methods include beach nourishment (pumping sand) and dune and marsh building.

Planning actions differ from engineering actions in that they do not attempt to influence the physical impacts of sea level rise; instead, they try to adapt to these impacts. Examples of planning responses include:

- the establishment of land-use policies that permit only certain types of development in low-lying areas;
- a requirement that sea level rise be taken into consideration in new construction;
- the acceptance of new development only in areas that can be protected later or are unlikely to be affected by sea level rise;
- the establishment of post-disaster plans that prohibit rebuilding or repairing storm-impacted properties likely to be lost to erosion from sea level rise;
- conditional zoning and other mechanisms to postpone investment in areas of potential hazard until we know how much the sea level will rise.

Each of these actions may be valuable in the Charleston study area. For example, sea walls and bulkheads may be appropriate for the peninsula area. Post-disaster plans could be a reasonable approach for coastal barriers such as Sullivans Island.[8]

The Value of Anticipating Sea Level Rise

Table 4 compares possible responses to sea level rise with actions that might be taken to prepare for sea level rise, as prepared by Gibbs. Under the low scenario, Charleston builds a sea wall around the peninsula by 2030; West Ashley-James Island undertakes an enclave strategy, in which all new development after 2050 takes place in a protected area around Wappo Creek and investments near the first bend in the Ashley River are reduced. The actions examined for the medium scenario are similar to those for the low scenario, but the community takes them sooner.

The overall effects of the various anticipatory actions on the study area are as follows:

- Charleston Peninsula: less area is lost to shoreline movement and less storm damage occurs because a sea wall is built sooner;
- West Ashley-James Island: the enclave strategy results in a small, protected, and intensively developed area;
- Mount Pleasant: losses due to shoreline movement are reduced by incorporating future sea level rise into current and future designs;
- Sullivans Island: investment is reduced so that when losses do occur there is less development to be lost or damaged.

Table 5 reports Gibbs' estimates of the economic impact were the sea level rise to be anticipated. The economic impact of the medium scenario sea level rise without such anticipatory responses would be $1.91 billion. Anticipatory responses to sea level rise could enable the community to reduce this impact by 62 percent. That is, the estimated value of anticipatory policies is $1.18 billion.

Anticipatory actions would require cooperation among the jurisdictions in the area. Protection of the peninsula would involve the cities of Charleston and North Charleston and the federally owned naval facility. The area west of the Ashley River includes James Island, the City of Charleston, and some unincorporated land controlled by the county. The amount of time necessary to coordinate the diverse interests is so great that today is not too soon to begin considering actions necessary twenty-five years in the future.

Table 4
ACTIONS TAKEN IN RESPONSE TO AND IN ANTICIPATION OF SEA LEVEL RISE

	Charleston Peninsula	West Ashley/ James Island	Mt. Pleasant	Sullivans Island
		LOW SCENARIO		
Shoreline retreat				
Response	Reduce rate 75% after 2050	Reduce rate 75% after 2050	No action	No action
Anticipation	Reduce rate after 2030	Enclave strategy after 2050	Stop retreat in 1990	No action
Storm surge				
Response	No action	No action	No action	No action
Anticipation	Stop below 100-year storm surge after 2030[a]	No action	No action	No action
Investment				
Response	No action	No action	No action	No action
Anticipation	No action	No action	No action	Stop in 2070
		MEDIUM SCENARIO		
Shoreline retreat				
Response	Reduce rate 50% after 2020 Stop retreat in 2060	Reduce rate 50% after 2020, 75% after 2060	Stop retreat in 2050	No action
Anticipation	Reduce rate after 2010	Enclave strategy	Stop retreat in 1990	No action
Storm surge				
Response	Stop retreat in 2060 for surges below 100-year elevation[b]	No action	No action	No action
Anticipation	Stop below 100-year storm surge in 2010	No action	No action	No action
Investment				
Response	No action	No action	No action	Stop in 2070
Anticipation	No action	No action	No action	Stop in 2030

(a) Elevation of 18 feet.

(b) Elevation of 22 feet.

Table 5
THE VALUE OF ANTICIPATING SEA LEVEL RISE

	Economic Activity	Economic Impact Relative to Trend Scenario[a]	Value of Planning for Sea Level Rise
Low scenario			
No planning	5,969	1,250	---
Planning	6,775	440	810 (65)[b]
Medium scenario			
No planning	5,305	1,910	---
Planning	6,485	730	1,180 (62)
High scenario			
No planning	4,705	2,510	---
Planning	6,105	1,110	1,400 (56)

Note: Impacts are in millions of 1980 dollars evaluated for a 3 percent discount rate after inflation and taxes.

(a) Value of economic activity in trend scenario was estimated at $7,215 billion.

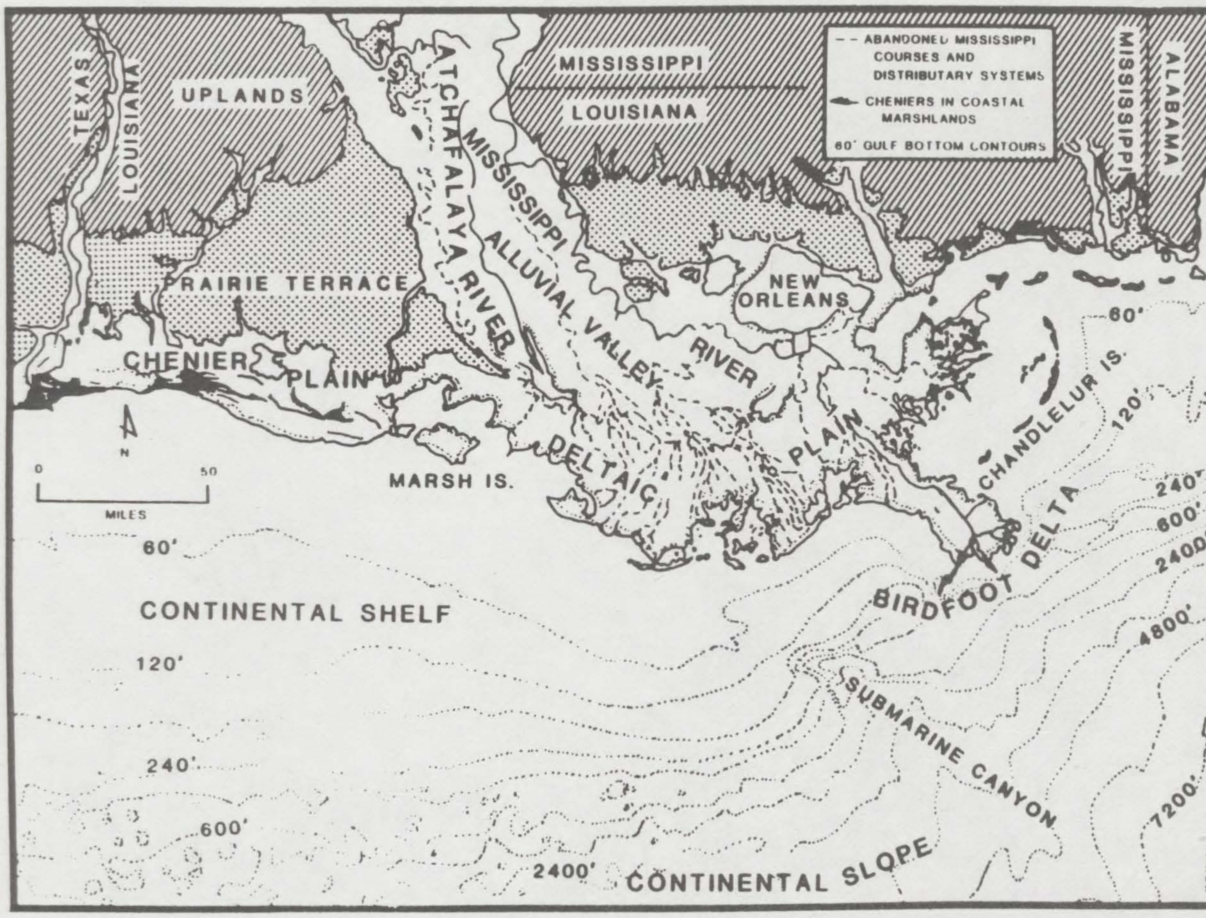
(b) Value of planning as a percentage of the impact incurred in the zero planning case.

THE IMPORTANCE OF SEA LEVEL RISE TO LOUISIANA

The Mississippi Delta (see Figure 3) was formed over thousands of years as the river deposited sediment along the river's mouth at the Gulf of Mexico. On both sides of the main channel, high ridges gradually formed and advanced into the sea; low-lying marshes formed farther away from the channel. Since this process lengthened the river's course, the river occasionally diverted its flow into a shorter route to the sea. Previous main channels include Bayou La Forche and a route through Lake Pontchartrain. Thus, coastal Louisiana has several thin ridges along present and former distributaries of the river, along which most development has occurred. In between are thousands of square miles of wetlands on which the seafood industry, the Cajun culture, many fur-bearing animals, and birds, including eagles, depend.

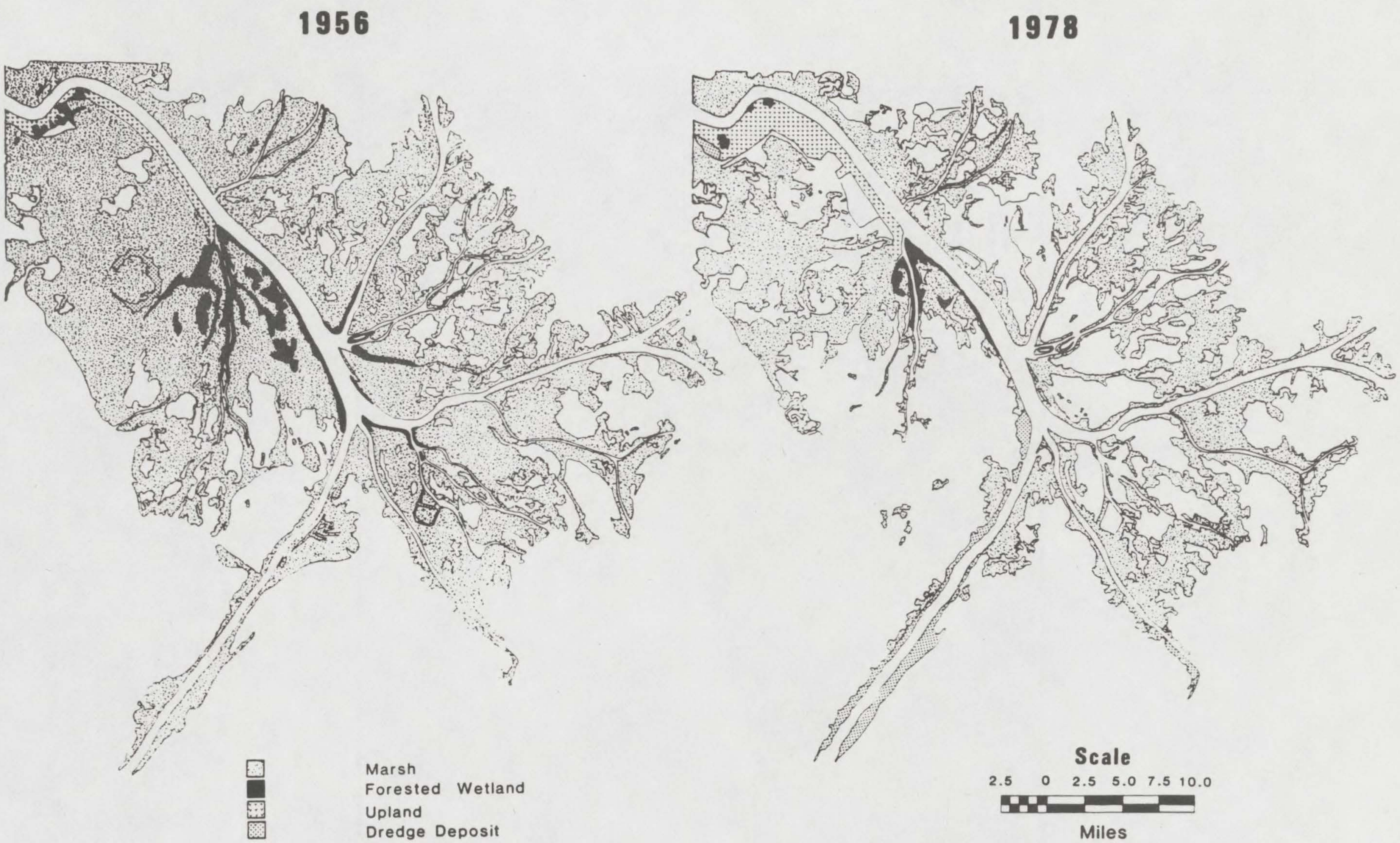
Most of us learned in school that the Mississippi Delta is growing into the Gulf of Mexico. Unfortunately, this is no longer the case. The natural processes that created and sustained the wetlands are being thwarted by human activities.[9] For instance, occasional river flooding used to deliver sufficient sediment for the marshes to keep pace with natural subsidence, estimated at a few feet per century, and with the slow rate of sea level rise. But levees have now been built along the distributaries to protect developments from floods, depriving the wetlands of sediment. These levees do not extend completely into the Gulf. However, channels for navigation purposes, upstream reservoirs, and the diversion of water away from the minor tributaries have all acted to prevent the outer marshes from receiving sediment. Hence, the sediment that does travel down the river appears to go mainly out the main channel and off the continental shelf.

Figure 3
THE MISSISSIPPI DELTA



As a result, Louisiana is now losing over forty square miles of land per year (see Figure 4). The barrier islands are breaking up, salt marshes are eroding away, and freshwater swamps are turning into open water. Furthermore, salt is intruding into freshwater swamps. At the current rates, two coastal parishes may completely vanish in the next century, as will most of the wetlands in Louisiana. Public officials regularly discuss the possibility that Baton Rouge will be on the coast, that Interstate 10 will be a causeway through the Gulf of Mexico, and that the nation's largest wetlands system and the species and industries that depend on it will be destroyed. Louisiana, it should be noted, has half of America's coastal wetlands and produces over one-quarter of the nation's fish catch.

Figure 4. THE ACTIVE MISSISSIPPI DELTA, 1956 AND 1978



Reprinted from "Wetland Changes in the Mississippi Active Delta, 1956-78," U.S. Fish and Wildlife Service, Slidell, La.

In response to this development, the state of Louisiana has created a $40 million trust fund to research and test methods of mitigating and halting marsh destruction. Individual parishes are also spending millions of dollars per year to develop their own strategies. They are seeking increased aid from the Corps of Engineers, which has been involved directly or indirectly with most activities involving wetlands creation and destruction.

However, the state of Louisiana, along with its parishes, needs better sea level rise projections than are currently possible.[10] For instance, if the rise is likely to be 4 feet in the next century, the state will have to either resign itself to the loss of virtually all of its salt marshes and a major coastal dike, or immediately develop a master plan for the supply of sediment to its wetlands. On the other hand, the current progress may be sufficient to maintain at least part of the wetlands if the rise is going to be 1 foot. But even a 2-foot rise in sea level could drastically change the relative merits of the response strategies now being formulated for, for example, Terrebonne Parish, which has a life expectancy of seventy rather than one-hundred years under such a scenario.[11] Given the long lead time needed to gain a public consensus on the massive public works that would have to be developed and/or dismantled, the decisions that these officials plan to delay until 2020 might be necessary in the 1990s.[12] As a result, Terrebonne Parish has become the first local government in the nation to officially acknowledge the importance of the greenhouse effect to its own activities and to call for additional federal research.[13]

OTHER IMPACTS OF SEA LEVEL RISE

Research has been undertaken on the impact of sea level rise on other activities. A 2.4-foot rise in sea level would allow salt water to intrude 10 to 20 miles upstream in the Delaware River, possibly contaminating parts of the Potomac-Raritan-Magothy aquifer in New Jersey, as well as Philadelphia's surface water supply during drought.[14] Significant beach erosion would occur at important beach resorts, including Ocean City, Maryland,[15] and Sea Bright, New Jersey,[16] and elsewhere.[17] Public works such as seawalls and coastal stormwater drainage systems would require important design changes.[18] A rise in sea level could also destroy much, if not most, of the coastal wetlands in the United States.[19] A 5-foot rise could drown 80 percent of the marshes in Charleston, South Carolina, which are less vulnerable to sea level rise than coastal marshes elsewhere.[20]

PLANNING FOR SEA LEVEL RISE VERSUS PREVENTION

The Charleston case study and the situation in Louisiana indicate that the greenhouse effect and sea level rise will have multibillion-dollar impacts on society. Our analyses indicate that better forecasts and planning could enable coastal communities to avoid a large portion of the economic and environmental losses associated with sea level rise. Nevertheless, we should not lose sight of the fact that many adverse impacts would not be avoided. Although planning could save Charleston hundreds of millions of dollars, hundreds of millions of dollars in damages would still be incurred. The majority of Louisiana's wetlands will still be lost, even though planning would allow Louisiana to save a portion.

Reprinted from "Wetland Changes in the Mississippi Active Delta, 1956-78," U.S. Fish and Wildlife Service, Slidell, La.

Hence, coastal officials in Louisiana and other low-lying areas are aware that they would lose even if greenhouse warming proves to be beneficial to society at large. Then why are coastal communities trying to adapt to sea level rise rather than advocating reduced emissions of the greenhouse gases? Influence and expertise are probably the major reasons. Local officials have little control over the composition of the earth's atmosphere, but they can have a major impact on the location of new construction and on the destruction of marshes. The officials are not experts on the technologies necessary to prevent emissions of the greenhouse gases. But communities that witness shoreline retreat and marsh disappearance due to sea level rise understand the need to prepare for the possibility that these trends will accelerate. People who are not interested in long-term energy or climate issues will listen when told that they can save money or wildlife through near-term adaptation, a fact that may favor an adaptive over a preventive response. Finally, a rise in sea level of a foot or so is probably inevitable because of the long lags in social, oceanic, and glacial cycles. Coastal cities would be greatly aided by efforts to limit sea level rise in the future, but they must consider responses to the rise that cannot be avoided.

Nevertheless, people who favor efforts to prevent a greenhouse warming should not view adaptive efforts as counterproductive. As coastal and other communities investigate adaptive measures in the next decade, they will learn which of the impacts are favorable, which can be mitigated through adaptive responses, and which must be avoided. If most of the impacts fall into the latter category, these people will make their voices heard. Then, and only then, will it be politically feasible to prevent a greenhouse warming. Thus, efforts to promote short-run adaptation need not divert attention from the need to prevent the greater warming that could occur in the long run. Rather, they will give the preventive argument a more thorough hearing, raising public awareness as to what the greenhouse effect means to particular individuals, resulting in better understanding of the overall net costs of climatic change to society.

CONCLUSION

Case studies of Charleston and other coastal communities show that the impact of a couple of feet of sea level rise could be extremely costly. By anticipating these impacts, individuals and communities can avoid many of the adverse consequences, particularly if additional research is conducted to provide them with better forecasts. In the long run, society may decide to take actions to prevent a very large rise in sea level; but coastal communities nevertheless must plan for the effects of a small rise in sea level, which is unavoidable. Toward that end, we offer the following recommendations.

First, we must be careful not to alarm or confuse the public. Press reports about a possible 20-foot rise from a disintegration of the West Antarctic Ice Sheet accomplish little when taken out of context, which they almost always are. Bottom-line estimates are always interpreted as either too awful to contemplate and plan for or too far in the future to arouse serious concern. By contrast, sea level rise from thermal expansion and incremental melting is better established, will occur sooner, and will have very important impacts, but is moderate enough that local officials can plan for it, at least in the United States.

Second, the parties likely to be affected by sea level rise should use the available estimates to determine which of their projects, if any, would be vulnerable to a rise in sea level. Alternative strategies should be developed--for instance, strategies to enable coastal communities to respond as better predictions become available. These analyses can be used to show public officials that climate and sea level research has a well-established payoff, and they may eventually reveal that the costs of sea level rise make efforts to prevent a global warming viable.

Third, the research community should structure its major efforts with an eye toward the interim use of its results. The course of human events may depend very greatly on whether we can say by 2010 that the West Antarctic Ice Sheet will disintegrate by 2200, 3000, or somewhere in between. But in the meantime, the success of coastal projects worth billions of dollars--many times the nation's carbon dioxide/climate research budget--will depend on our near-term abilities to say with some certainty when the sea is likely to rise 1 or 2 feet.

We conclude by emphasizing that concern for the greenhouse effect is not a new ultra-liberal cause. We are concerned about the protection of the most fundamental of values--our heritage. There is legitimate scientific disagreement about the danger of a greenhouse warming, but cautious people will plan for a rise in sea level because they have more to lose by failing to do so, especially given the current trend of a 1 foot rise per century along most coasts of the United States. If the National Academy of Sciences is wrong, the greenhouse warming never takes place, and we plan for a rise in sea level a few decades before it occurs, posterity will say that we were unwise. However, history will be far less kind if we fail to prepare and it really does happen.

Note: This paper was written in the author's private capacity. The views expressed herein do not represent the official views of the U.S. Environmental Protection Agency or the U.S. Government.

NOTES

1. J. Charney, *Carbon Dioxide and Climate: A Scientific Assessment* (Washington, D.C.: Climate Research Board, National Academy of Sciences, 1979).

2. World Meteorological Organization, *WMO Global Ozone Research and Monitoring Project*, Report of the Meeting of Experts on Potential Climatic Effects of Ozone and Other Minor Trace Gases, report no. 14 (Geneva: World Meteorological Organization, 1982).

3. R. Revelle, "Probable Future Changes in Sea Level Resulting from Increased Atmospheric Carbon Dioxide," in *Changing Climate*, Carbon Dioxide Assessment Committee, National Research Council (Washington, D.C.: National Academy Press, 1983).

4. J. Hoffman, D. Keyes, and J. Titus, *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs*, EPA 230-09-007 (Washington, D.C: U.S. Environmental Protection Agency, 1983). The factors about which assumptions were varied include: CO_2 emissions, the fraction of carbon emissions that remains in the air, trace gas concentrations, climate sensitivity, thermal expansion of the oceans, and the impact of a global warming on terrestrial deglaciation.

5. The most detailed description of this study and a parallel study of Galveston, Texas, can be found in M. Barth and J. Titus, eds., *Greenhouse Effect and Sea Level Rise: A Challenge for This Generation* (New York: Van Nostrand Reinhold, 1985).

6. See notes 3 and 4 above.

7. T. Kana et al. in Barth and Titus, note 5 above. They found that Charleston's freshwater-saltwater interface could shift landward by up to 60 meters (200 feet). Because the continued pumping of the area's coastal aquifers will result in much more severe saltwater intrusion than that predicted from a rise in sea level, the 60-meter shift was judged to be negligible. The impact of salt intrusion could be more important in the Delaware River basin and Louisiana.

8. See James Titus, "Planning for Sea Level Rise in the Aftermath of a Coastal Disaster," in Barth and Titus, note 5 above.

9. S. Gagliano, K. Meyer Arendt, and K. Wicker, "Land Loss in the Mississippi Deltaic Plain," in *Transactions of the 31st Annual Meeting of the Gulf Coast Association of Geological Societies* (Corpus Christi, Tex.: Gulf Coast Association of Geological Societies, 1981), pp. 293-300; R. Jantzen, "statement before the House Committee on Merchant Marine and Fisheries, Subcommittee on Fisheries and Wildlife Conservation and the Environment," November 20, 1981, Washington, D.C.; R. Baumann, J. Day, and C. Miller, "Mississippi Deltaic Wetland Survival: Sedimentation Versus Coastal Submergence," *Science* 224 (1984): 1,093; Louisiana Coastal Commission, *Coastal Protection Task Force Report to Governor David C.*

Treen et al. (Baton Rouge: Louisiana Department of Natural Resources, 1982); U.S. Army Corps of Engineers, "Notice of Study Findings: Louisiana Coastal Area, Louisiana, Land Loss and Marsh Creation," New Orleans District, 1984; and D. Boesch, ed., *Proceedings of the Conference on Coastal Erosion and Wetland Modification in Louisiana: Causes, Consequences, and Options* (Washington, D.C.: U.S. Fish and Wildlife Service, Biological Services Program, 1982).

10. Letter from William Huls, Secretary for Natural Resources, State of Louisiana, to William Ruckelshaus, Administrator, U.S. Environmental Protection Agency, May 11, 1984.

11. Letter from J.D. Boudreaux, Council Chairman, Terrebonne Parish, Louisiana, to William Ruckelshaus, Administrator, U.S. Environmental Protection Agency, May 11, 1984.

12. For a description of the issues raised by sea level rise on coastal Louisiana, see J. Titus et al., "Sea Level Rise, Coastal Erosion, and Wetland Loss in Louisiana: The Need for a Comprehensive Policy Study," in *Proceedings of the 13th Annual Conference of the American Association of State Floodplain Managers*, 1984.

13. See Appendix A.

14. U.S. Environmental Protection Agency and Delaware River Basin Commission, "Greenhouse Effect and Water Quality: The Impact of Sea Level Rise on Salinity in the Delaware Estuary," forthcoming.

15. S. Leatherman et al., "The Impact of Sea Level Rise on the Beach at Ocean City, Maryland," forthcoming.

16. R. Sorenson, "The Impact of Sea Level Rise on Coastal Structures and the Beach at Sea Bright, New Jersey," forthcoming.

17. See note 8 above.

18. C. Kuo and J. Titus, "Possible Impacts of the Expected Greenhouse Warming on Municipal Storm Drainage Systems in Coastal Areas: Outline of Possible Case Studies," working paper, available from the author.

19. J. Titus, T. Henderson, and J. Teal, "Sea Level Rise and Wetlands Loss in the United States," *Wetlands Newsletter*, Environmental Law Institute, September, 1984.

20. T. Kana and J. Siah, "The Impact of Sea Level Rise on Wetlands Around Charleston, South Carolina," 1984.

Appendix A

OFFERED BY: Mr. B. Bonvillain.
SECONDED BY: Mr. W. Henry.

RESOLUTION NO. 84-0794

A Resolution supporting continual research investigating the forecast of sea-level rise.

WHEREAS, Terrebonne Parish loses 17 acres of land per day due primarily to subsidence and salt intrusion and at this rate all of our erodable land will be gone in 100 years, and

WHEREAS, the Environmental Protection Agency and others have estimated that the expected greenhouse warming could raise sea-levels several feet by the year 2075, which would substantially accelerate current erosion, and

WHEREAS, the Environmental Protection Agency has shown that current scientific knowledge is insufficient to state whether the sea will rise as little as 1 foot or as much as 5 feet, but that additional research could substantially reduce these uncertainties, and

WHEREAS, in the next decade our strategies to stop land loss will require decisions that depend critically on whether sea-level is expected to rise 1 foot, 2 feet or more, and

WHEREAS, other coastal parishes in Louisiana face similar problems with coastal erosion, salt intrusion and relative sea-level rise.

NOW, THEREFORE BE IT RESOLVED that the Terrebonne Parish Council supports efforts by the Environmental Protection Agency and polar research scientists to develop forecasts of sea-level rise in the next century; and

BE IT FURTHER RESOLVED that the Terrebonne Parish Council strongly urges our congressional delegation to be briefed and work for increased federal support of research that will enable scientists to develop forecasts of how much sea-level will rise in the next 25, 50 and 100 years.

THERE WAS RECORDED:

YEAS: N. Bergeron, Jr., C. Duet, A. Bonvillain, W. Henry and B. Bonvillain.

NAYS: None.

NOT VOTING: L. Klingman, Jr.

ABSENT: W. Bonvillain, Jr.

The Chairman declared the Resolution adopted on this 6th day of June, 1984.

* * * * * * * * * * *

I, PAUL A. LABAT, Clerk of the Terrebonne Parish Council, do hereby certify that the foregoing is a true and correct copy of a Resolution adopted by the Parish Council in Regular Session on June 13, 1984, at which meeting a quorum was present.

GIVEN UNDER MY OFFICIAL SIGNATURE AND SEAL OF OFFICE THIS 14th day of June, 1984.

Paul A. Labat

PAUL A. LABAT
COUNCIL CLERK
TERREBONNE PARISH COUNCIL

SECTION 4: GREENHOUSE POLICY INTEGRATION

INTRODUCTION TO SECTION 4

The preceding sections have considered the feasibility of preventive and adaptive responses. This section considers how one might choose between these two very different types of policy response. There are many ways the choice can be made. It can be based on the feasibility or infeasibility of any one response. It can be based on cost or on the separation of impacts and emissions in time. Some analysts suggest that benefit-risk calculus is the best framework for assessment. Others consider the timing of necessary actions and the implications of that timing for present policy or the implications of the problem's irreversibility.

Using one approach, one might look at the institutional demands of different responses and how well they fit the outline of the climate change problem. As is evident from the preceding sections, both preventive and adaptive responses can be effected by either the market or governmental action. The market seeks to optimize the use of resources; as the effects of resource depletion are incorporated into the costs of goods and services, the use of these resources declines. As the technology of resource exploitation improves, the costs of resource use decline and the rate of use increases proportionately. By adjusting production and consumption to depletion and changing technology, the market can change the rates at which resources are used. As a result of market forces, the rate of increase in carbon dioxide emissions has declined markedly in recent years.

By contrast, state action is often directed to sources of significant market failure. In responding to perceived deficiencies in the operation of the market, the state seeks to resolve basic social problems by directing market forces through the use of incentives and penalties or through outright regulatory action and police power.

One can find many examples of market failure in the climate change problem. The market responds to present, rather than future, conditions and is largely oblivious to the future effects of present-day activities. It takes no account of the welfare of future generations and little or no account of the condition, either in the short-term or the long-term, of the biosphere. It does not act to ensure an equitable distribution of income and resources. It sometimes fails to price resources to reflect depletion.

Mintzer and Miller note that the climate change problem is particularly ill-suited to resolution by the market, and they address the need for state intervention. They argue that, due to poorly defined property rights and other factors, the market is not competent to limit emissions of carbon dioxide. Although the rate of increase in fossil fuel use has fallen from 4.5 percent per year fifteen years ago to about 1.5 percent per year at present, some interventionist action will be needed; the market, acting according to its own internal logic, will not be able to effect long-term ameliorative action.

By contrast, the authors note numerous examples of succcessful types of state interventions in the marketplace. As a result of interventions in energy markets, it has been possible to significantly increase the rate of end-use efficiency improvements. As a result of regulatory actions, it has been possible to limit emissions of some of the chlorofluorocarbons. Due to the responsiveness of the energy sector to pricing and other policies, it has also been possible in the past to intervene in energy markets to a significant degree for purposes of environmental and social policy.

The authors advocate a "middle road" response to the climate change problem, one that would take into account the costs of environmental change, which have heretofore remained outside of the economic balance sheet. Rather than seeking a purely preventive or a purely adaptive response, the authors suggest heightened state intervention in both energy planning and in those sectors of society most likely to be affected by changing climate. The authors recognize the complementary nature of preventive and adaptive responses. The debate between those who advocate one or the other of these responses is troubled, they believe, by an all-or-nothing attitude. The authors suggest that the regulatory power of the state be used to facilitate adaptation to a changing climate in affected sectors and to implement preventive measures that would yield economic benefits in and of themselves or impose no net cost on society.

It is possible to broaden the policy inquiry beyond such minimalist responses to include consideration of much more stringent actions. Some changes in climate will not be well suited to minimalist responses. Based on two very dissimilar physical descriptions of the problem, Lave, and Ciborowski and Abrahamson consider the policy implications of such climate changes.

Lave assumes the worst case to be a warming of 4 degrees Celsius by the 22nd century, and within that context he considers the responses of industrialized nations. He considers three cases successively: the best case, a median case, and the worst case. Given the size of the climate-sensitive sectors of the economy, he suggests that the effect of changes in the median case would, in terms of lost productive capacity, be something less than 2 to 3 percent of gross world product. The effects in the less developed countries could be quite traumatic.

The author then directs his attention to the policy implications of such changes, and, although he acknowledges the significance of the losses in gross world product, he also argues that this does not provide much guidance with regard to policy. It would need to be evaluated in light of the costs of avoiding climate change. Further, it does not constitute a clear catastrophe for society. In the absence of a clear indication of a catastrophic change in climate, it will not be politically possible to restrict the use of the fossil fuels. Given present uncertainties about the future rates of carbon dioxide release, about the climate's response, and about the response of society to the climate, Lave argues that it is impossible to demonstrate the likelihood of a catastrophic change in the climate. To the degree that we must reconcile ourselves to what is politically possible, preventive intervention is not plausible as a response to the prospect of changing climate.

Ciborowski and Abrahamson adopt a somewhat similar approach in their assessment of the situation. Building from a physical description of the problem, they assess the degree to which the uncertainties in the climate change problem limit a preventive response. However, in contrast to Lave, they suggest that, although uncertainties in the present physical description of the problem are significant, they cannot be shown to constrain preventive responses as severely as they are often thought to.

Based on an assessment of the parameters governing the rate of climate change, the authors initially conclude that without preventive action an average global warming on the order of 5 to 6 degrees Celsius is likely to be realized in the next century in the base case. From this, the authors describe the most probable warming and assess impacts at this level of global warmth. They argue that the impacts at this level are significant. The authors consider worst case parameters, which, given the range of values suggested by scientists for climate sensitivity, the contribution of the minor greenhouses gases, and other factors, suggest a worst case warming on the order of 9 degrees Celsius.

Worst case parameters, the authors note, effectively introduce society into a climate about which, essentially, nothing is known, and which, therefore, holds the potential for worst case outcomes. They conclude that adaptation to the changes is a tenuous proposition if only the rate of climate change is considered. At the regional level, climate change will not take the form of a simple linear movement from the present state to some unitary future state but will present itself as a number of different climate changes. This will be particularly true as the planetary warming rises beyond the 3 degrees Celsius level. The more closely these changes are bound together, the more difficult it will be for society to adapt to them.

Noting that the tolerance of society for such a change is questionable, the authors investigate the policy implications of limiting the average global surface warming below this level of unacceptable change. Using a 4 degrees Celsius ceiling as a baseline, they find that, given realistic estimates for the parameters governing climate change, preventive action, if it is to be effective, would need to be implemented in the immediate future.

As the authors note, this assessment points to the need for realistic estimates of the physical parameters of climate change. It also points to the need for a more reasonable approach to assessment than is normally applied to the climate change problem. Too often, they argue, the best case, rather than the base or median case, or even the worst case, is used in establishing policy, and too often assessments of each case's likelihood of occurrence go unused. If such assessments are employed, the authors conclude, it is difficult to deny the imperative of a preventive response.

LIVING IN A GLOBAL GREENHOUSE: A COALITION BUILDING APPROACH

Irving Mintzer and Alan Miller
World Resources Institute, Washington, D.C.

INTRODUCTION

Many economic activities, including energy use and production, have undesirable environmental and social consequences. In most instances, these social costs are not incorporated into the market prices of products or services. Since the 1972 Stockholm Conference on the Human Environment, increased attention has been focused on these market externalities as scientists, energy analysts, and policy-makers have come to realize that global environmental concerns are central, not peripheral, to energy and development problems. Holdren,[1] Erlich,[2] and others have suggested that the most appropriate response to the energy problem might involve a course that both avoids the economic consequences of the availability of too little energy and escapes the environmental consequences of the consumption of too much.[3] Mounting evidence suggests that environmental costs, rather than the unavailability of resources or "purely" economic costs, will form the ultimate constraint to the future rate and type of energy use, and perhaps to economic activity in general.

The policy implications of this constraint are best understood upon identification and evaluation of the environmental risks of human activities. Here the focus is on the causal linkages by which activities lead to actual or potential environmental damage including the linkages between activities undertaken in the research, construction, operation, or decommissioning of economic production facilities, insults to the immediate environment, and the pathways by which these insults translate into environmental stress and damage.[4]

Complete descriptions of environmental consequences trace all causal linkages. However, such complete information rarely exists. The most difficult problems often arise in investigations of the ways human activities affect complex physical systems, for example the oceans or the atmosphere, or in analyses of dose-response relationships. Because of these difficulties, many environmental impact assessments merely measure the initial effects of human activities, for instance the number of tons of the emission of some substance, rather than the consequences of the emission. However, without more complete analyses, such figures must often substitute for better measures of environmental damage.

Climate change resulting from the emission of greenhouse gases constitutes one such problem, and it can therefore best be considered in light of such initial effects and of other qualitative indicators of severity, rather than quantitative measures of local insults or damages. Some typical qualitative information that is useful includes that related to: (a) the distribution of damages over space, time, and classes of victims; (b) the degree of difficulty and the cost of preventing or mitigating the damage; (c) the degree to which such damage is irreversible; (d) the response of the environment to emissions or climatic stress; and (e) the degree of uncertainty in these characterizations. In the following paper, we address various policy instruments for responding to the greenhouse problem in light of several of these--irreversibility, equity, and uncertainty--which make a purely market solution to the problem impossible.

THE GREENHOUSE EFFECT

Over the last century, the concentration of carbon dioxide in the atmosphere has increased by about 25 percent, from approximately 270 parts per million (ppmv) to its present value of 345 ppmv.[5] The trend is continuing.[6] Global combustion of fossil fuels in 1981 and 1982 resulted in estimated annual atmospheric releases of over 5 billion tons (gigatons, or GT) of carbon as carbon dioxide.[7] The atmospheric concentration of carbon dioxide will reach twice the preindustrial level by the middle of the next century if fossil fuel use continues to grow at approximately the rate it has for the last ten years. But if carbon dioxide emissions from fossil fuel use level off at the current annual rate of 5 GT of carbon, such a doubling will not occur for well over one-hundred years.

In addition to carbon dioxide, other trace gases, many of which are present in the parts per billion (ppbv) range, can contribute to the greenhouse effect. These include methane, nitrous oxide, the chlorofluoromethanes, and others. The rates of annual release for these greenhouse gases have not been pegged so precisely. Graedel and McRae estimate that methane concentration has increased from about 1.6 to 1.7 ppmv between 1968 and 1975.[8] Based on an analysis of ice cores, Craig and Chow suggest that atmospheric methane concentrations were on the order of 0.7 ppmv before 1500.[9] Nitrous oxide concentrations appear to have increased from 290 to 305 ppbv between 1970 and 1980. Concentrations of the chlorofluoromethanes (CFMs) which are unknown in nature, have increased over the last thirty years from nothing to 320 and 190 parts per trillion (pptv) in the cases of dichlorofluoromethane (CFC-12) and trichlorofluoromethane (CFC-11) respectively.

The world scientific community now agrees that significant changes in global climate will occur as a result of the atmospheric buildup of carbon dioxide and the other greenhouse gases.[10] Most scientists agree that a doubling of the atmospheric level of carbon dioxide will be accompanied by a rise of 1.5 to 4.5 degrees Celsius in mean global surface temperature, with the largest increases observed at the poles.[11] Chamberlain et al. have estimated that mean global temperature would roughly double again, were the atmospheric concentrations of the major trace gases also to be doubled.[12] Generally, the effect of increased concentrations of each of these other gases is thought to be additive. For comparison, the annual mean surface temperature in the northern hemisphere has varied plus or minus 0.5 degrees Celsius since 1579.[13]

The observed increase in atmospheric carbon dioxide is primarily due to fossil fuel use in the northern industrialized countries.[14] Carbon dioxide is emitted when any fossil fuel is burned. Noncombustive uses of fossil fuels (e.g., the use of petroleum or natural gas as a chemical feedstock) contribute little to increased atmospheric levels of carbon dioxide. However, most analysts have identified the biosphere as a modest net source of carbon dioxide, with deforestation for slash-and-burn agriculture, the clearance of pastureland, and fuelwood releasing perhaps 0 to 2 GT of carbon per year.[15]

No consensus has yet emerged regarding the main sources of nitrous oxide, methane, and other minor gases. Chamberlain identifies bacterial action in soils, industrial fixation, and fossil fuel combustion in the case of the former gas.[16] Biological processes, including anaerobic digestion in rice paddies and swamps, enteric fermentation in the digestive tracts of cows,[17] and anaerobic fermentation by termites,[18] are thought to contribute to the present upward trend in the atmospheric methane concentration. According to some analysts, other sources, for instance the ocean floor[19] and the outer continental shelf,[20] also may be important. Increased tropospheric ozone concentrations are associated with an increase in the terrestrial emission of another gas, carbon monoxide, which competes with ozone for a limited atmospheric photochemical sink and hence helps to reduce the rate at which ozone is destroyed in the troposphere. The CFMs, which are used as aerosol propellants, in foam-blowing applications, as cleaning and degreasing agents in the semiconductor industry, and as refrigerants, are released to the atmosphere during routine manufacturing processes, spray can use, and through leakage from or the destruction of refrigeration units.

The scientific attention directed toward the greenhouse gas buildup is motivated primarily by a concern for the risks resulting from changes in the global climate. Such changes would result in increased planetary heating, which will expand the upper layer of the ocean and transfer water mass from continental glaciers to the sea.[21] Revelle estimates that the sea level could rise by as much as 70 centimeters (cm) in the next one-hundred years as a result. Analysts at the U.S. Environmental Protection Agency project a much larger rise in sea level, about 2 meters, associated with a 3 degree Celsius increase in mean global surface temperature.[22] In addition, some analysts have suggested that the Arctic sea ice could disappear in the summer and that the West Antarctic Ice Sheet could disintegrate,[23] although a major breakup of the West Antarctic Ice Sheet, which alone would raise sea level 5 to 7 meters, is unlikely in the next two-hundred years.[24]

Such a large global climate change will also affect regional climates, which could in turn significantly affect the productivity of agriculture, forests, and fisheries.[25] These sectors are particularly sensitive to climate variations. Increased temperatures during critical growth periods can decimate key agricultural crops in certain regions. Changes in the timing and quantity of precipitation and in the rate of evaporation from the soil can affect local microclimates, especially soil moisture and its availability to shallow-rooted plants. Unseasonal rains can alter the productivity of rain-fed agricultural lands. Reductions in regional rainfall can render some irrigation systems less useful and promote the mining of groundwater. Hence, climatic changes could have a significant impact on the world's principal agricultural regions. In the wake of a global warming, growing seasons may increase in certain regions, but these may lack rainfall during critical periods, or may lack fertile, productive topsoil, which makes the larger global agricultural response, as well as the world food situation, something of a crapshoot.

THE PROBLEM FOR POLICY-MAKERS

The formulation of policy is a difficult but important task for decisionmakers, particularly with regard to the greenhouse problem, which requires prudent public policies to forestall or cope with anthropogenic climate changes. But persistent uncertainties and unquantifiable measures of the severity of the impact of climate change suggest to many that any action is premature until further research is done. They assume that the signals of the market are sufficient to guide society's choice of energy technologies and sources of supply.

Unfortunately, it is extremely unlikely that market mechanisms alone will internalize the costs of a greenhouse gas buildup given the significant and unavoidable gaps in our present understanding. As a result, it will be impossible to incorporate environmental externalities into the price of energy services and other goods in the absence of governmental intervention in the marketplace. Fortunately, the government can direct market forces through various policy instruments (e.g. subsidies or preferential taxation), and thereby influence economic choices.

The fundamental information problem has several elements. First, persistent uncertainties continue to pervade our understanding of many aspects of the carbon dioxide problem, inhibiting the development of anything like a complete description of the physical processes involved. These uncertainties begin with the simplest pieces of information on the generation of the various greenhouse gases and enlarge themselves into a cascade of uncertainties as one follows the chain of physical causation from carbon dioxide emission to potential local environmental change. For instance, the photochemical interactions of the various greenhouse and non-greenhouse gases are poorly understood at best. But it is clear that increased tropospheric ozone concentrations are related to increased carbon monoxide and methane concentrations; that methane results in part from increased surface emissions of carbon monoxide; and that carbon dioxide derives in part from increased methane emissions. The terrestrial sources of many of the gases are not well understood and the response of these sources to rising mean global temperature is poorly known, although it is believed possible that a warming could cause wetlands and continental shelf sediments to release significant amounts of methane and peatlands to release carbon dioxide.

In addition, a large number of minor gases have only recently been identified, and their sources and future rates of release are not well understood. The potential biotic contribution to increasing atmospheric carbon dioxide concentrations is also controversial. Some analysts suggest a net contribution of 5 GT per year through deforestation.[26] The debate is important, since this contribution figures as an important term in calculating the fraction of emitted carbon dioxide that remains airborne. This is typically estimated at 40 to 50 percent in conventional analyses but can be as low as 30 percent if high deforestation estimates are employed.[27]

Some other uncertainties, among many not mentioned, involve: possible changes in the fraction of emitted carbon dioxide that remains in the atmosphere as the upper layer of the ocean becomes saturated with dissolved carbon dioxide, the ocean's circulation slows, and the density of the polar waters decreases with glacial melt; the overall sensitivity of the climate to increased carbon dioxide concentrations; countervailing effects (e.g., the effect of desertification-related tropospheric dust); the effect of unidentified processes involving the earth's major biogeochemical cycles; and potential changes in local temperature and precipitation, which might induce local environmental changes like desertification. There is no unequivocal measure of the probable impact on commercially important cereal-producing regions or fisheries; the dose-response relationships for most crops, forest species, and fish are not well known. It is not clear whether fundamental non-linearities will occur in response to increasing levels of environmental stress, although such threshold levels have not yet been identified. Finally, since the current scientific understanding of the ocean/atmosphere system is limited, in the next several decades it probably will not be possible to predict the regional distribution of climate change or impacts.

Second, without a comprehensive and systematic long-term record, it will be difficult to establish popular agreement about the reality of the carbon dioxide problem. Atmospheric scientists cannot reach a consensus about whether a distinct carbon dioxide signal can be identified in the recent record of climatic change.[28] They also disagree about the strength of the trend. With so much disagreement over the identification of potential sources of stress, policy-makers and others may be tempted to merely wait and see.

Third, the problem is complicated by the inherently stochastic nature of the global climate. Even if humanity's activities did not modify the biogeosphere, natural interannual variation would occur in regional and local climates, and such variations can make it hard to associate specific local or regional effects with any one of the many potential sources of climate change. Hence, the establishment of strong causal connections between specific activities in one locale and variations in climate regimes in any other will be difficult, if not impossible. The problem of tracing causality is further complicated by time lags. Insults to the atmosphere today may not be expressed as climatic alterations for years or even decades to come.[29]

In addition, no obvious technical fix can be inexpensively applied to ameliorate the carbon dioxide/climate problem. Although several prominent American physicists assert that some method of scrubbing carbon dioxide or other greenhouse gases out of the atmosphere or from the ocean may be found, none has yet been identified. A reversal of climate changes will be difficult once a global greenhouse warming has occurred.

A related problem, the CFC/ozone depletion problem, also complicates the analysis. The chlorofluoromethanes, which are very efficient absorbers of infrared radiation, are removed from the atmosphere through a set of upper atmospheric chemical reactions, which also tend to result in the destruction of significant amounts of stratospheric ozone. This tends to increase the hard ultraviolet radiation received at the Earth's surface and therefore has important health and agricultural impacts. The rate of ozone destruction varies with stratospheric temperatures, which an increase in atmospheric carbon dioxide should depress. This places policy measures to limit global warming in opposition to the measures designed to prevent ozone depletion.

These problems combine with an incomplete or inappropriate recognition of property rights to create a typical "tragedy of the commons" effect. Since causal relationships between specific insults and observed damages to the common property cannot be established, liability would be difficult to assess, and the incorporation of the costs of observed damages into individual market transactions would be difficult. Few individuals would have an incentive to absorb the costs of the emission of the greenhouse gases, even if responsibility for environmental impacts could be attributed to the commission of certain acts (e.g., the burning of fossil fuel in a car or a furnace). Nor would it be easy to establish a mechanism whereby the beneficiaries or sellers of energy services could find, much less compensate, the "victims" of climate change. Even if the victims could be found, the monetary value of the damages or the extent of any party's liability would be difficult to assess. What rules would apply? Should everyone who knowingly burned fossil fuels be held equally culpable? Should a penalty be applied to each transaction in proportion to the amount of carbon in the fuel consumed? Should the selling price for goods or services include a consideration for impacts from carbon dioxide that might have been released in materials production or manufacturing operations? Should compensatory intergovernmental payments account for differences in national populations and fossil fuel use? If so, who should pay whom?

With inappropriate or unrecognized property rights and only incomplete information linking buyer, seller, and victim, market mechanisms alone are not likely to capture these externalities. Nor are scientists likely to resolve the persistent uncertainties in the next few decades. Thus, prudent public policy must either be formulated to incorporate market-like mechanisms to influence economic choices among energy technologies and industrial compounds or otherwise deal with the large potential consequences of a greenhouse warming in the face of risk, ambiguity, and uncertainty.

THE CURRENT POLICY DEBATE: TWO POLAR VIEWS

In recent years, two schools of thought have emerged regarding policy responses to the greenhouse problem. These two schools--one stressing adaptation to what it perceives as inevitable climate changes and the other emphasizing preventive approaches to the atmospheric accumulation of the carbon dioxide--are often treated as mutually exclusive. The adaptive approach reflects a series of assumptions which we oversimplify here for discussion purposes. This approach presupposes the inevitability of global warming due to the buildup of carbon dioxide and other greenhouse gases in the atmosphere, and hence presupposes the need for society to prepare for a new climate regime. Many believe that energy demand is inflexible and unresponsive to policy changes and that timely reductions in fossil fuel use are all but impossible.[30] They perceive few or no alternatives to fossil fuels that are either economically attractive or can penetrate the market fast enough to make a difference before the middle of the next century, when the atmospheric concentration of carbon dioxide is likely to have doubled.

Some proponents of the adaptive approach forecast a rather slow rate of change in the climate, with a correspondingly long transition period. They argue that it may be possible to adapt incrementally to a warmer climate through gradual poleward extension of agricultural production, forestry activities, and the infrastructure required for commercial development.

Others stress the need to prepare immediately for the effects of unchecked global warming. To prepare for hot, dry years in the cereal-growing regions of the midwestern United States, for example, some contend that it may be necessary to breed new crop species through genetic engineering. It is believed essential to develop drought-resistant varieties through selective breeding programs and to improve water-use efficiency and water management practices. As a hedge against the breakup of the West Antarctic Ice Shelf, some advocate planning for the relocation of coastal cities inland, while others focus on the need to exercise extreme care when siting long-lived facilities and new infrastructure.

Advocates of prevention would preserve the Earth and its atmosphere as we know them, seeking not only to reduce the rate of increase in fossil fuel use but also to reduce the absolute amount of carbon dioxide and other greenhouse gases annually released into the atmosphere. The more extreme preservationists would reduce fossil fuel use at all costs, either through the widespread use of renewable energy sources or through significantly increased energy end-use efficiency. Coal combustion is a special target, since about twice as much carbon dioxide is released per unit of energy supplied during the combustion of coal as during the combustion of natural gas (24.6 million metric tons [MTe] of carbon per exajoule compared with 13.7 MTe), and about 1.4 times as much carbon dioxide is released per unit of energy supplied during the combustion of coal as during the combustion of oil.[31] There has also been discussion of preventive solutions involving fission technologies, which, it might be noted, would produce other environmental risks at least as threatening as a greenhouse warming. A more mainstream approach would reduce the use of fossil fuel through improved energy efficiency and through the use of renewable energy sources wherever they can compete economically with fossil fuel.

Some advocates of prevention would also control the release of the other greenhouse gases. However, the costs and difficulty of limiting trace gas emissions are not well known at this time. Methane and nitrous oxide may prove difficult to control, since the sources and sinks for these gases have not yet been well identified or quantified. Alternative compounds for some important industrial uses of the chlorofluorocarbons have not yet been identified, though economically competitive alternatives exist for some CFM applications, notably aerosol propellants and cleaning agents in semiconductor manufacturing.

FINDING A MIDDLE ROAD

In view of the potential global impacts of a greenhouse warming, we believe that systematic and comprehensive policies must be formulated now to enable society to respond to the prospect of anthropogenic climate change. Although uncertainties and ambiguities in the atmospheric research persist, only quick action will minimize the risks inherent in such a climate change and allow us to mitigate some of the negative impacts. Such action need not necessarily be exclusively of a preventive or adaptive nature; the choice between adaptive and preventive strategies is useful only as a classification device. However, some policy action is necessary, since we risk exacerbating the problem through delays incurred while all the ambiguities are resolved.

The carbon dioxide problem is only one element of a linked network of policy questions related to energy policy, global climate change, and clean air. The carbon dioxide buildup cannot be treated separately from the accumulation of other greenhouse gases, since the effects of an atmospheric buildup of other greenhouse gases would be similar to those of carbon dioxide-induced warming. Policy reponses to the larger greenhouse problem also cannot be evaluated in isolation. It is important to design national energy strategies and global development programs that address many other interlocking issues--for instance, the ongoing changes in the chemical composition of the atmosphere, as raised by acid rain and ozone depletion.

The middle road proposed here involves a least-cost solution to the greenhouse problem, one that takes account of the social and environmental costs that have not until now appeared on the economic balance sheet. The main elements of this program, which evolved at the World Resources Institute (WRI) Conference on the Global Possible, follow from three functional goals: (1) the preservation of the basic physical and chemical characteristics of the atmosphere through measures that are both technically feasible and economically efficient; (2) the timely identification of the impacts of human activities on the atmosphere; and (3) the mitigation of disruptive changes in climate, whether from a greenhouse warming or other causes.

PROPOSALS FOR ACTION

Although large and significant uncertainties remain, scientists now know enough about atmospheric problems to propose immediate action to hedge against plausible risks. Below, we propose such a program of immediate action built upon recent research which suggests that it may be possible, although costly, to prevent some of the impending climate changes through changed energy and industrial policies, and through measures that facilitate societal adaptation.

Improving the Efficiency of Energy Use

Efforts to improve the efficiency of energy use constitute the most important step toward the control of carbon dioxide emissions, and hence toward the amelioration of future climate changes. Such an effort would need to be pursued internationally, since fossil fuel combustion is increasing worldwide. Tax, trade, and fiscal policies can be used to encourage the elimination of outright waste and increase the efficiency with which energy is used.

Such policies provide multiple benefits. A more efficient use of oil lessens dependence on petroleum imports. Conservation and the use of alternative fuels to coal and petroleum reduce the amount of acid rain, carbon dioxide, nitrogen dioxide, and other trace gases produced in or released to the atmosphere, especially when coal is replaced by non-fossil fuel alternatives. Conversely, most air pollution clean-up programs reduce emissions of one or more greenhouse gases while restricting the emission of particulate, lead or other non-greenhouse gases. For example, controls on the emissions of the chlorofluoromethanes would limit the degree of possible future climate change and limit CFM-induced destruction of stratospheric ozone.

Numerous studies in recent years have demonstrated the potential for substantially improved energy end-use efficiency. Williams et al. have identified numerous technically feasible measures to improve the efficiency of energy use in the industrial, residential, transportation, and commercial sectors.[32] Non-fossil alternative technologies could satisfy heating and cooling demands and supply electricity, shaft power, and liquid fuels in wide-ranging end-use applications. In some applications, these technologies need cost no more per unit of energy saved than fossil fuels per unit of energy supplied. The Congressional Research Service (CRS) has compared two strategies for meeting the U.S. demand for electrical services through the year 2000.[33] One plan was based on traditional investments in large central station power plants and the other on a combination of investments in improved efficiency, load management, waste heat recovery (cogeneration), and renewable energy supply technologies. CRS concluded that alternatives to additional central station electrical generation capacity were available at a cost of about half that of new power plants, even without continued plant cost escalation.

Numerous studies have produced similar results for specific regions,[34] for specific sectors,[35] and for specific states.[36] In each case, the least-cost approach requires no additional base load power plants. Hence, although the economic feasibility of the rapid and widespread introduction of such conservation measures has not yet been completely and systematically evaluated, it appears to be possible to substantially improve energy end-use efficiency, as is suggested by recent research and by the uncoupling, over the last decade, of total energy use and regional economic growth.[37]

The effectiveness of such measures has also been considered. One recent study has suggested that annual U.S. emissions of carbon dioxide could be reduced by as much as 30 percent without reducing the physical output of goods and services.[38] This would involve the widespread use of currently available energy conservation measures and the substitution of solar and wind-electric systems for a fraction of the oil and gas-fired electricity generation capacity.

Of course, net reductions in energy use will not be possible among the poorest segments of the world's population, which will require more energy. The electrical generating capacity of the less developed countries will probably also need to expand, and hydroelectric systems and other renewable energy technologies may not be available or economical in many cases. However, development should be possible with less energy than is consumed in the now-industrialized nations, a fact of considerable importance to future atmospheric carbon dioxide levels.[39] Also important is the fact that a relatively small number of countries are responsible for a significant percentage of the world's fossil fuel consumption.[40] Even allowing for significant growth in the developing countries, this relationship will continue for some time. Thus, action by relatively few countries could make a substantial difference.

Chlorofluoromethane Control and Reforestation

The chlorofluoromethanes are extremely efficient absorbers of infrared radiation. Emissions of chlorofluoromethanes can be controlled through measures that restrict their aerosol uses. The marginal cost of such measures has been investigated and shown not to be economically prohibitive in the United States, where a ban reduced emissions more than 50 percent. The effect of measures taken in the United States, Canada, and elsewhere is evident in annual emissions of CFC-12 and CFC-11, which dropped from an estimated 0.4 and 0.33 million tons, respectively, in 1973 to approximately 0.36 and 0.27 millions tons, respectively, in 1979.[41] Much smaller reductions have been achieved in some countries and in some of the other major uses, suggesting that significant further reductions can still be implemented at a low cost. Studies done for the Environmental Protection Agency have also demonstrated that at least some reductions in nonaerosol emissions can be achieved at a reasonable cost.[42]

Controls on deforestation constrict a source of carbon dioxide, and net reforestation withdraws carbon from the atmosphere and permanently stores it in the terrestrial biota. By the same token, provisions for unpredictable weather require many of the same steps as adaptation to climate change, whether the change be induced by greenhouse gases, increased volcanic activity, or long-term variations in solar output.

Recommendations

The following recommendations reflect all these considerations:

- Energy planning must account for the possibility of global warming. This requires a significant effort to promote conservation and improve the efficiency of energy use. A high priority must be placed on the flexibility and diversity of supply, and on an increased reliance on solar and other non-carbon energy sources. Due attention must be given to the inadvertent environmental impacts of these alternatives.

- Research is needed to help all nations meet their energy needs without increasing the risks of a global climate change. Long-term energy needs are best understood through the analysis of energy end-use services. Special attention must be given to energy efficiency opportunities in the industrial countries, as well as to mechanisms to help developing countries meet their energy supply needs. Nations should not be forced to choose between energy shortages and increased risks of climate change.

- Nations should be encouraged to avoid policies that result in the subsidization of fossil fuels use or that commit the world to the large-scale, long-term use of coal or oil shale. Coal has an important transitional role to play in the energy future of many countries, but its use should be governed by the need to limit the atmospheric build up of carbon dioxide to tolerable levels. Industrialized countries of the northern hemisphere, as the largest emitters of carbon dioxide, must take the lead in reducing rates of fossil fuel use. Special attention should be directed to policy instruments that encourage full-cost (including environmental costs) pricing of energy technologies and supplies and that eliminate preferential subsidies. In this process, adequate consideration must be given to the needs of the poor, although not necessarily through the subsidization of energy prices.

- Global deforestation trends should be reversed and reforestation efforts encouraged.

- Since not all climate change can be prevented, systematic plans are necessary to help society adapt to the changed frequencies of drought and other extreme weather events and to a slow rise in sea level. Appropriate policies include: improved water management in agricultural and industrial areas; expanded emergency preparedness programs; low-cost credit program for disaster relief; and careful siting for long-lived facilities such as dams and toxic waste dumps.

Proposals for Further Research

Much recent research on atmospheric contaminants has been conducted in a crisis-response mode and has been in response to government concern about the consequences of such contaminants. However, an intensified long-term program of study of atmospheric processes might constitute a far more effective approach, perhaps broadening pre-crisis insights into the physical aspects of atmospheric problems. Early studies might also help avoid some of the polarization inherent in crisis calculations, whether that polarization be industry against environmentalists or rich countries against poor countries.

Research on the role of the oceans and the biosphere in the emission and storage of carbon dioxide, and on the effect and rates of release of non-carbon dioxide greenhouse gases, should be greatly expanded. Programs should be established to investigate the regional implications of increased mean global surface temperature, especially the effects on rainfall and soil aridity, and the synergistic effects of multiple environmental stresses on human health and ecosystems. Research is not now directed toward the possible interactions between ultraviolet radiation, carbon dioxide, drought, and other factors. Research on new techniques for improving water-use efficiency should be pursued, especially since it may be essential to any effort to maintain productive agriculture and forest areas in dry years. Expanded research and selective breeding is also necessary to identify and develop drought-resistant varieties of major agricultural crops.

The quality of the present global monitoring network should also be substantially improved. More stations are needed, as are increased efforts to obtain consistent, reliable data on the trends in atmospheric chemistry and in sea-surface and other temperatures.

Other important research is more closely related to policy evaluation. Greater efforts should be made to develop new ideas and new methods for the capture and disposal of combustion-derived carbon dioxide. Economic and environmental research should be pursued to better quantify the value of any damages due to climate change, especially since such research will provide the basis for cost-benefit analyses of the various control options for carbon dioxide and other greenhouse gases. Such research may also provide the basis for evaluating competing adaptive and preventive responses.

Existing mechanisms for the official exchange of scientific information tend to be ad hoc and slow. This results from the narrow disciplinary bounds within which the flow of information is often constrained. In addition, communication with the centrally planned economies, which is vital in any effort to slow the present increase in the atmospheric concentration of carbon dioxide, has tended to be less than effective. The developing countries have not been well informed of their stake in these issues.

A number of mechanisms might be created to rectify this situation. The United Nations Environmental Programme's Climate Impact Study Program and the World Meteorological Organization's World Climate Program should be expanded and given regular, long-term funding. The proposed International Biosphere-Geosphere research program sponsored by the International Council of Scientific Unions should be given strong support. A formal, multi-year exchange program for energy analysts and atmospheric scientists from the United States, the Soviet Union, the People's Republic of China, Japan, and the European Community should be initiated immediately to study energy conservation opportunities and plan coordinated responses to the greenhouse problem. All these measures may substantially increase the exchange of scientific and policy information, and hence should be pursued.

REASONS FOR OPTIMISM

Several cogent arguments have been advanced as to why we should expect opposition to a program like that which we propose. First, analysts have noted that such proposals require action in advance of a clear demonstration of the damage caused by climate change, and perhaps in advance of evidence of a clearly distinguished upward trend in global temperatures. Governments, on the other hand, have historically been slow to respond to environmental problems until their seriousness has been categorically proved. It has been noted that initiatives to encourage changes in energy use patterns, such as those we have offered, will have to be implemented in the context of numerous other societal goals (e.g. economic growth, national security, other environmental concerns), some of which may conflict with the pursuit of substantial reductions in fossil fuel consumption. Some analysts also have questioned whether government policies forceful enough to significantly curtail the use of fossil fuels can be implemented.[43] Since economic growth and patterns of energy use imply continually increased emissions, they argue that the prospects for significantly reduced emissions are virtually nil over any time horizon of interest. The considerable energy price increases already experienced are cited as evidence that high taxes or other meaningful controls on fossil fuels will not be easily implemented.

It is also noted that proposals similar to ours require a cooperative international solution of the kind that is most likely to evolve in the presence of information that identifies the major greenhouse gas emitters as the nations that are most likely to be adversely affected--a condition that cannot be satisfied at present. This has opened the door for optimism with regard to future regional climate changes, some of which, it is argued, might be beneficial to strategically placed powers, making them potential "net winners" and less inclined to preventive action. Lastly, resistance to preventive action is cited as an obstacle, since such action, it is thought, could require major changes in energy production and use and significant new investments or changes in behavior on the part of established economic interests.

We address some of these considerations in this last section, with special attention given to the constraints to the formulation of domestic energy policies and the development of an international consensus. These are considered in light of various precedents, which suggest that the various constraints need not necessarily constitute insurmountable obstacles to policy action.

Precedents for Effective Government Policies

We have already addressed various issues relating to the technical feasibility of the program we support. These might best be promoted through substantially increased energy prices--for instance, through the use of various taxation schemes.

The prospect for direct government regulation of fossil fuel use, at least in the short term, is much more doubtful. Many government energy programs have had only marginal impact, particularly when compared to the influence of price increases.[44] However, government policy indisputably influences the choice of technologies deployed in industry, the schedules for investment in electrical generation capacity, and other key determinants of energy use. Some government research and conservation programs, such as support for the development of photovoltaic cells and minimum efficiency standards for appliances, have undeniably affected energy use and constitute more effective policy instruments than is often allowed.[45]

Precedents for International Action: The CFMs

Precedents for international cooperation in response to global environmental problems are rarer. Relevant precedents include actions on fisheries, acid rain, and regional seas. Most past successes have involved no more than the agreement to exchange information. The willingness to fund and undertake cooperative research is less frequent, particularly when the problem involves a potential future risk rather than a palpable damage is involved. The process of developing multilateral consensus is a painfully slow and difficult one and has often broken down over political issues only peripherally related to the environmental problems under discussion.

The effort to reduce the risk of stratospheric ozone depletion constitutes one interesting and relevant analogy to efforts to control or adapt to the greenhouse effect. The effort to promote international cooperation, including preventive steps, began in the mid-1970s, soon after scientists warned of the risk of ozone depletion from anthropogenic emissions of various gases, first in the context of a debate over the supersonic transport and subsequently as a consequence of chlorofluoromethane emissions.[46] Eventually, these efforts resulted in multilateral and international agreements on research and information exchange. In addition, several countries unilaterally reduced CFM emissions, despite the knowledge that only global reductions would fully address the problem.[47]

In the last three years, the governments most concerned about ozone modification have supported an international convention to protect the ozone layer.[48] The general concept of a convention has received very broad support, but a proposed protocol that would require cutbacks in emissions has been controversial. Some opposition has arisen as a result of lower estimates made recently of the expected rate of ozone depletion.[49] However, the role of unilateral actions in significant emission reductions has been important; international agreement has become less pressing due to the effectiveness of these unilateral actions.

This precedent suggests that the evolution of international efforts is likely to be slow and piecemeal but not necessarily ineffective. Public debate, example, and the slow accumulation of experience with sets of limited measures seem, in this case at least, to have created the conditions for the formation and continued consolidation of a politically significant consensus. As is often the case, expanded research efforts seem to have been approved only after a significant debate over the need for action. This is similar to what has happened in the United States with government- and utility-supported acid rain research, which has grown enormously in response to the debate over the need to restrict sulfur dioxide emissions. Without this controversy, proposals to expand research on acid rain would have stood little chance of approval.

Pressure for broader international agreement seems to have resulted at least in part from the example of the unilateral actions of individual countries--especially those involving substantial, and sometimes costly, commitment. Thus, the aerosol ban adopted in the United States and several other countries undoubtedly had an exemplary effect and contributed to significant unilateral reductions, even by countries opposed to a total ban. Experience with limited actions now seems likely to evolve into resolute, even "radical," measures, perhaps because small steps seem to imply an initial agreement that the atmospheric problem warrants government attention and legitimize further action. The regulation of nonaerosol uses of chlorofluoromethanes is now being discussed in the United States. Such restrictions, which will cost more than did controls on aerosol uses, were not seriously discussed until the ban on CFMs in aerosols had generated a consensus on the problem's severity.

All of these factors suggest a much less bleak prognosis on international cooperation than is usually suggested.

Successful Incremental Approaches

The same as has been true for international cooperation on CFMs has also been true for most environmental policies, the adoption and implementation of which has been an incremental process. In short, expanded research tends to follow calls for action, and significant unilateral action tends to follow modest initial steps; international action seems to be a possible extension of unilateral action in the case of important environmental problems--for example the CFM-ozone depletion problem. Hence, policy responses to the greenhouse problem need not immediately and fully eliminate all risks of climate modification to be worthwhile. Relatively modest initial steps by even a few countries can have a real impact. Although reductions of perhaps 20 percent in emissions of carbon dioxide and perhaps 50 percent in CFMs will not eliminate the risk of climate modification, they will buy time until more aggressive actions become politically realistic. Since some modest initial steps must precede more sweeping measures, initial steps should be taken as soon as possible.

The Fallacy of the "Net Winners"

The notion of winners and losers in the larger carbon dioxide problem is highly misleading, since it is not at all clear that any country will be a net winner once the social costs, infrastructure investments, and types and quality of information needed to take advantage of changes in climate are fully considered. Given the regional distribution of impacts, it is not unwarranted to expect all nations to suffer at least some short-term dislocation as society adapts to climate changes, whether they are beneficial or harmful over the long term. Such dislocation can involve significant costs even in the former case; it could be especially serious in the latter case. Anticipatory adaptation can help ameliorate losses but requires much more precise information than does a preventive policy, including information on the nature, distribution, and timing of climate change. To be a net winner, a country would have to make major investments in irrigation, water storage, and agricultural land development. It would not be enough to know that a particular region might be warmer and wetter; to justify such large agricultural investments, investors would have to know the expected distribution of rainfall and the likelihood of crop destruction from extreme weather events.

Given this situation, it is difficult to imagine the conditions under which a government would oppose preventive action based on the expectation of benefits from a changed climate. The existing uncertainties, particularly those concerning the nature, timing, and extent of the effects, ought to be sufficient to shatter any government's hopes of profiting significantly from climate modification. Hence, the concept of winners and losers only clouds the debate.

Other Reasons for Optimism

As the previous discussion indicates, a considerable basis exists for a meaningful a short-term international action program. At least four additional factors provide a basis for optimism. First, many of the potential solutions to the carbon dioxide problem do much more than prevent or mitigate global warming.[50] Energy conservation, renewable energy utilization, more efficient irrigation technology, and the development of crop varieties that flourish in a wider range of climate conditions are all economically desirable, whether or not a global warming occurs.

Second, many of the proposed actions can be promoted without threatening existing economic interests. Conservation does not have to completely substitute for coal to have a major impact.[51] Renewable energy technologies can help reduce carbon dioxide emissions without resulting in the loss of jobs in the coal industry. Moreover, many large energy companies are likely to participate in and profit from these alternatives. Insofar as these investments are (as expected) cost effective, the global economy will benefit, not suffer.[52]

Third, many valuable and effective steps can be taken without a formal international agreement.

Fourth, the sectors that require the principal attention--agriculture and energy--are those in which most governments have traditionally had a major role, so the prospect of further governmental intervention is not unthinkable. The responsiveness of these sectors to pricing and other policies has also been repeatedly demonstrated--a fact that, in conjunction with the considerations already noted, leaves us a good deal more sanguine about the prospects for effective governmental action than are most analysts.[53]

CONCLUSION

We have no illusions about the obstacles that might impede an effective response to the atmospheric buildup of greenhouse gases. Indeed, regardless of what we do in the future, it already may be too late to prevent a serious climate change.

However, we are convinced that the initial steps in both an adaptive and a preventive program of response are now justified. Many control strategies are both technically feasible and economically justified. Governments should adopt energy policies that encourage investments in increased energy efficiency and renewable energy technologies, thereby limiting the rate of fossil fuel combustion. International cooperation will ultimately be necessary, but unilateral actions can affect the rate of fuel consumption and are probably a prerequisite to extensive cooperative efforts.

In addition, it is imperative to expand the range of interests supporting a carbon dioxide action program. Although a program of global response to climate change is often thought to be supported by only a small band of well-informed scientists and environmentalists, it is evident that the potential constituency for such a program is much larger. As the body of knowledge concerning potential climate effects grows, the number of countries with an identifiable interest in such a program of action will increase. Recent developments suggest that coalition building among concerned industries may have already begun. In July 1984, the forest products industry sponsored a seminar on the consequences of climate change. This industry is accustomed to long planning horizons and is well aware of the sensitivity of forestry to environmental influences. The agricultural industry is less sensitive to the need to prevent long-term environment-related losses, but it too is a potential source of political support. Clearly, diverse and broad-based economic interests are at risk.

NOTES

1. J. Holdren, "Environmental Impacts of Energy Production and Use: A Framework for Analysis," in *Energy Information*, W. Hogan, ed. (Stanford, Calif.: Institute for Energy Studies, 1978).

2. For instance, see P. Ehrlich, A. Ehrlich, and J. Holdren, *Ecoscience: Population, Resources, Environment* (San Francisco: W.H. Freeman and Co., 1977).

3. J. Holdren, G. Morris, and I. Mintzer, "Environmental Aspects of Renewable Energy Sources," *Annual Review of Energy* 5 (1980): 241.

4. J. Holdren, "Energy Resources," in *Environment*, W. Murdoch, ed. (Sunderland, Mass.: Sinauer Co., 1975); and R. Budnitz and J. Holdren, "Social and Environmental Costs of Energy Systems," *Annual Review of Energy* 1 (1976): 553.

5. T. Wigley and P. Jones, "Detecting CO_2-Induced Climatic Change," *Nature* 292 (1981): 205.

6. C. Keeling, R. Bacastow, and T. Whorf, "Measurements of the Concentration of Carbon Dioxide at Mauna Loa Observatory, Hawaii," in *Carbon Dioxide Review: 1982*, W. Clark, ed. (New York: Oxford University Press, 1982).

7. R. Rotty, "Estimated CO_2 Emissions from Fossil Fuels," paper presented at the Oak Ridge National Laboratory Life Sciences Symposium, Knoxville, Tenn., October 31-November 2, 1983.

8. T. Graedel and J. McRae, "On the Possible Increase of Atmospheric Methane and Carbon Dioxide Concentrations During the Last Decade," *Geophysical Research Letters* 7 (1980): 977.

9. H. Craig, and C. Chou, "Methane: The Record in the Polar Ice Cores," *Geophysical Research Letters* 9 (1982): 1,221.

10. National Research Council, *Carbon Dioxide and Climate: A Scientific Assessment* (Washington, D.C.: National Academy of Sciences, 1979); Carbon Dioxide Assessment Committee, National Research Council, *Changing Climate* (Washington, D.C.: National Academy Press, 1983); and S. Seidel and D. Keyes, *Can We Delay A Greenhouse Warming?* (Washington, D.C.: U.S. Environmental Protection Agency, 1983).

11. W. Clark et al., "The Carbon Dioxide Question: Perspectives for 1982," in Clark, note 6 above; and National Research Council, *Carbon Dioxide and Climate* and Carbon Dioxide Assessment Committee, *Changing Climate*, in note 10 above.

12. J. Chamberlain et al., "Climate Effects of Minor Atmospheric Constituents," in Clark, note 6 above.

13. B. Groveman and H.E. Landsberg, "Simulated Northern Hemispheric Temperature Departures: 1579-1880," *Geophysical Research Letters* 6 (1979): 767.

14. C. Pearson and A. Pryor, *Environment: North and South* (New York: John Wiley and Sons, 1978); see also Clark et al. in note 11 above.

15. W. Broecker et al., "Fate of Fossil Fuel Carbon Dioxide and the Global Carbon Budget," *Science* 206 (1979): 409; World Climate Programme, *Assessment of the Role of Carbon Dioxide and Climate Variations and Their Impact* (Geneva: World Meteorological Organization, 1981); and J. Olson, "Earth's Vegetation and Atmospheric Carbon Dioxide," in Clark, note 6 above.

16. See note 12 above.

17. R. Rasmussen and M. Khalil, "Atmospheric Methane (CH_4): Trends and Seasonal Cycles," *Journal of Geophysical Research* 86 (1981): 9,826.

18. P. Zimmerman et al., "Termites: A Potentially Large Source of Methane Carbon Dioxide and Molecular Hydrogen," *Science* 218 (1982): 563.

19. J. Wehlan and H. Craig, "Methane and Hydrogen in East Pacific Rise Hydrothermal Fluids," *Geophysical Research Letters* 6 (1979): 829.

20. R. Revelle, "Methane Hydrates in Continental Slope Sediments and Increasing Atmospheric Carbon Dioxide," in Carbon Dioxide Assessment Committee, National Research Council, note 10 above.

21. R. Revelle, "Probable Future Changes in Sea Level Resulting from Increased Atmospheric Carbon Dioxide," in Carbon Dioxide Assessment Committee, National Research Council, note 10 above.

22. J. Hoffman, D. Keyes, and J. Titus, *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs* EPA 230-09-007 (Washington, D.C.: U.S. Environmental Protection Agency, 1983).

23. J. Mercer, "West Antarctic Ice Sheet and the CO_2 Greenhouse Effect: A Threat of Disaster," *Nature* 271 (1978): 321.

24. C. Bentley, "The West Antarctic Ice Sheet: Diagnosis and Progress," in *Proceedings of the Carbon Dioxide Research Conference*, CONF-820970 (Washington, D.C.: U.S. Department of Energy, 1983).

25. D. Abrahamson and P. Ciborowski, "Harvest of Sand," *Amicus Journal* 5 no. 4 (1984): 38.

26. G. Woodwell, "Earth's Vegetation and the Carbon Dioxide Question," in Clark, note 6 above; and G. Woodwell et al., "Global Deforestation: Contributions to Atmospheric Carbon Dioxide," *Science* 222 (1983): 1,081.

27. See Clark et al. in note 11 above.

28. Ibid.

29. J. Hansen et al., "Climate Sensitivity: Analysis of Feedback Mechanisms," in *Climate Processes and Climatic Sensitivity*, J. Hansen and T. Takahashi, eds. (Washington, D.C.: American Geophysical Union, 1984).

30. J. Hoffman and S. Seidel, "Limits to Preventing a Global Warming," this volume.

31. I. Mintzer and A. Miller, *Some Impacts of Energy Conservation and Renewable Energy Technologies on Global Emissions of Carbon Dioxide* (Washington, D.C.: World Resources Institute, forthcoming); see also note 7 above.

32. R. Williams et al., "A Global End-Use Energy Strategy," this volume.

33. Congressional Research Service, "A Perspective on Electric Utility Capacity Planning," prepared for the Subcommittee on Energy Conservation and Power, House Committee on Energy and Commerce (Washington, D.C.: Government Printing Office, 1983).

34. Northwest Power Planning Council, *1983 Northwest Conservation and Electric Power Plan*, vol. 1 (Portland, Oreg.: Northwest Power Planning Council, 1983); and Comptroller General of the United States, *New England Can Reduce It's Oil Dependence Through Conservation and Renewable Resource Development*, report to Congress (Gaithersburg, Maryland.: U.S. General Accounting Office, 1981).

35. R. Williams, G. Dutt, and H. Geller, "Future Energy Savings in U.S. Housing," *Annual Review of Energy* 8 (1983): 269.

36. California State Energy Resources Conservation and Development Commission, *1983 Electricity Report* (Sacramento, Calif., 1983); and G. Thompson and L. Weld, *A Second Chance: New Hampshire's Electricity Future As a Model for the Nation* (Cambridge, Mass.: Union of Concerned Scientists, 1983).

37. National Research Council, *Energy in Transition 1980-2000*, Report of the Committee on Nuclear and Alternative Energy Systems (Washington, D.C.: National Academy Press, 1980).

38. Mintzer and Miller in note 30 above.

39. See note 31 above.

40. Pearson and Pryor in note 13 above.

41. See note 12 above.

42. Rand Corporation, *Economic Implications of Regulating Chlorofluorocarbon Emissions from Non-aerosol Applications*, report to the U.S. Environmental Protection Agency (Washington, D.C.: Environmental Protection Agency, 1980).

43. See Seidel and Keyes in note 10 above.

44. U.S. Department of Energy, *Sunset Review: Program-By-Program Analysis*, Report to Congress (Springfield, Vir.: National Technical Information Service, 1982).

45. Energy Research Advisory Board, *Solar Energy Research and Development: Federal and Private Sector Roles*, A Report to the U.S. Department of Energy (Washington, D.C.: Government Printing Office, 1982); and Pacific Gas and Electric Co., *Long-Term Planning Results, 1983-2002* (San Francisco: Pacific Gas and Electric Co., 1983).

46. L. Dotto and H. Schiff, *The Ozone War* (Garden City, N.Y.: Doubleday Co., 1978).

47. T. Stoel, A. Miller, and B. Milroy, *Fluorocarbon Regulation: An International Comparison* (Lexington, Mass.: D.C. Heath and Co., 1980).

48. H. Heimsoeth, "The Protection of the Ozone Layer," in *Environmental Policy and Law*, vol. 10 (Amsterdam: North-Holland Publishing Co., 1983).

49. National Research Council, *Causes and Effects of Changes in Stratospheric Ozone: Update 1983*, report of the Committee on Causes and Effects of Changes in Stratospheric Ozone (Washington, D.C.: National Academy Press, 1984).

50. D. Scroggin and R. Harris, "Reduction at the Source," *Technology Review* 84 (1981): 22.

51. D. Rose, M. Miller, and C. Agnew, *Global Energy Futures and CO_2-Induced Climate Change*, MITEL 83-015 (Cambridge, Mass.: Massachusetts Institute of Technology Energy Lab, 1983).

52. L. Rodberg, *Local Employment Impacts of Energy Conservation and Renewable Energy Programs* (New York: Public Resources Center, 1982).

53. J. Acton and P. Mitchell, "The Effect of Time-of-Use Rates: Facts Versus Opinions," *Public Utilities Fortnightly*, 107 (1981): 19.

THE GREENHOUSE EFFECT: THE SOCIOECONOMIC FALLOUT

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INTRODUCTION

My assignment is to visualize a worst-case carbon dioxide/climate scenario during the early part of the twenty-first century, when there would still be time to take some action and the worst climate effects would not yet have come to pass. "Worst" is something of an ambiguous concept here, since it could refer to the worst climate effect or to worst outcome for any particular climate effect. The former notion focuses on Mother Nature and what she might do, given our current ignorance about atmospheric processes and the effects of increased atmospheric carbon dioxide. The latter notion focuses on human reactions to whatever climate changes do occur.

To ensure that my task is not too pedestrian, I am also asked to think about techniques for estimating risks and how well they might work. Would any such techniques be able to anticipate a carbon dioxide catastrophe reliably enough that scientists would believe the forecast and be able to convince political leaders and the general public? If so, can anything be done to avoid the catastrophe or at least to moderate the damage? I do not think of myself as modest, but I was a bit taken aback by the organizers' notion of a short essay. If I had the least good sense, I would stop at this point, throw myself on your mercy, and not undertake such an impossible assignment. But it is tempting to think about these issues...

A BEST-CASE CARBON DIOXIDE SCENARIO

To provide the setting for the extreme worst-case scenario, I want to sketch the outlines of an extremely benign scenario, one in which increased atmospheric carbon dioxide would have little or no effect on the climate. While this best-case scenario would appear to merit little attention, I beg your indulgence.

Major uncertainties about the effect of increasing atmospheric carbon dioxide concentrations form one of the central foundations upon which I will construct my best-case scenario. Such uncertainties have long been a part of the carbon dioxide issue. However, if such uncertainties continue, there will be no way to disentangle the usual variations in climate from the possible effects of increasing atmospheric carbon dioxide. Thus, were there to be a drought or unusually hot weather, some people, and even some scientists and the governments of some nations, would claim that this was the result of increased atmospheric levels of carbon dioxide and demand action. Lest this seem farfetched, I remember endless discussions during the 1950s of how each instance of bad weather was due to the atmospheric testing of nuclear weapons. Many people blamed every storm or drought on nuclear testing, although even at the time there was little scientific uncertainty about the degree to which such testing could affect the weather. Perhaps an even better example might involve the concern about the health effects of pesticides--for instance Agent Orange or ethylenedibromide--or from low-level radiation from nuclear power plants.

Public hysteria, even when it is in opposition to reasonably well-established scientific fact, can lead to extreme government action, such as the prohibition of various substances. When the scientific evidence is less firm, the actions can be even more extreme, as in the case of Love Canal or Times Beach. Frustration at an inability to understand the scientific basis of the hardware essential to our daily lives tends to produce extreme, irrational reactions.

Thus, one could sketch a worst-case outcome to even the best-case scenario, even one in which increased atmospheric carbon dioxide concentrations had no effect on climate. A cyclic drought, flood, or change in temperature could cause intense public feeling, which might be translated into extreme or even irrational government actions. Suppose, for instance, that in 2010 there were a reoccurrence of the dust bowl--half a decade of intense drought in the nation's breadbasket. Surely some people would ascribe this drought to the effect of increased atmospheric concentrations of carbon dioxide; they might be led by scientists claiming that the drought was due to the greenhouse effect. Models predicting precisely this midcontinent drought might form the basis of their "proof." If many people were to believe that increased atmospheric carbon dioxide concentrations were the cause of the drought, it is possible there would be precipitous action to shut down fossil fuel power plants, to stop coal exports, and to warn the Soviet Union and China that their failure to take similar actions would constitute a cause for war. From there it is not hard to continue the scenario right up to nuclear war.

But that scenario is absurd. Or is it? Current models do indicate that a midcontinent drought is a likely outcome. There is ample precedent for a severe prolonged drought. There are scientists now who ascribe current climate effects to increased atmospheric carbon dioxide. If the people of Minnesota, Iowa, Kansas, and so on were to be assured by credible scientists that drought could be due to elevated carbon dioxide concentrations, might they not demand immediate action of the sort I have sketched? China and the Soviet Union would be the focus of U.S. action, since our three countries have almost 90 percent of the world's coal reserves. In a twenty-first century context, the world is likely to be much more dependent on coal than at present. Oil would certainly not be the dominant fuel. Dependence on coal is likely to be highest in the three nations with the greatest coal reserves. Indeed, think of what our allies and trading partners might say were we suddenly to prohibit coal exports, which might by then have become their staple fuel. I don't know about you, but this scenario is worth one or two sleepless minutes to me some night. And this is the scenario with no carbon dioxide/climate effects.

A MID-RANGE SCENARIO

Now, consider instead carbon dioxide effects that are about the mid-range of what current atmospheric models predict. By the early part of the twenty-first century, there would be about a 40 percent increase in the atmospheric concentration of carbon dioxide relative to the preindustrial level. This would give rise to perhaps a 1.5 degree Celsius increase in average global temperature, with perhaps a 4 degree Celsius warming at the poles and no warming at the equator. This warming is somewhat greater than the temperature range observed in this century but smaller than the temperature range observed during the last thousand years. Changes in storm patterns could be more significant than the temperature rise, leading to precipitation changes. However, even such a change in precipitation patterns could easily be within the range of variation observed in the twentieth century.

Disruption In the United States Would be Small

What sorts of stress would such changes impose on the economy in particular and on society in general? Without seeming to be a linear descendant of Dr. Pangloss, I tend not to be terribly concerned about stress in the United States. Particularly in the post-World War II period, farmers have coped well with climate changes, and society seems to have averted catastrophes. This is not to say that there haven't been large costs associated with droughts, heat waves, and floods. However, the associated economic losses and loss of life have been tiny compared to the background levels and variation that would have been expected in the absence of the unfortunate events.

It is important to distinguish between the adjustments the individual worker, farmer, and distributor can make and the adjustments that require social action. Individual farmers can change the cultivars they plant or their cropping patterns. They can stop flooding their fields and utilize trickle irrigation. But they cannot undertake huge water projects that would bring millions of acre-feet of water from a thousand miles away.

Individual adjustment is likely to proceed more smoothly than social adjustment, since individuals will experiment and successful innovators will be copied. In contrast, the decision to commit billions of dollars to a water project is a large step. There must be general agreement that the project is socially desirable, funds must be available to pay for it, and water rights, the transport route, and the distribution of the water at its destination must be negotiated. One cannot experiment with such projects to determine social need and then slowly develop consensus on the best way to proceed. Thus, there is a good possibility that social adjustment would be slower, more ponderous, and less helpful than individual adjustment. Although I have vast faith in American farmers, I do not have the same level of trust in the institutions that would have to decide on water projects.

But will twenty-first century farmers, for example, be as good at coping with climate stress as current farmers? Again, I would observe that things seem to have gotten better, especially as a result of the extensive education of farmers, and also as a result of information and early warning, and of new equipment for coping with problems, including new stress-resistant cultivars. There is no firm assurance that this progress will continue, but I would put my money on the American farmer and other affected individuals.

World Disruptions Would Be Larger

When I look outside the United States, I am not sanguine. The Japanese are determined to grow large quantities of rice; consequently, they subsidize agriculture. Even a moderate climate change could make it much more difficult to grow rice in Japan. One can picture some stubborn Japanese farmer continuing to plant rice, no matter what occurred. Nor is it hard to imagine a stubborn Japanese government that continues to subsidize the production of rice even with domestic rice five to ten times more expensive than foreign rice. Or picture the French wheat grower: neither the resolutions of the French governments nor pressure by the Common Market appear to have had the slightest effect on the determination of French farmers to continue producing crops at costs significantly above world prices.

Fortunately, agriculture represents only a tiny proportion of these economies. Hence, not even a doubling or tripling of costs would sink the economies of Japan or France. The farmers of Japan and France seem to be able to ward off imports better than our steel or auto makers. Each nation has its sacred cows, and each seems extraordinarily willing to dump virtually unlimited amounts of money into defunct industries, thereby saving them from the rigors of competition. I do not criticize--that would be uncharitable, narrow-minded, and characteristic of someone who did not fully understand local reasons. However, I do note the possibilities for vastly increased agricultural subsidies in the developed countries, and for policies that direct much of the economic surplus into such a "rat hole."

Possible Disaster for the Less Developed Countries

The developed countries will survive--even survive handsomely. More worrisome are the less developed countries, whose gross national products (GNP) are dominated by agriculture (up to 90 percent of the GNP in some cases), and where there is less of a tradition of quick adaptation to change. The less developed countries possess much less of a resource base in educated farmers, agricultural extension services, and companies to invent and distribute new equipment, for instance irrigation, and cultivars that are better adapted to new climates. If one compares the drought in the Sahel with that in the U.S. midwest, one cannot help being struck with the triviality of the effects in the United States compared with the devastation wrought in Africa.

The lesson here is that the effects of increased atmospheric carbon dioxide will have much more to do with people than with climate. If humans and human institutions were to adapt quickly and competently, then even large climate changes would be likely to cause only a minor ripple in human events. If humans were to misperceive the events and their behavior were to prove dysfunctional, even the absence of climate effects could prove devastating. This is my central message, and I will repeat it in a number of ways. It is the lesson I want to take into the construction of a worst-case carbon dioxide/climate scenario, my assigned topic.

A Less Panglossian Assessment

Before doing that, it is worth examining whether I have pushed this observation too far. What would be the effect of a moderate climate change? Would it have no effect on farmers, the recreation industry, and society in general?

The costs of climate change would be large. Changed cropping patterns could lower the incomes of individual farmers significantly and cause many bankruptcies. Surviving farmers would have to spend large amounts of money adapting to the changed climate. However, since agriculture currently represents about 10 percent of the GNP, the magnitude of loss (with capital expenditures spread out over the lives of the investments) would be less than 1 to 2 percent of the GNP. Although this is a large amount of money, it is certainly not a catastrophe. Even after accounting for disruptions in transportation, the relocation of populations and industries, and effects on the recreation industry, the total loss would be unlikely to be as much as 2 to 3 percent of the GNP.

I hasten to add that a loss of 2 to 3 percent of the GNP is quite significant. However, it is not a disaster. Such a loss would have to be evaluated in terms of the probability of its occurrence and the cost of avoiding future climate changes. I will argue that the cost of avoiding climate change and the current estimates of the probability of its occurrence would not lead to definitive action. That would be warranted only if a genuine catastrophe were threatened.

A WORST-CASE SCENARIO

In view of the argument so far, it should be clear that a worst-case scenario is defined more in terms of human reactions than climate effects. Short of climate changes that make the world virtually uninhabitable, which no one is suggesting, human adaptation is more important than the changes to which humans have to adapt. This is certainly true for the early twenty-first century, when carbon dioxide/climate effects would necessarily be relatively small. But it is also true for the twenty-second century, when climate change could be really important. By then, we could have a full doubling of atmospheric carbon dioxide concentrations, a 10 degree Celsius increase in temperature at the poles, and a 4 degree Celsius temperature increase averaged over the globe. Precipitation and storm patterns could be greatly affected, with areas like the Great Plains in a permanent drought.

Sylvan Wittwer notes that a doubling of atmospheric carbon dioxide cannot be all bad for plants. They grow much better in high carbon dioxide environments. The elevated temperature is likely to produce more precipitation, although not necessarily in the same spots as at present. However, we transport water over great distances now. We also manage to grow crops in desert areas, such as the Imperial Valley in California or the Negev desert in Israel. Trickle irrigation uses a tiny proportion of the water ordinarily required for irrigation. There is clearly a trade-off between capital and other costs and water use. Trickle irrigation requires a substantial capital expenditure. Plastic stretched over the ground slows evaporation. Some cultivars are less sensitive to heat and require less water. It seems likely that even dramatic climate changes could be managed with the knowledge and capital in developed countries. It also seems likely that the less developed countries would fare less well than the developed countries.

So, we are back to my central theme: how will people react? Will their behavior be responsive and helpful or will it be dysfunctional? Will they have sufficient resources--scientific and economic--to react properly or will the capital requirements of, for instance, trickle irrigation, exceed their means? Will they be able to construct multibillion dollar projects to bring in water for irrigation? Will they be able to solve the agronomic problems encountered in a carbon dioxide-induced climate change, including those relating to insects, weeds, and disease? Will they be willing to shift their diet toward foods that grow best under the changed climate conditions, such as wheat rather than rice? Will they be able to cope with new patterns of international trade, with new nations exporting food?

RESEARCH AND DEVELOPMENT AND RISK ASSESSMENT

Not having a crystal ball, I have no ready answers to my conundrum. But I do have some predictions, or at least ways of thinking the problem through. A good deal of money is currently being spent to improve the models used to predict the climate effects of increased carbon dioxide concentrations. I wonder whether that should be the focus of present research and development. On the straight science side, there is much to be done in exploring techniques for trapping water and bringing it in for irrigation. What is the next generation after trickle irrigation? There is a need to develop cultivars that are more heat and drought resistant. There is a need to develop ways of coping with pests. As the climate warms, areas further north will no longer have a hard winter freeze to kill pests. The warmer climate will change the microecology of our best farm land. There are a long list of questions needing answers, and many of these answers would be valuable in some areas today under the current growing conditions.

The larger need is to understand how cultures and institutions react to particular stresses. How adaptable are current institutions? What can be done to make them more adaptable? Which nations are likely to be most at risk, with the gravest consequences? I cannot promise results, and especially not helpful results, from the behavioral research. But it is easy to conclude that the other solutions won't matter unless the behavioral problems are solved.

It seems obvious that the less developed countries will be hardest hit by climate change. Even a "beneficial" climate change will cause problems if the developing countries continue to plant the old crops in the old ways. Although a catastrophe for the developed countries is unlikely, there is a far greater chance of catastrophe for the less developed countries. One scenario that could translate into catastrophe for the United States might involve Third World terrorism, even nuclear terrorism, perhaps designed to convince the United States to stop the burning of fossil fuel and help the starving nations. One way or another, something would have to be done by the developed nations to help the less developed nations.

Forecasting and Assessing the Risk

Current risk-assessment techniques focus on two basic problems: (1) an estimation of the probability of a particular undesirable event occurring--for example a boiler explosion or an airplane crash; and (2) an estimation of the probability of a disease resulting from exposure to toxic substances. In the former case, the outcome is easy to specify; what is difficult is imagining the ways each element interacts with others to affect the probability of a mishap. In the latter case, we know that exposure to some substances at high doses is likely to cause disease in rodents. We do not know what happens to humans at low exposures; assumptions are involved when one extrapolates from rodents to humans and from high to low doses. Although both issues involve various assumptions, more assumptions are required in the latter case.

The effects of carbon dioxide are more like the latter case than the former. At present, we do not know the extent of future carbon dioxide emissions, the effect of carbon dioxide emissions on the climate, or how society will cope with climate change. Thus, three levels of uncertainty interact to obfuscate analysis.

As a result, no confident predictions can be given. This inability to predict is combined with the enormous cost of carbon dioxide emissions' reductions. Fossil fuels are by far the cheapest current source of energy. In the developed countries, there is a widespread reluctance to increase reliance on nuclear power, even apart from the increased cost. A decision to terminate fossil fuel combustion in the United States would be a momentous one in terms of cost, life style, and the acceptance of new technologies and their dangers. But over a period of several decades, it would be possible to implement such a decision. In the less developed countries, such a decision would be impossible to implement. Even if the developed nations offered to pay for a switch to non-fossil fuels and provide the expertise for doing so, one might forgive the developing countries for being suspicious and reluctant to completely entrust their fate to the United States, the Soviet Union, and the former colonial powers. Furthermore, technologies such as nuclear power are unsuited to the life styles encountered in developing countries and are not really substitutes for fossil fuels. Thus, if the world found itself in a situation in which it was desirable or necessary to stop all fossil fuel combustion, the developed countries would probably resist due to the cost and fear of nuclear technology, and the less developed countries would probably be reluctant to throw themselves at the feet of the developed countries or adopt technologies unsuited to their ways of life. I doubt that a worldwide switch to non-fossil fuels could be accomplished without a major war.

Far short of that, it is difficult to believe that the developed nations would curtail the use of fossil fuels, or even curtail the growth of fossil fuel use, without convincing evidence of major and undesirable carbon dioxide-induced climate effects. Given the cost of action, I am pessimistic that anything would be done until the climate effects had been demonstrated, and this would require a substantial further increase in atmospheric carbon dioxide concentrations. If you were advising the president or Congress, what level of assurance would you want before advocating a program costing hundreds of billions of dollars and requiring substantial decreases in energy use, major changes in life style, and principal reliance on nuclear energy?

CONCLUSION

Let me state the theme one last time: significant climate change could impose large costs on the U.S. economy, possibly on the order of 2 to 3 percent of the GNP. The costs in other developed countries could be even larger, particularly in countries that seek to continue producing crops that would have to be grown under increasingly artificial conditions. However, with adaptation, the cost would be much smaller. In view of the monetary and other perceived costs associated with a limitation on fossil fuel use, I doubt that the United States would be willing to stop or even significantly diminish fossil fuel burning until the effects of atmospheric carbon dioxide buildup were shown to be large and costly. Only a threatened catastrophe, which seems unlikely in the developed countries, would motivate immediate action.

The costs and catastrophes associated with the greenhouse effect are specific to the poor countries. There, even a moderate climate change threatens disaster and vast changes in their current cultures. However, the change from fossil to nonfossil fuels creates special problems for these countries, since they do not have the required technology and the technologies tend to be unsuited to their life styles.

If a catastrophe is in store for the developed countries, it is likely to be in the form of war or terrorism stemming from attempts to compel other nations, developed or poor, to stop large-scale fossil fuel combustion.

If the costs of climate change are to be kept to bearable levels, emphasis must be placed on adaptative measures, particularly measures which make individuals and institutions adaptable and which provide for the transfer of farming practices and cultivars adapted to a changed climate. A great deal of research and development is required, almost all of which would be of value today. The agenda for current action is different from the one that is usually advocated.

THE GREENHOUSE PROBLEM: THE ROLE OF UNCERTAINTY

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INTRODUCTION

The combustion of any fossil fuel releases carbon dioxide to the atmosphere. Carbon dioxide is a greenhouse gas and acts to alter the energy balance of the planet. Large-scale fossil fuel energy systems emit an enormous amount of this gas, which can accumulate in significant concentrations in the atmosphere. Given significant accumulations, the Earth's climate will change.

A number of governmental and quasi-governmental bodies have examined the issues surrounding the release of carbon dioxide to determine whether sufficient information is now available for society to establish a policy on further emissions. The widely held view, as perhaps best represented by the National Academy of Science's Carbon Dioxide Assessment Committee (NAS-CDAC), holds that this information is still lacking.[1]

An assessment of the adequacy of the available information depends on the information that is thought to be important, and this can entail subjective, even political, judgements. Hence, many different assessments may be possible. We examine the evidence below, concentrating on those issues which either are thought to be too poorly defined to inform the issue at hand or are thought to confirm the NAS-CDAC's judgement as to the inadequacy of the available information. To focus the discussion, we have narrowly constrained it to a single issue: the advisability of the continued release of carbon dioxide. In so doing, we find that, although uncertainty is an important element of the problem, it by no means precludes a policy response.

THE CARBON DIOXIDE PROBLEM

The carbon dioxide problem results from the emission of carbon dioxide to the atmosphere.[2] Carbon dioxide is a by-product of the combustion of fossil fuels. Carbon dioxide is important principally as an infrared active gas; it is essentially transparent to short-wave solar radiation, but is opaque to long-wave radiation or heat. Once present in the atmosphere, carbon dioxide allows short-wave solar radiation to penetrate relatively unimpeded to the surface of the earth, and to warm it, but impedes the escape of infrared radiation, or heat, to space. In increasing concentration, it acts to increase the atmosphere's resistance to the loss of heat, thereby raising global surface temperatures. Due to society's present commitment to the fossil fuels, a doubling or tripling of the present atmospheric concentration of carbon dioxide is not thought unlikely. Such an increase in the atmospheric level of carbon dioxide would substantially raise the surface temperature of the earth.

Carbon dioxide is not the only pollutant that is important for the future of the climate. Particulates can act to cool the planet. Other gases, like methane and the chlorofluorocarbons, act in the atmosphere like carbon dioxide and tend to warm the planet. The effect of particulates is small. The warming contributed individually by the other gases is relatively small, although in aggregate the other gas warming may be large.[3] It is generally agreed that the rate of atmospheric accumulation of carbon dioxide is the single most important factor governing the future of the climate. In conjunction with the other gases, it will result in a climate change broadly analogous to the largest changes of the last twenty or so million years.

THE CARBON DIOXIDE ASSESSMENT BOARD

Inherent in the carbon dioxide, or greenhouse, problem, one finds not one policy problem but many. Some that come readily to mind revolve around the legal ramifications of long-term environmental change and around considerations and mechanisms of international equity. Others center on the role of international institutions and on questions of intergenerational equity. Still others focus on the political relevance of the problem.

One policy question stands before all others: should present policies that promote, or do not hinder, releases of carbon dioxide be continued? It is often suggested that the uncertainties that surround these releases make any realistic policy assessment impossible. The NAS-CDAC concludes that the uncertainties in the physical science of climate change and our inability to predict future economic and technological developments render hopeless any current attempt to formulate policy.[4] Welfare economics, it notes, offers little guidance regarding either the utility of control measures or, if controls are to be implemented, the stringency of controls. It concludes that, rather than preemptive preventive action, a well-developed program of research should be instituted to narrow the uncertainties.

The NAS-CDAC stresses the risks of unnecessary action. It notes our inability to forecast technological change or those market conditions that will govern the future rate of fossil fuel use, concluding that actions taken now to reduce carbon dioxide emissions may be unnecessary. It notes that the existence of uncertainties in the physical science underlying our understanding of climate change may lead to the same conclusion. Given the risks of unnecessary action, the NAS-CDAC categorically rejects the preventive response.

To reject the preventive response, it is necessary to propose an alternative, and the NAS-CDAC advocates an adaptive response. Due to the assumptions it makes about the sensitivity of mean global temperature to carbon dioxide, and about the rate of its atmospheric accumulation, the NAS-CDAC assumes a very limited warming, about 1.5 to 3 degrees Celsius over the next ninety years. Thus, it is able to assume a fairly narrow assemblage of impacts. By assuming a relatively small warming, and future boundary conditions not much different than those of the present, the NAS-CDAC is able to conclude that adaptation is feasible. To the degree that adaptation is reasonably certain, the NAS-CDAC is able to largely ignore the risks of inaction and to center its argumentation on the risks of unnecessary action.

But there is some question as to whether a 1.5 to 3 degrees Celsius mean global warming is a reasonable warming against which to weigh policy. There is evidence that the climate sensitivity that was employed to make this estimate might have been better chosen to more appropriately bound the uncertainties.[5] In addition, carbon dioxide is the only gas considered, and the other gases like methane, which the NAS-CDAC suggests might be more easily limited than carbon dioxide, are left out of the calculation. There is little reason to believe that releases of most of these gases are controllable, but much evidence to suggest that these gases are best treated as background changes upon which the effect of a changing atmospheric carbon dioxide concentration will be superimposed.

In addition, the NAS-CDAC assumes an ease of societal adjustment to climate change which makes its analysis suspect. Arguing from an analogy to the historical movements of peoples across climatic boundaries, the NAS-CDAC suggests that a change in climate would not be a new experience to the individual but a common one born of sporadic cross-country relocations. From this, as well as from such pieces of logic, as "there is probably some positive association between what we can predict and what we can accommodate,"[6] the NAS-CDAC concludes that human beings and societies are highly adaptable. But the analogy is not persuasive, since the unit of interest is not the individual but society, and the latter is much more complex than the individual, and its operation is less well understood. Neither is the NAS-CDAC's appeal to successes in two limited areas--American agriculture and the Netherlands' effort to hold back the sea--convincing. The NAS-CDAC does not consider the economic costs of an adaptive response, and makes no effort to rigorously address its nature or preconditions.

Taken together, these considerations render the NAS-CDAC analysis suspect. The assessment addresses the risks of unnecessary action but not the risks of inaction. It advocates that society direct its collective speculative faculty to future adaptations as a means to inform policy, but fails to ask the hard questions regarding the informational requirements of adaptation or the magnitude and rates of climatic change to which adaptation is best suited. Most problematic of all, in assuming a warming of less than 3 degrees Celsius in about a century, it never has the opportunity to test its analytical approach against a realistic estimate of the impending changes.

To test our own analytical approach, we attempt in the following sections of this paper to rethink the policy response in light of more realistic estimates. In the first section, we present a physical description of the problem. In the second, the conditions that might possibly justify inaction are considered. In the third, the most important physical science uncertainties are treated, and in the fourth section, the policy responses that are open to society are considered in light of uncertainty, the intensity of the expected changes in climate, irreversibility, and other considerations. In the final sections, objections to the preventive response are treated.

ESTIMATING FUTURE CLIMATES AND IMPACTS

Policy will be made based on climate changes taking place on at least three different time-scales: the next twenty to thirty years; the entire period of anthropogenic change (e.g., the next several hundred years); and the next 100 years. Below the effects of climate changes on these three different time-scales are considered.

An Algorithm for Estimating Future Warming

The rate of future warming is controlled by a limited number of parameters. These include: the climate sensitivity; the fractional increase in the atmospheric level of carbon dioxide; an other gas parameter; and the ocean thermal delay. The climate sensitivity determines the climate response to an increase in the atmospheric level of carbon dioxide. The carbon dioxide concentration is controlled by the rate of fossil fuel combustion and the emission of carbon from other sources, many of which are temperature sensitive. The other gas parameter, a scaling parameter that amplifies the carbon dioxide-induced warming by some fractional amount, accounts for the effect of gases like methane. The ocean thermal delay adjusts for the time of warming. Given a projected atmospheric buildup of carbon dioxide, it is a reasonably simple matter to calculate the climate response to it, and an approximate value for the other gas warming, resulting in a rough estimate of the resultant warming, and then place it effectively in time. The relationship between the climate response and the atmospheric level of carbon dioxide is logarithmic; that between the other gas warming and the carbon dioxide-induced warming is roughly linear and additive. The "other carbon emission" can be treated as a constant unit increase in the level of carbon dioxide at the time of a doubling.

Rough estimates for each of the controlling parameters, or for their principal components, are given in Table 1. To provide a benchmark around which to ground the discussion, the warming that might be experienced at the time of a doubling of the atmospheric carbon dioxide level is also given.

Table 1
PARAMETERS GOVERNING FUTURE WARMING

Parameter	Value
Climate sensitivity to a doubling of CO_2	2-4 degrees C
Other gas warming	100-150% of CO_2
Other carbon emission	75-125 ppmv
Ocean thermal delay	15-40 years
Warming at the time of a doubling	4-5 degrees C

Adapted from: P. Ciborowski and D. Abrahamson, this volume.

The Next One-Hundred Years

Based on contemporary energy forecasts, the emission of carbon dioxide to the atmosphere from fossil fuel combustion will raise its atmospheric concentration to about 440 to 480 parts per million (ppmv), 540 to 600 ppmv, and 670 to 760 ppmv by 2025, 2050, and 2075, respectively.[7] In response, mean global temperature would rise on the order of 1 to 2, 2 to 4 and 3 to 6 degrees Celsius, respectively, and the other gases would double this.[8] From Table 1, the ocean's heat capacity will delay the full response from fifteen to forty years. Thus, by 2075, a 4 to 5 degrees Celsius rise in mean global surface temperature would result.

Over the short-term, the next thirty years, mean global temperature might rise 1 to 1.5 degrees Celsius. In response, a generally drier middle latitude climate would result.[9] The largest effects would be on agriculture. The results of crop-weather models for the changes in climate that are likely in thirty years are shown in Table 2. While worrisome, they are probably not of a sufficient magnitude to elicit a policy response.

The same cannot be said of the one-hundred year change. By 2075 the climate will be very different from that of the present, probably something akin to the climates of 5 to 40 million years ago when, during the late Tertiary, the Arctic basin was without the present floating ice cap.[10] The clearance of ice from the Arctic basin probably marks a point at which the climate undergoes radical reordering. The removal of the pack ice, first occasionally in summer, then permanently in summer, and finally year-round, would fundamentally alter the boundary conditions on climate, and this suggests a schedule of radical, discontinuous changes and climates remarkably different from those of the present.[11]

Not a great deal is known about the particulars of the climate under such conditions. Geological evidence extracted from past climates suggests a poleward recession of climatic boundaries in the middle and high latitudes many hundreds of kilometers (km) from their present position.[12*] But, by and large, the conditions of such a change in climate are a mystery, and it is particularly from this mysterious quality that many of the most disturbing aspects of the change arise.

Finally, based on a realistic portrayal of the delays resulting from the heat capacity of the oceans,[15] and on a slightly wider range of parameter estimates than is given in Table 1,[16] the mean global temperature rise would be on the order of 0.5 to 1 degree Celsius per decade (see Figure 1).[17]

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*These included a more northerly placement than at the present of the boundaries of subtropical (600 to 1200 km) and temperate (800 to 1200 km) climates;[13] easterly displacement of arid climates in North America (850 to 1300 km, from central Texas, eastern New Mexico and Utah, and eastern Oregon to southern Alabama, central Missouri, and eastern Montana); and displacement of the arid zone in the European sector (800 to 1500 km, from Gibraltar, Sicily, and Greece to central France, Poland and the Ukraine).[14]

Table 2
IMPACTS BY LATITUDINAL REGION

Region or Country and Latitude	Increase in Regional Temperature (degrees C)	Change in Rainfall (in percent)	Change in Agricultural Yields (in percent)
35-42 N United States	2	-5	corn, soybeans -10[a]
35-48 N United States	2	-10	winter, spring wheat -10[b]
48-52 N Canada	2	0	spring wheat +4[a]
40-53 N U.S.S.R. (20-45 E)	1	-5	winter wheat +0.1 to -9[b,c]
45-60 N U.S.S.R. (45-90 E)	1.4	+6	spring wheat +7[d]
25-30 N India	0.75	0	wheat -4[d]
7-12 N India	0.75	+2	rice -0.5[d]
22-32 S Brazil	0.75	+2	corn, soybeans -2[d]
22-32 N China	0.75	+2	rice -0.5[d]
32-40 N China	1	+2	wheat +1.5[d]
33-38 S Argentina	1	+2	wheat -3.5, corn -3[d]
30-37 S Australia	1	+2	wheat -4.5[d]

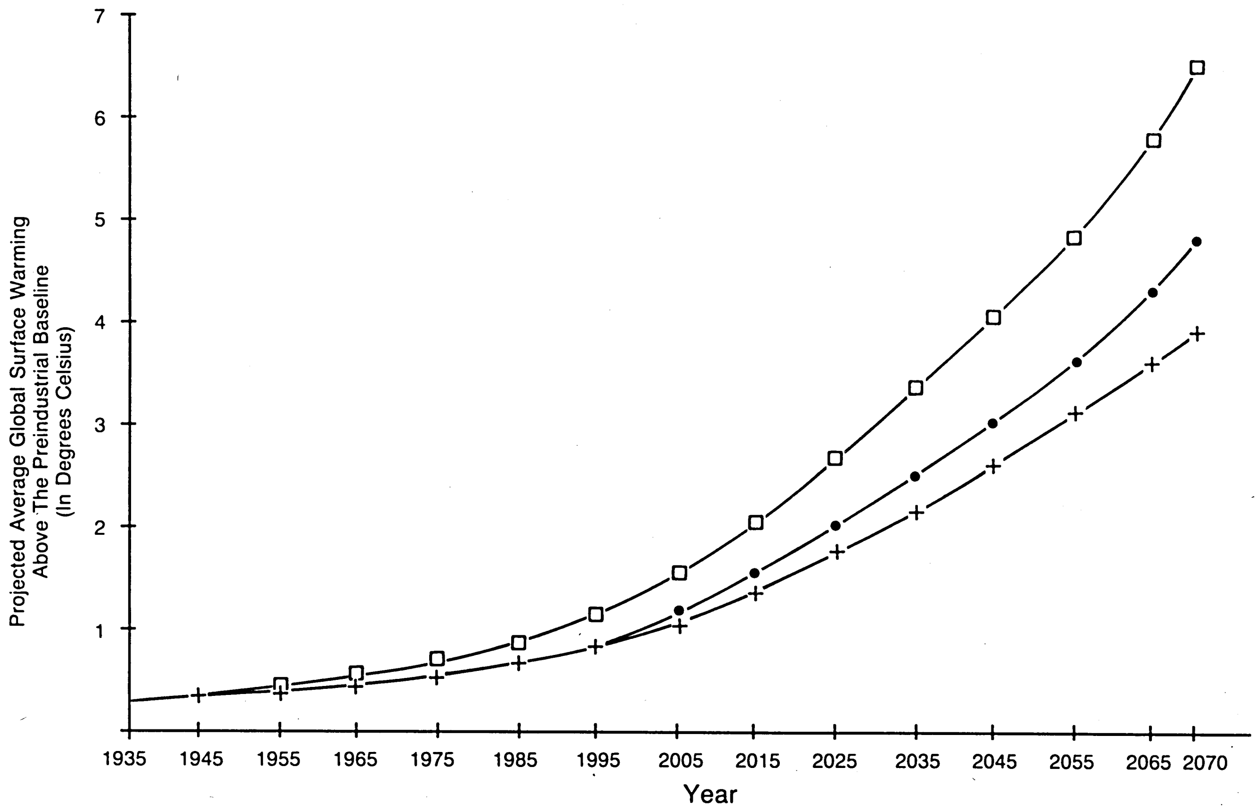
(a) See National Defense University, as reported in R. Shaw, "Climate Change and the Future of American Agriculture," in *The Future of American Agriculture as a Strategic Resource*, S. Batie and R. Healy, eds. (Washington, D.C.: Conservation Foundation, 1980).

(b) See Climatic Impact Assessment Program, *Impacts of Climatic Change on the Biosphere*, CIAP monograph 5 (Washington, D.C.: U.S. Department of Transportation, 1975).

(c) The effect of a 5 percent reduction in precipitation is assumed to be the average of the yield response for cases in which precipitation is reduced 0 percent and 10 percent.

(d) National Defense University, *Crop Yields and Climate Change to the Year 2000*, vol. 1 (Fort Lesley J. McNair, Washington, D.C.: National Defense University, 1980).

Figure 1
PROJECTED MEAN GLOBAL SURFACE WARMING FOR THREE CLIMATE SCENARIOS



□-□ = Case A (high case): fossil fuel-related carbon dioxide emissions increasing 2 percent per year, 4.2 degrees Celsius climate sensitivity, and an other gas (OGG) warming equal to 150 percent of the carbon dioxide-induced warming.

●-● = Case B (medium case): fossil fuel-related carbon dioxide emissions increasing 2 percent per year, climate sensitivity of 3.5 degrees Celsius, and an OGG warming equal to 100 percent of the carbon dioxide-induced warming.

+-+ = Case C (low case): fossil fuel-related carbon dioxide emission increasing 1.5 percent per year, climate sensitivity of 2 degrees Celsius, and an OGG warming by 2070 of 2.2 degrees Celsius.

<u>The Very Long-Term Warming and Its Impacts</u>

Complete combustion of the fossil fuels would result in an atmospheric level of carbon dioxide approximately four to six times the present level and in a warming of 4 to 10 degrees Celsius.[18] If we account for the other gases, the long-term warming at its peak would be at least three to four times greater than the warming addressed by the NAS-CDAC.

The decay times associated with any high atmospheric level of carbon dioxide are typically estimated in many hundreds of years; about 700 years is needed for a one-third decay of any particularly high atmospheric level of carbon dioxide.[19] In the case of a sustained global surface warming, this would be delayed somewhat by the emission of carbon dioxide from the oceans, which when warm are able to hold less dissolved carbon dioxide, and the biosphere. Soil respiration increases with surface temperature.[20] The estimates suggest long-term releases on the order of 700 to 1300 gigatons (GT).[21] Upon its final decay, approximately one-seventh of all carbon dioxide added to the atmosphere during the industrial age will remain, leading to a steady-state level in the case of the combustion of 100 (50) percent of economically exploitable fossil resources of about 550 (415) ppmv.[22]

Over long periods, a substantial warming would affect the earth's ice sheets. The resulting three hundred-year rise in sea level might be as much as 4.6 to 9.7 meters.[23] Over shorter periods, 110 years, sea level would rise perhaps 1.5 to 2 meters.[24] Cities that would be affected by a sea level rise of 0 to 3 meters (0 to 10 feet) are shown in Table 3.

Mean global surface temperature will remain substantially elevated for a lengthy period of time--as much as 1 to 4 degrees Celsius even after steady-state levels are achieved. It is in this essential irreversibility that the policy significance of the very long-term warming resides.

Impacts of the One-Hundred Year Warming

The potential impacts of the one-hundred year warming will be pervasive and affect nearly all sectors of society. Below we consider the nature of the impacts, their sign, and their intensity.

Sensitivity of Society to Climate Change: From a global perspective, temperature and water availability represent the principal climate constraints to human activities. Constraints of extreme cold limit the populations of the cool and cold climates to but a small fraction of global population. Most of humanity can be found in tropical and subtropical climates, and here the effects of persistent heat and water scarcity represent the dominant climatic barriers to development.

In the future, most of humanity will continue to live in the tropics and subtropics, if only due to the population dynamics in the developed, or middle and high latitude, nations, which are likely to favor only slight changes in population, or to international barriers to migration.* A global warming will tend to increase heat-related constraints in tropical and subtropical regions, and, given the distribution of global population, this will represent the principal effect on the global population.

Economic Impacts: The economic impacts have been estimated for some climate-sensitive activities, including salt water intrusion control and coastal water consumption,[25] coastal flood control,[26] tourism,[27] coastal and

*To represent a significant trend, migration from the south to the north would need to be on a scale that, were it to be directed toward Canada or the Soviet Union, would overwhelm existing populations and, in this sense, is politically impossible.

estuary development and recreational use,[28] agriculture,[29] electrical consumption, other consumption and wage rates,[30] streamflow-dependent activities (e.g., irrigation, power generation),[31] and beach erosion and snow removal activities.[32]

Table 3
WORLD CITIES AT SEA LEVELS BELOW VARIOUS EXPECTED SEA LEVEL RISES

Approximate Sea Level Rise (in feet)	Cities
0-2	Cartagena; Kochi, Japan.
3-4	Bahrain; Hampton, U.K.; Pandang, Indonesia; Severodvinsk, U.S.S.R.; Szczecin, Poland; Tokoshima, Japan; Venice, Italy.
5-6	Amsterdam; Apia, Samoa; Dunedin, N.Z.; Galveston, U.S.; Miami Beach, U.S.; Mobile, U.S.; New Orleans, U.S.; Papeete, French Polynesia; Tuticorn, India.
7-8	Calais, France; Coatzacoalcus, Mexico; Daytona Beach, U.S.; Florianopolis, Brazil; Fort Lauderdale, U.S.; Fukuoda, Japan; Georgetown, Guyana; Gdynia, Poland; Key West, U.S.; Leningrad, U.S.S.R.; Nigata, Japan; Saint Augustine, U.S.; Semarang, Indonesia; Trieste, Italy; U. Pandang, Indonesia; Ganjul, Gambia.
8-10	Abadan, Iran; Alicante, Spain; Alborg, Denmark; Annaba, Algeria; Atlantic City, U.S.; Bandar Seri, Begwan; Basra, Iraq; Bilbao, Spain; Bremen, West Germany; Bridgeport, U.S.; Cannes, France; Charleston, U.S.; Charlottetown, Canada; Chinwangtoa, China; Delft, Netherlands; Gillingham, U.K.; Guayaquil, Ecuador; Haarlem, Netherlands; Hialeah, U.S.; Hollywood, U.S.; Hull, U.K.; Iwaki, Japan; Keelung, Taiwan; Kurashiki, Japan; Lagos, Nigeria; La Spezia, Italy; Livorno, Italy; Libreville, Gabon; Malmo, Sweden; Messina, Italy; Miami, U.S.; Natal, Brazil; Newport, U.S.; Niteroe, Brazil; Norfolk, U.S.; Noumea, New Caledonia; Okajama, Japan; Palm Beach, U.S.; Peterborough, U.K.; Pontianik, Indonesia; Port Arthur, U.S.; Portsmouth, U.S.; Seattle, U.S.; Tel Aviv-Jaffa, Israel; Utrecht, Netherlands; Valencia, Spain; Vallejo, U.S.; Veracruz, Mexico; Visakhapatnam, India; Victoria, Brazil; Yokkaichi, Japan; Yonkers, U.S.; Zaanstad, Netherlands.
11	Gibraltar, U.K.; Tientsin, China; Yingkow, China.

Source: V. Showers, *World Facts and Figures: A Collection of Comparative Information about Cities, Countries, and Geographical Features of the World* (New York: John Wiley and Sons, 1974).

Climate-related economic impacts result from a number of factors. Impacts can result from changes in the yields of biological resources or of water yields in drainage basins.[33] Other impacts can result from the direct effects of increased temperature on heat-sensitive activities, such as space heating or cooling. Human performance is affected by heat and humidity, and impacts on biological, water, or labor yields affect the location of production centers.

Efforts to remedy the effects of climate change on human activities can also involve significant economic costs, a few of which have been estimated (see Table 4). These suggest that the secondary costs of some regional climatic changes could be large. Examples of particularly costly adaptations include: the expansion of the operating parameters of water projects to account for all possible future climate states; and the planned relocation of primary agricultural and forestry lands and sensitive human populations.

Regional Carrying Capacities: Climate impact assessment has focused on a few isolated economic activities and has rarely considered the cumulative effect on society of sustained multiple economic and ecological pressures. This is problematic, if only because systems-level responses, for instance the long-term response of the economic system to inter-regional capital movement, can be among the most important regional consequences of a change in climate. Effects accumulate; pressures from multiple impacts build and create new, larger, and more complex problems; the net effect can exceed the sum of all the individual effects.

Change in regional carrying capacity is a good indicator of such systems-level change. Many spring and summer activities in the midwestern and western United States, for example, are climate sensitive (see Table 5). The expected change in the United States is toward a warmer, much drier climate.* Average regional temperatures in the central United States will be 4 to 10 degrees Celsius warmer.[35] Reductions in available spring and summer soil moisture of 15 to 50 percent are thought likely in response to increased surface evaporation,[36] and, since precipitation in continental interiors tends to vary with available soil moisture, summer precipitation should also decline.** The frequency of summer drought should increase.

Initial calculations also suggest reduced surface runoff and reduced streamflows and lake levels for the five month spring and summer period.[37] If evaluated solely in terms of precipitation change, the decline in summer runoff in arid regions might, with a 10 percent reduction in precipitation, be about 50 percent;[38] if more terms are entered into the equation, reductions in

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*For purposes of estimating impacts, Tertiary-like changes are taken to be the likely changes.[34]

**Globally, precipitation is expected to increase about 7 percent. But summer precipitation constitutes, on average, 40 percent of the annual rainfall total throughout the heart of the region (from west Texas and New Mexico to North Dakota and eastern Montana), which therefore seems unlikely to experience much of an increase in storable water.

Table 4
SOME EXAMPLE ECONOMIC COSTS OF ADAPTING TO GLOBAL WARMING

Example U.S. Impact, 2 to 3 Degrees Celsius Warming, 2000 to 2025	Cost (in billion $)
Agricultural relocation[a]	$27 (1971 $)
Increased electrical generating capacity[b]	$7-12 (1985 $)
Corn belt irrigation[c]	
Capital costs	$21-32 (1982 $)
Operating costs	$0.8-1.3 per year
Ogallala-Missouri-Arkansas transfers[d]	$3.6-20 (1977 $)
Superior-Missouri transfers[e]	$20 (1982 $)

(a) See J. Niedercorn, "The Capital Costs of Climatically Induced Shifts in Agricultural Production: The Example of the American Corn Belt," in *The Urban Costs of Climatic Modification*, T. Ferrar, ed. (New York: John Wiley and Sons, 1976).

(b) This assumes a 10 percent increase in needed capacity. See E. Larson, D. Abrahamson, and P. Ciborowski, "Effects of Atmospheric Carbon Dioxide on U.S. Peak Generating Capacity," *IEEE Technology and Society Magazine*, December 1984. Present capital costs are assumed to be $570 per kilowatt of installed capacity. See F. Horn and M. Steinberg, "Control of Carbon Dioxide Emissions from a Power Plant," *Fuel* 61 (1982): 415. Present generating capacity is 98,765 megawatts of electricity, and is assumed to increase 1.5 percent per year to 2030.

(c) Assumes a capital cost of $400 to 600 per acre, and 59.5 million presently unirrigated acres in the corn belt, lake states and northern plains producing region; see W. Sundquist, K. Menz, and C. Neumeyer, *A Technology Assessment of Commercial Corn Production in the United States*, Agricultural Experiment Station, Station Bulletin 546-1982 (Minneapolis: University of Minnesota, 1982). Ten percent of present acreage with present cultivars is assumed to go without irrigation; see T. Blasing and A. Solomon, "Response of the North American Corn Belt to Climatic Warming," *Progress in Biometeorology* 3 (1984): 311.

(d) See High Plains Associates, "Six-State High Plains-Ogallala Aquifer Regional Resources Study," a report to the U.S. Department of Commerce and the High Plains Study Council, Six State High Plains-Ogallala Study, Austin, Tex., 1982.

(e) See J. Bulkley, S. Wright, and D. Wright, "The Diversion of 283 cubic meters per second (10,000 cfs) from Lake Superior to the Missouri Basin, *Journal of Hydrology* 10 (1982): 22.

Table 5
CLIMATE SENSITIVE ACTIVITIES AFFECTING FUTURE REGIONAL CARRYING CAPACITY

Activity	Sensitive Climate Variable
Animal agriculture	Summer dryness
Grain and vegetable agriculture	Peak heat, dryness
Ranching and grazing	Summer dryness
Natural fiber production	Summer dryness
Chemical use in agriculture	Season length
Forestry	Dryness, peak heat
Inland sport fishing and hunting	Summer dryness
Water-based recreation	Dryness, season length
Inland water transport	Dryness, season length
Water dependent industrial production	Summer dryness
Hydroelectrical power generation	Summer dryness
Sewage disposal and water quality protection	Summer dryness
Tourism	Dryness, peak heat
Water dependent inland energy production	Summer dryness
Urban and rural water consumption	Summer dryness
Summer energy consumption	Peak heat
Water supply activities and flood control	Summer dryness
Environmental protection	Heat, summer dryness
Desertification control	Summer dryness

runoff in the western and midwestern U.S. will be more intense.* Measured against the withdrawals projected for the year 2000, a 40 to 50 percent reduction in runoff results in streamflow demand-to-supply ratios in some basins in the western and plains states well in excess of unity,[43] along with a lengthening of the typical two-month summer period in which off-stream uses of plains' water exceed 90 percent of streamflows.[44] In the southern sector of the region, a northward displacement of the boundary of winter snow cover will exacerbate late spring and summer moisture availability problems. Since irrigation in the high plains constitutes an important source of present precipitation,[45] long-term depletion-related decline of high plains' irrigation will further exacerbate the situation.

*With no change in precipitation, a 6 degree Celsius warming will result in negative changes in runoff of 40 to 50 percent or more.[39] Precipitation effects are similar. The effects of heightened ambient carbon dioxide on transpiration rates can lessen these. But, for instance, to reverse the sign of the change in the case of precipitation decline, annual rainfall could decline no more than about 10 percent.[40] Changes in transpiration rates can have little effect on runoff in the case of winter precipitation, and spring snowmelt and runoff.[41] The latter is an important source of water for most western rivers, and changes in the time of snowmelt are an important cause of runoff decline in the models.[42]

These changes point to a significant future change in the level of likely land-use. Agriculture in the plains states and in some midwestern states probably could not be maintained at the present high level of intensity, as is evident from typical yield responses and crop requirements[46] and from the types of cultivars which can be economically grown without irrigation in steppe climates, where present spring and summer soil moisture conditions are about 70 to 80 percent of plains levels. As dry steppe climates expand eastward into the Great Plains, and prairie climates are displaced into middle western producing regions, production must fall. Increased maximum summer temperatures will also restrict the areas suitable for several cultivars.* Wind erosion may exert a similar influence.

Given the suggested northern and eastern invasion of desert and steppe climates, forestry and water-dependent activities in the southern and north-central states would likewise seem to be in trouble.[48]

The present density of settlement probably could not be maintained, given water supplies, peak heat considerations, and other factors. With a Tertiary-like climate change, a 500 to 1,000 km northward expansion of the area of average peak July-to-August temperature of 99 degrees Fahrenheit, the most often cited temperature threshold for heat-related illness and death among the elderly, might be expected.** Current population trends in the southwest could not be sustained without substantial new sources of fresh water.

Taken together, these impacts suggest a marked change in the economic viability of the region,[49] and given its political importance, national social and political impacts will follow.

<u>Adapting to this Change</u>: Planned or anticipatory adaptation is assumed in most or all attempts to estimate the impacts of climate change. Planned adaptation assumes that society can ameliorate impacts through technological intervention and timely relocation of production centers, actions which depend on the rate of change in the environment.[50]

Several characteristics of the adaptive response are notable. First, the characteristic times of national capital stocks are typically long. The lifetimes of most public works capital investments exceed several decades; the time required for major changes in technological systems varies between twenty and fifty years, and major water projects have lead-times of between thirty to fifty years.[51] Second, the adaptive response requires relatively certain projections of long-term local trends in precipitation, drought frequency, and the like, and at present we do not possess these and are not likely to possess them for decades.[52]

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*With a 5 to 7 degree Celsius regional warming, the geographical area of agronomically injurious June-July maximum daily temperatures (90 and 95 degrees Fahrenheit respectively for wheat and corn), expands to include the region from northern Texas to northeastern Nebraska and central South Dakota and Iowa (wheat), and from southwestern Oklahoma into North Dakota and the lake states (corn).[47]
**From the Texas-Mexico border.

Hence, most planned changes in technological or other capital-intensive systems that could be directed at climate change probably involve time-scales for design and construction that themselves would be substantially longer than the time-scales of most climate impacts.

A case in point involves precipitation change. Rainfall is the most difficult aspect of the climate to model. Past changes in rainfall have been very noisy. We think that in the central region of North America it will grow increasingly dry as it warms. But we cannot attach any date to the impending drying--whether it will be experienced in 2005 or will be postponed to as late as 2040. We cannot say that once a drying trend sets in it will not be reversed, and we do not know whether a trend toward a drier climate will set in suddenly as an abrupt change or will only gradually envelop the region.

The effects of climate change will probably be experienced most intensely through changes in rainfall (see Table 5). The principal mechanisms of adaptation would, therefore, be directed to precipitation change. If adverse changes in precipitation are experienced early in the next century, society will be unable to adapt through infrastructural changes involving surface water diversions[53] and the like. If it is delayed until 2025, it would still be impossible to adapt, given the time-scales of change in this infrastructure and of climate modeling. On the other hand, if adverse changes in precipitation occur later in the century, but are subject to quick reversal as the warming continues, they would rapidly render investments in infrastructural changes obsolete. In either of these three cases, an anticipatory response would be frustrated.

Public and private monies are committed to long-term projects on the basis of an expected return on investment. The certainty of that return is important. Faced with highly uncertain outcomes, neither the public nor the private decision-maker is in a position to commit sizable resources to public undertakings. The system is geared to minimize risk. Given other competing short-term uses to which the economic surplus might be put with more certain benefits, it is unlikely that the anticipatory response will be widely patronized.*

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*If we take the upper end of the accepted ranges for the parameters governing the rate of future warming (a 2.5 percent per year increase in carbon dioxide emissions, a climate sensitivity to doubled atmospheric concentrations of carbon dioxide of 4 to 5.5 degrees Celsius, and a warming due to the other gases at 300 percent that of carbon dioxide) and compute the expected change, the case against the adaptive response is even more evident. In such a case, a Tertiary-like change in climate could be expected in forty to forty-five years, which, even if we assume that adaptive measures would need to be directed only at Tertiary-scale changes, would leave society but a decade or two (e.g., 2010 to 2025 or 2030) in which to institute the entirety of its program of adaptation. A continued rise in mean global temperature would bring it to 6 to 7 degrees Celsius above the preindustrial value after mid-century, introducing society to a climate about which essentially nothing is known and to which, as a result, it would be impossible to adapt in an anticipatory fashion.

Of course, more traditional non-planned adaptations are available. Some examples of these include: changed soil or water management practices in agriculture, water-use controls, strengthened drought relief programs, or enhanced preparedness for floods or hurricanes. But business-as-usual responses are probably poorly matched to Tertiary-scale climate changes. At best, they could be employed by society in responding to the short-term crisis aspects of climate change; they do not address the resource base underlying the effects of climate change on regional economies.

It is possible that, were the change in climate to be stretched out long enough, the marketplace could effectively adapt society through incremental changes in the capital and technological base of society. Like the anticipatory response, the market is limited by informational constraints: it cannot adapt to what cannot be forecast. So an effective market response depends on a slow rate of change in the climate. At present, a slow rate of warming cannot be demonstrated.

Finally, there are a number of other constraints: to anticipatory adaptation arising from the impacts to representative institutions and to the efficiency of markets of heightened state intervention in society; and to the market response from the accelerating nature of the warming. If Figure 1 is correct, later in the next century the climate will change so rapidly that none of the conditions that might prevail at any one date could probably be assumed to prevail just a decade later, leading even short-term climate-defensive investments not to be made. These constraints act to further constrict the prospects for the adaptive response.

Net Economic Effect: Various researchers have offered estimates of the aggregate economic costs of future climatic changes (see Table 6). These estimates were derived indirectly from evidence of the climate sensitivity of economic activity in the developed world, around coastlines, and in agricultural regions, and from the costs of adaptation. They are by their nature incomplete and at best very approximate estimates. However, most of them do tend in the same direction, especially when the larger changes in climate are considered. They also compare favorably with middle latitude heat wave effects. As these studies assume climate changes much smaller than those envisioned for the next century, they probably underestimate the economic impact. This impact, it might be noted, would add to the losses from the present interannual variability of temperature and precipitation--currently estimated at about 1 percent of gross production.[54]

Effects to Yet be Considered: To date, impact assessments have considered only a limited set of effects. As this set expands, the perceived importance of climatic change will change. Sectors for which effects have yet to be considered in any detail include: forestry,[55] animal agriculture,[56] hurricane losses,[57] estuarine fisheries,[58] off-shore fisheries,[59] hydro-electrical production, fire losses, Great Lakes shipping,[60] river transport, wetlands loss,[61] ground water availability,[62] capital turnover times,[63] the incidence of inland flooding,[64] wilderness and protected areas, migration,[65] mining and energy production, the productivity of outdoor labor,[66] and species loss.[67]

Table 6
ESTIMATED ECONOMIC COSTS OF CLIMATIC CHANGE

Author	Average Global Warming (degrees Celsius)	Change in Gross World Product (in percent)[a]
Laurmann[b]	2.5	-3
Laurmann[b]	5	-8
Lave[c]	2	-2 to -3
Schelling[d,e]	2-3	-2
CIAP[f]	0.5	slight benefit
Nordhaus[g]	1.5-3	-3[h]
1980 Heat Wave[i]	--	-0.8[j]

(a) Change in gross output in some targeted year and in each of the ten to twenty years that bracket the target year.

(b) For relocation of production regions, all capital stocks. J. Laurmann, "Assessing the Importance of CO_2-Induced Climatic Change Using Risk-Benefit Analysis," in *Interactions of Energy and Climate*, W. Bach, J. Pankrath, and J. Williams, eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1980).

(c) L. Lave, this volume.

(d) T. Schelling, "Climatic Change: Implications For Welfare and Policy," in *Changing Climate*, Carbon Dioxide Assessment Committee, National Research Council (Washington, D.C.: National Academy Press, 1983).

(e) For agriculture and sea level rise effects only.

(f) Climatic Impact Assessment Program, *Economic and Social Measures of Biologic and Climatic Change*, CIAP monograph 6 (Washington, D.C.: U.S. Department of Transportation, 1975).

(g) W. Nordhaus, *Thinking about Carbon Dioxide: Theoretical and Empirical Aspects of Optimal Control Strategies*, Cowles Foundation discussion paper 565 (New Haven, Conn.: Yale University, 1980).

(h) With a range of uncertainty of (+)5 to (-)7-12 percent.

(i) Assessment and Information Service, *U.S. Impacts of the Great 1980 Heat Wave and Drought* (Washington, D.C.: Assessment and Information Service, 1980).

(j) The impacts may have been over-reported, but even 50 percent over-reporting still gives a lower limit approaching 0.5 percent of 1980 U.S. GNP.

Ecological Change: A change to a Tertiary-like climate would result in profound ecological changes. In the Arctic and sub-Arctic, the displacement of ecological regions by hundreds of kilometers would accompany a 4 to 5 degree warming,[68] making it possible that entire ecological regimes could contract to insignificance or disappear. Species that depend on the present ice pack will find survival difficult; those that depend on the existence of the tundra may survive, but only in narrow bands at the very furthest polar reaches. Evidence from the last interglacial is unequivocal: the Eurasian tree line stretched to the Arctic coast and only the wooded tundra survived.[69]

Elsewhere, ecological changes depend on large-scale changes in moisture availability and the degree to which human activities allow species migration, the means by which nature has sustained species diversity during past climatic changes. Given the ubiquitous human settlement of the planet, it seems likely that many species will simply disappear as the climate warms. The diversity of species may recover, although the time-scales for such a recovery must be very long.

Impact on Agriculture in Less Developed Countries: Many developing countries are experiencing high population growth rates, which require sustained annual increases in food production[70] from agricultural systems which appear fragile in the face of changed precipitation patterns.[71]

Two considerations are of interest with regard to a significant climate change: heat affects on outdoor labor productivity and temperature and moisture effects on crop yields. A limited number of studies suggest that significant reductions in labor productivity, perhaps as high as 10 percent, are possible in the humid tropics with increased effective temperatures,[72] implying the possibility of reduced agricultural productivity independent of the crop response.

Regarding the crop response, an increase in tropical and subtropical temperatures will, on average, negatively affect yields by about 4 or 5 percent per degree Celsius.[73]

Increased moisture availability could compensate somewhat for heightened temperatures. However, we cannot at present forecast the direction of regional soil moisture change. The most that can be said is that soil moisture seems as likely to decline as to increase at most locations in the tropics and subtropics, and that regional responses are sufficiently varied so as to ensure that some nations will be negatively affected. Given the expected population increase, adverse changes in some populous nations are inevitable. The consequences of adverse changes in agricultural productivity in the developing world range from economic loss to subsistence crises or large-scale movements of people.

Higher Order System Change: Social and political systems, the international economic system, and the strategic balance between the superpowers all will be affected by climate change. As highly complex systems, these are all subject to various instabilities--recessions, social unrest, revolution, and military conflict--from which derives at least some risk as the climate changes. As the past record demonstrates, political and social systems, particularly in the developing world, have sometimes grown quite unstable in the face of periodic or sustained drought or other natural climatic fluctuations.

Higher order effects are difficult to assess. Relatively little is understood about the conditions leading to instability in human systems. Such effects depend on the particular approaches that society takes in response to changing climate (e.g., whether in trying to manage impacts on the economy it does so through a cooperative approach or through many autarkic approaches). We simply do not understand the implications of sustained aggregate economic impacts such as are suggested in Table 6. Nor do we understand the implications of the convergence of a climate change with existing environmental pressures (see Table 7). It is possible that we facing a new era of large-scale migrations. If so, what might be the implications? The most that can be said at present is that, by increasing the pressure on society, climate change probably will increase the potential for serious systems failures.

Table 7
ENVIRONMENTAL PROBLEMS WHICH MAY BE EXACERBATED BY GLOBAL WARMING

Tropical Africa: deforestation; deforestation-related flood damage and soil destruction; species destruction; mangrove destruction; per capita availability of food; availability of safe, potable water; temperature-related disease incidence; fertilizer/pesticide-related stream pollution; incidence of surface water-related diseases; chronic poverty.

Sahelian, Saharan, and North Africa and Horn of Africa: soil erosion; desertification; fuelwood crisis; per capita availability of food and water; availability of safe, potable water; societal sensitivity to drought; temperature-related disease incidence; soil salinization and alkalinization; fertilizer/pesticide-related stream pollution; incidence of surface water-related diseases; chronic poverty.

Southern Asia and the Middle East: same as semi-arid Africa, plus species extinction; deforestation-related flood damage and rill erosion in the Ganges basin; and deterioration of urban conditions.

Sources: G. Barney ed., *The Global 2000 Report to the President of the U.S.*, vol. 1 and 2 (New York: Pergamon Press, 1980); International Institute for Environment and Development and World Resources Institute, *World Resources 1986* (New York: Basic Books, 1987).

<u>The Policy Implications of This Change</u>: The nature and number of impacts resulting from a 4 or 5 degree Celsius warming suggest that warming will result in significant disruption. To the degree that it is the role of governmental policy to minimize disruption, governmental intervention to limit the rate of warming would logically follow. However, the nature and number of impacts do not in themselves determine policy. The importance of any one impact or set of impacts will be evaluated in light of the feasibility and ease of response, the present-day valuation of the future benefits of action, and other terms in what can often be a lengthy, well-elaborated decision analysis. Depending on the larger structure of argumentation, a 4 to 5 degree Celsius warming over one hundred years may call for an interventionist, preventive approach centering on emissions control, or benign neglect. Hence, to continue our analysis, we must turn to the larger structure of argumentation on which the inactive response rests.

THE CONDITIONS OF AN INACTIVE RESPONSE

Inaction appears to be reasonable only to the degree to which a set of rather stringent conditions can be fulfilled. There must be considerable uncertainty about impacts, particularly about their overall sign. The change in climate must not be of a scale or intensity that would overwhelm that uncertainty or that, given that effects tend to vary broadly with the intensity of climate change, would make an intuitive estimate of severe negative impact likely. There needs to be an explicit lack of concern for impacts on future generations or for the irreversibility dimension of the problem. Due to the high number of future generations affected, concern for any future effects may, in absence of an explicit disavowal of the future, overwhelm other considerations. Social and time discounting techniques often form a basis for inaction.

It is a further condition of the inactive response that little consideration be given to the possibility of high-risk, low-probability outcomes. Ideally, the likelihood of a climate change of any kind would itself be subject to question. Measured against the supposed uncertainty of climate change, the certainty of the present-day effects of emissions controls dominates the decision-making process.

If it is not possible to completely discount the problem on the basis of scale or probability of occurrence, it is necessary to discount it on the grounds that action is infeasible. To sustain an argument based on the infeasibility of response, it is necessary to show that, for a limited climate change, the response most economically fitted to it--a limited response--will have little net effect on the overall rate of the accumulation of carbon dioxide in the atmosphere. In absence of a limited warming, it is necessary to affirm a robust estimate of society's ability to adapt to climate change.

Finally, if it cannot be shown unequivocally on the grounds of scale, infeasibility, or ease of adaptation, that action **can** be avoided, it will be necessary to show that there are enough uncertainties in the basic physical aspects of the problem that action **may** prove unnecessary and would best be delayed until further study could clarify the matter. If one is arguing that we should wait and study the problem more fully to ascertain its exact dimensions, it helps to show that in doing so we would not significantly forfeit our ability to act.

In the following section, we consider the first of these requirements, that of uncertainty. The others follow in subsequent sections.

UNCERTAINTY IN THE PHYSICAL PARAMETERS OF CLIMATE CHANGE

The degree to which uncertainties in the physical science underlying our understanding of climate change do or do not constitute an insurmountable obstacle to policy formulation depends on the nature of the uncertainties and whether they can be bounded. Three parameters governing the rate and intensity of future climatic changes are of special interest: the future atmospheric buildup of carbon dioxide; the emission of and warming due to the other gases; and the climate parameter.

Carbon Dioxide

The projected atmospheric carbon dioxide level depends largely on the rate of the expected increase in fossil fuel combustion, and on the fraction of each incremental unit of carbon dioxide that remains in the atmosphere once emitted from the surface. There is significant debate over likely future values for either of these factors. But, whereas uncertainties as to the precise value for the fraction of emitted carbon dioxide that remains airborne might account for a variation in the projected atmospheric carbon dioxide level on the order of 50 to 150 ppmv over the next century, the range of possible future energy trajectories is wide and accounts for a variation in the projected atmospheric carbon dioxide level three to four times this.[74] The wide range of possible future atmospheric levels of carbon dioxide is not, strictly speaking, the result of scientific uncertainties but an extension of the wide range of possible energy trajectories and policies.

The scientific uncertainties that are in evidence can be modeled and the uncertainty appropriately bounded. These scientific uncertainties include the rate of release of carbon from non-fossil sources and the rate of atmospheric retention of emitted carbon dioxide.

Estimates for the rate of retention, or airborne fraction, are given in Table 8. A lower limit to the rate can be established at 0.4. This rate will rise with any long-term increasing rate of emission greater than 1 to 1.5 percent per annum,[75] and will decline at constant 1985 fossil energy production. This effect can be approximated through the use of a cumulative airborne fraction (i.e., the average airborne fraction from 1985 to 2075) roughly 5 percent higher than the assumed 1985 value in the case of annually increasing emissions,[76] and 5 percent lower in the case of constant 1985 emissions. This gives a lower limit to the average long-term airborne fraction of 0.35 to 0.45.

Based on the estimated cumulative airborne fraction, and on the estimated future non-fossil sources of carbon, a total future carbon input into the atmosphere can be suggested for different energy strategies. One is given in Table 9 for a 2 percent per year fossil path.

The effects of uncertainty in the airborne fraction are estimated from Table 9. As is evident, variation in the rate of atmospheric retention does not serve to alter the fundamental nature of the problem. In 2070, a doubling of the atmospheric carbon dioxide level is still realized, despite the employment of a low rate of retention. Estimates for the non-fossil carbon input from sources like deforestation and methane decay are also shown in Table 9. These are more speculative. But the number of potential sources is large, and the calculated total input of carbon to the atmosphere is big enough to be interesting. Assuming that the estimates are wrong by even 50 percent, the net input to the atmosphere would still be on the order of 50 to 75 ppmv, and we take this as a lower bound to the "other carbon" input.

Table 8
ESTIMATES OF THE AIRBORNE FRACTION

Type of Estimate	Airborne Fraction
Estimates from ocean models[a]	0.57-0.80
Deforestation-based estimates[b]	0.34-0.53
Estimates from sources of error[c]	0.38-0.70
Apparent airborne fraction[d]	0.55-0.58
Best range[e]	0.40-0.70

(a) See: C.F. Baes, Jr., A. Bjorkstrom, and P. Mulholland, "Uptake of Carbon Dioxide by the Oceans," in *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, DOE/ER-0239, J. Trabalka, ed. (Washington, D.C.: U.S. Department of Energy, 1985), table 5.3; and J. Trabalka et al., "Human Alterations of the Global Carbon Cycle and the Projected Future," ibid., table 10.16.

(b) See G. Woodwell, "Biotic Effects on the Concentration of Atmospheric Carbon Dioxide: A Review and Projection," in *Changing Climate*, Carbon Dioxide Assessment Committee, National Research Council (Washington, D.C.: National Academy Press, 1983).

(c) See H. Oeschger and M. Heimann, "Uncertainties of Predictions of Future Atmospheric CO_2 Concentrations," *Journal of Geophysical Research* 88 (1983): 1,258.

(d) See J. Trabalka et al., in note (a) above; and C. Keeling, "The Oceans and Biosphere as Future Sinks for Fossil Fuel Carbon Dioxide," in *Interactions of Energy and Climate*, W. Bach, J. Pankrath, and J. Williams, eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1980).

(e) The lower value is based on the deforestation estimates of Houghton et al., "Carbon Dioxide Exchange Between the Atmosphere and Terrestrial Ecosystems," in Trabalka, note (a) above.

Table 9
ESTIMATED FUTURE SOURCES OF ATMOSPHERIC CARBON DIOXIDE

Source	Net Increase in Atmospheric Carbon Dioxide (ppmv) 2030	2070	Eventual
Fossil fuel combustion[a]	104	318	
Deforestation[b]	10-45	45-72	
Biotic respiration[c,d]	7-12	15-20	
Global soils[e]			125-250?
Methane decay[f]	6-13	17-35	
Cement production[g]	2-4	7-17	
Mixed oceanic layer[h,d]	4	8	?
Average airborne fraction, 1980-2070[i]			
Low (45)	--	(-) 81	
High (70)	--	(+)118	

Note: The net amount of carbon dioxide added to the atmosphere from the listed sources is calculated for an airborne fraction of 0.56, and the aggregate amount from all sources is adjusted in the last two lines for higher and lower airborne fractions.

(a) Assumes that emissions from fossil fuels increase 2 percent per year.

(b) See World Climate Programme, *An Assessment of the Role of CO_2 on Climate Variations and Their Impact* (Geneva: World Meteorological Organization, 1981); G. Woodwell, "Biotic Effects on the Concentration of Atmospheric Carbon Dioxide: A Review and Projection," in *Changing Climate*, Carbon Dioxide Assessment Committee, National Research Council (Washington, D.C.: National Academy Press, 1983); R. Revelle and W. Munk, "The Carbon Dioxide Cycle and the Biosphere," in *Energy and Climate*, Geophysics Research Board, National Research Council (Washington, D.C.: National Academy of Sciences, 1977); and J. Trabalka et al., "Atmospheric CO_2 Projections with Globally Averaged Carbon Cycle Models," in *The Changing Carbon Cycle: A Global Analysis*, J. Trabalka and D. Reichle, eds. (New York: Springer-Verlag, 1986). Complete tropical deforestation would add about 70 to 75 ppmv.

(c) Respiration increases about 20 to 30 percent per degree Celsius. See G. Kohlmaier et al., "The Role of the Biosphere in the Carbon Cycle and Biota Models," in *Carbon Dioxide: Current Views and Developments in Energy/Climate Research*, W. Bach et al., eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1983), table X, high scenario, respiration releases less carbon incorporated into living biomass as a result of a temperature-induced rise in Net Primary Productivity.

(d) Assumes a mean global warming of 2.4 and 4.5 degrees Celsius at 2025 and 2070, respectively, from Figure 1.

(e) One-hundred to two-hundred gigatons per degree Celsius. See R. Loomis, "CO_2 and the Biosphere," in *Workshop on the Global Effects of Carbon Dioxide From Fossil Fuels*, W. Elliot and L. Machta, eds., CONF-770385 (Washington, D.C.: U.S. Department of Energy, 1979).

(f) Assumes a four- to nine-year residence time for atmospheric methane, and an increase in the atmospheric methane level to 6 to 7 ppmv from a continuation of present trends in agricultural activities (1.5 ppmv), increased rates of anaerobic respiration (1.2 to 1.5 ppmv), and methane release from clathrates (1.1 to 2.2 ppmv). See M. Khalil and R. Rasmussen, "Causes of Increasing Atmospheric Methane: Depletion of Hydroxyl Radicals and the Rise of Emissions," *Atmospheric Environment* 19 (1985): 397; S. Hameed and R. Cess, "Impact of a Global Warming on Biospheric Sources of Methane and Its Climatic Consequences," *Tellus* 35B (1983): 1; P. Guthrie, "Biological Methanogenesis and the CO_2 Greenhouse Effect," *Journal of Geophysical Research* 91 (1986): 10,847; R. Revelle, "Methane Hydrates in Continental Slope Sediments and Increasing Atmospheric Carbon Dioxide," in Carbon Dioxide Assessment Committee, note (b) above. (For a similar estimate of the increase in atmospheric carbon dioxide from the decay of methane, see Revelle ibid.)

(g) The upper value assumes a continuation of 1970 to 1980 growth rates (3.4 percent per year) in cement manufacture; the lower value assumes a 2 percent per year increase.

(h) See F. MacIntyre, "On the Temperature Coefficient of pCO_2 in Seawater," *Climatic Change* 1 (1978): 349.

(i) The average airborne fraction for the period from 1980 to 2070 is calculated with an approximate 10 percent increase in the airborne fraction between the present and 2070.

Other Gas Emissions

The uncertainties that surround the other gas emissions can be bounded through an assessment of the sources of present and future releases and through argumentation about what might constitute a reasonable estimate of future releases. As noted elsewhere in this volume,[77] the effects of these releases are now typically approximated through the use of a sensitivity, or scaling, parameter that amplifies the projected carbon dioxide-induced warming by some constant factor. This is necessary due to:

- the large number of gases involved;[78]
- uncertainties over the future rate of surface emission of each individual gas;
- the future effects of photochemically active gases on the OH chemistry of the troposphere, and the effects on infrared absorbing gases that are scavenged from the troposphere through interactions with OH (a large number of these may be involved);[79]
- the effects of temperature dependencies on the release of methane;[80]
- the large number of candidate infrared absorbing gases whose absorption band strengths have not been determined;[81]
- uncertainty in the projected long-term rate of global industrial expansion and in the nature of future regulation.

Estimates for this scaling parameter that account for some of these effects are shown in Table 10. By and large, they do not account for the temperature dependency of methane and they largely ignore the potential effects of candidate infrared absorbing gases. A lower bound of about 50 percent is suggested.

Table 10
ESTIMATED AGGREGATE WARMING FROM THE OTHER GREENHOUSE GASES

Author	Effect of the OGGs as a Percent of the CO_2 Effect Possible	Best Guess	Full Range
Chamberlain et al.		100	
Dickinson and Cicerone			125-144
Flohn			50-100
MacDonald			80-120
Machta	100		
Ramanathan		80	
Ramanathan et al.		115	50-300
Volz			46-123
Wang	100		
Wang et al.			112-128
WMO			50-100
Present trend[a]	2	150	

(a) See Table 11.

Sources: J. Chamberlain et al., "Climate Effects of Minor Atmospheric Constituents," in *Carbon Dioxide Review: 1982*, W. Clark ed. (New York: Oxford University Press, 1982); R. Dickinson and R. Cicerone, "Future Global Warming from Atmospheric Trace Gases," *Nature* 319 (1986): 109; H. Flohn, *Possible Climatic Consequences of a Man-Made Global Warming*, RR-80-30 (Laxenburg, Austria: International Institute for Applied Systems Analysis, 1980); G. MacDonald, *Climate Change and Acid Rain*, MP86W00010 (McLean, Vir.: The Mitre Corporation, 1986); L. Machta, "Effects of Non-CO_2 Greenhouse Gases," in *Changing Climate*, Carbon Dioxide Assessment Committee, National Research Council (Washington, D.C.: National Academy Press, 1983); V. Ramanathan, "Climatic Effects of Anthropogenic Trace Gases," in *Interactions of Energy and Climate*, W. Bach, J. Pankrath, and J. Williams eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1980); V. Ramanathan et al., "Trace Gas Trends and Their Potential Role in Climate Change," *Journal of Geophysical Research* 90 (1985): 5,547; A. Volz, "Climatic Effect of Trace Gases, Aerosols, Land-Use Changes and Waste-Heat Release," in *Carbon Dioxide: Current Views and Developments in Energy/Climate Research*, W. Bach et al. eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1983); W.-C. Wang, "Climatological Effects of Atmospheric Ozone: A Review," in *Atmospheric Ozone*, C. Zerefos and A. Ghazi eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1983); W.-C. Wang et al., "Greenhouse Effects Due to Man-Made Perturbations of Trace Gases," *Science* 194 (1976): 685; World Meteorological Organization, Global Ozone Research And Monitoring Project, *Report of the Meeting of Experts on Potential Climatic Effects of Ozone and Other Minor Trace Gases*, report 14 (Geneva: World Meteorological Organization, 1982).

Control of the other gases will be difficult due to such factors as the temperature dependency of methane release, the number of yet-to-be-evaluated gases, and the effects of global industrialization. The latter favors effective decentralization of chlorofluorocarbon (CFC), chlorocarbon, and fluorocarbon production. Under such conditions, the potential for emissions control is limited. Not only are the effects of individual gases small (tenths to hundredths of a degree Celsius), but production is subdivided many times over. This fragmentation makes it impossible for any one nation to limit the warming due to any one gas by more than a few hundredths of a degree Celsius and, to this degree, makes such action unworkable. The importance of yet-to- be-evaluated gases (CFC-21, CFC-114, PAN, Halon-1301, and perhaps fifteen or twenty others) is suggested by their number. If only a few are found to be important future infrared absorbers, the other gas parameter would move upward, making control more difficult.

For a global surface warming of about 5 degrees Celsius, the methane temperature dependency is estimated to result in releases from which an additional warming on the order of 0.4 to 0.5 degrees Celsius could result.[82]

At present, the atmospheric concentrations of the other gases are increasing annually 1 to 6 percent (see Table 11). If continued, this would result in a warming roughly equal to 150 percent of the warming induced by a doubling of the atmospheric level of carbon dioxide.* (In the case where controls are imposed on carbon dioxide emissions, the other gas warming as a percent of the carbon dioxide-induced warming certainly would be on the order of 100 to 150 percent.) With stringent emissions controls on CFC-11 and CFC-12, the other gas warming as a percent of the carbon dioxide warming would be on the order of 100 percent.

Dickinson and Cicerone suggest that, as an upper limit, by 2050 the other gas effect could be as much as 4.8 degrees Celsius.[84] (As a point of reference, a 1.5 to 3 degree Celsius warming by 2050 from increased concentrations of the other gases might be thought to represent a lower bound on their effect.**)

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*A warming by 2050, calculated at equilibrium, of 2.1 to 4.2 degrees Celsius, compared with 1.4 to 2.8 degrees Celsius for atmospheric carbon dioxide increased to 535 ppmv over the same period.[83]

**Assuming a climate sensitivity of 2 degrees Celsius per doubled atmospheric concentrations of carbon dioxide, the warming might be distributed as follows: methane contributes 0.4 degrees Celsius; nitrous oxide, 0.1 degrees Celsius; tropospheric ozone, 0.3 degrees Celsius; the chlorofluorocarbons, 0.3 degrees Celsius; and others, 0.2 degrees Celsius.[85]

TABLE 11
OTHER GREENHOUSE GASES: RATES OF INCREASE AND CONTRIBUTION TO GLOBAL WARMING

Greenhouse Gas	Present Rate of Increase (%/yr)[a]	Climate Sensitivity: Change in Concentration	Climate Sensitivity: Temperature Change (degrees C)[b]	Date of Increase at Present Rate of Growth: 1 ppbv	Date of Increase at Present Rate of Growth: 2 ppbv	Date of Increase at Present Rate of Growth: Twice Today's Level
Tropospheric ozone	1	2x	0.6-1.2	--	--	2055
CFC-11 and CFC-12	5	2 ppbv	0.3-0.6	1995	2010[c]	--
CFC-22	10-14	1 ppbv	0.05-0.1	2005	2010	--
Carbon tetrachloride	1	1 ppbv	0.08-0.16	distant	2070	--
Carbon tetrafluoride	3	1 ppbv	0.06-0.12	2080	--	--
Methyl chloroform	6	1 ppbv	0.02-0.04	2015	2025	--
Methylene chloride	5	1 ppbv	0.03-0.06	2055	2070	--
Nitrous oxide	0.2-0.4	2x	0.4-0.8	--	--	distant
Methane	1	2x	0.3-0.6	--	--	2050
CFC-116	6	1 ppbv	0.13-0.26	2070	--	--
Stratospheric water vapor	?	2x	0.6[d]	--	--	distant

(a) See P. Ciborowski and D. Abrahamson, "The Global Greenhouse Problem," this volume, Table 4.

(b) Taken from V. Ramanathan et al., "Trace Gas Trends and Their Potential Role in Climate Change," *Journal of Geophysical Research* 90 (1985): 5,547. The first of these paired values is scaled to a climate sensitivity of 1.8 degrees Celsius, and then is doubled to account for a more representative range of climate sensitivity.

(c) Calculated with a 3 percent per year increase after Ramanathan et al., note (b) above.

(d) See D.R. Blake and F.S. Rowland, "Continuing World-wide Increase in Tropospheric Methane, 1978 to 1987," *Science* 239 (1988): 1,129.

Climate Sensitivity

Of the parameters of interest in the climate change problem, the climate sensitivity parameter is the most studied. It is an indication of the amount of surface warming that would result from a given increase in the atmospheric carbon dioxide level. It is estimated for a doubling of this level. Given estimates for the other parameters (other gases, airborne fraction, etc.), it is possible to evaluate the importance of the uncertainties in the present estimates of this parameter by estimating what the climate sensitivity would need to be were the climate change problem not to be problem, and then comparing this to what in fact would constitute a lower bounds estimate of the climate parameter. A global surface warming of 2 to 3 degrees Celsius can be used as a measure of whether or not a problem exists. To meet such a ceiling, a doubling of the atmospheric carbon dioxide level could yield no more than a 1 to 1.2 degrees Celsius warming. Estimates for the lower bound to climate sensitivity are higher than this by a factor of about 1.5 (see Table 12).

A broader discussion of a more exact estimate of climate sensitivity is given elsewhere in this volume.[86] Climate sensitivity is estimated through various mathematical models. There are advantages and disadvantages to the use of different model types. Suffice it to say that the results of the latest generation of general circulation models (GCMs) are to be preferred in estimating climate sensitivity.

The response of mean global temperature to changed concentrations of the greenhouse gases is made up of two distinct processes: the direct radiative effects and the subsequent response of the climate system to these effects. There is no question as to the correct estimate for the former.[87] A warming of about 1.3 degrees Celsius would result from the direct radiative effects of a doubling of the atmospheric carbon dioxide level.[88]

The climate response is more uncertain. The response of the climate system will amplify the warming initiated by the direct radiative effects. The degree of the amplification could range from 50 to 200 percent. Of the feedbacks that determine the climate response, the response of cloud cover is the most uncertain; the equations that govern the ice-albedo, water vapor, and other feedbacks are relatively well understood. The cloud feedback parameter is comprised of three distinct components: cloud height, cloud distribution, and cloud optical thickness, and is complex. In the most advanced generation of GCMs, the feedback is estimated to be positive. But it is suggested that it could, in total, reduce the climate sensitivity by up to 50 percent.[89] Evaluated against the climate sensitivities of the most advanced GCMs (3.5 to 4.2 degrees Celsius), this yields an effective lower bound of 1.8 to 2.1 degrees Celsius.[90] (It is unlikely to be as low as 1.5 degrees Celsius. Climate sensitivity in the zero-order feedback case is 1.3 degrees Celsius, or essentially equivalent to this low value.)

Aside from the cloud problem, all the objections to the basic calculation that have suggested significantly lower sensitivities than are given above have been answered.[91]

Table 12
CLIMATE SENSITIVITY TO DOUBLED ATMOSPHERIC LEVELS OF CARBON DIOXIDE: SUMMARY OF RECENT ANALYSES

	Warming from Doubled Levels of Carbon Dioxide (degrees Celsius)	
Climate Model Type	Possible	Likely
One- and two-dimensional models		
Schneider	0.75-6[a]	1.5-3
Kandel	<1-5	
Watts	2.2-6.3	
General circulation models		
Schlesinger and Mitchell[b]		3.4-4.2
Schlesinger		2-3
Full range of model types		
World Climate Programme		2-3
National Research Council		1.5-4.5
Budyko, Vinnikov and Yefimova		2.5-3.5
Bolin et al.		1.5-5.5

(a) Schneider estimates that, due to unknown or improperly modeled feedback mechanisms, the range of likely climate sensitivity could be higher or lower by several-fold.

(b) Review of advanced GCMs.

Sources: B. Bolin, et al., eds., *The Greenhouse Effect, Climate Changes and Ecosystems* (Chicester, U.K.: John Wiley and Sons, 1986); M. Budyko, K. ya. Vinnikov, and N. Yefimova, "The Dependence of the Air Temperature and Precipitation on the Carbon Dioxide Concentration in the Atmosphere," *Meteorology and Hydrology* 4 (1983): 5; R. Kandel, "Simple Climate Models and the Greenhouse Effect," in *Carbon Dioxide: Current Views and Developments in Energy/Climate Research*, W. Bach et al., eds. (Dordrecht, Netherlands: D. Reidel, Publishing Co., 1983); National Research Council, *Carbon Dioxide and Climate: A Scientific Assessment* (Washington, D.C.: National Academy of Sciences, 1979); M. Schlesinger, "Simulating CO_2-Induced Climate Change with Mathematical Climate Models: Capabilities, Limitations and Prospects," in *Carbon Dioxide, Science and Consensus*, CONF-820970 (Washington, D.C.: U.S. Department of Energy, 1983); M. Schlesinger and J. Mitchell, "Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide," in *Projecting the Climatic Effects of Increased Carbon Dioxide*, M. MacCracken and F. Luther, eds., DOE/ER-0237 (Washington, D.C.: U.S. Department of Energy, 1985); S. Schneider, "On The Carbon Dioxide-Climate Confusion," *Journal of the Atmospheric Sciences* 32 (1975): 2,060; R. Watts, "Climate Models and CO_2-Induced Climatic Changes," *Climatic Change* 2 (1980): 387; World Climate Programme, *An Assessment of the Role of CO_2 on Climate Variations and Their Impact* (Geneva: World Meteorological Organization, 1981).

Regional Climate Change

By contrast, efforts to model local and regional climate changes are problematic. Despite the ability of the models to duplicate some of the gross features of past changes in temperature and precipitation, the models do not possess sufficient resolution capacity to incorporate small-scale weather processes. The distance between grid points in the models is on the order of 500 km. Processes of smaller spatial dimensions must be treated statistically rather than as physical processes. Since the processes that dominate regional weather are determined by sub-grid phenomena like precipitation and local cloud amounts, projections of regional changes in climate are largely speculative.

Uncertainties in the Societal Response

The response of society will, in part, depend on the unpredictable ways in which people react. But something can be said about the response based on the conditions under which market and administered decision-making systems do and do not function well. From the analysis we have presented, it can be determined that the prospects for adaptation are in fact limited. Other constraints to the adaptive response are reviewed in the Introduction to Section 3 of this volume, and other guidance can be taken from the better critiques of societal decision-making.[92] On the basis of these, a pessimistic assessment of society's ability to respond to a warming seems warranted.

THE EFFECTS OF UNCERTAINTY

Any attempt to limit the intensity of the future warming will depend on the actions that society takes to restrict fossil fuel combustion. The degree to which the warming might be limited under any one set of governmental actions will depend on the sensitivity of the climate to increased atmospheric levels of carbon dioxide and other factors. Hence, the energy policy effects of uncertainty can be taken as an indication of the overall importance of uncertainty to policy formulation.

Table 13 shows the results of an analysis in which the total amount of fossil fuel carbon that might be added to the atmosphere under a 4 degrees Celsius ceiling on the mean global temperature rise, is shown. Given an estimate of the as yet unrealized effects of gases released from 1860 to 1985,[93] it is possible to calculate backward what carbon dioxide concentrations might need to be to realize a ceiling on a carbon dioxide-induced warming. Subtracting out the effects of carbon released from deforestation and other lesser sources,[94] it is then possible to estimate the total amount of fossil fuel carbon dioxide that might be emitted at different ceilings. By varying the non-fossil fuel parameters controlling the aggregate rise in mean global temperature (e.g., the climate sensitivity, the other gas parameter, the airborne fraction) it is possible to estimate the amount of carbon that can be added to the atmosphere in the best, worst, and average cases, and the degree to which the variation in the parameters affects this total carbon input.

Table 13
SENSITIVITY ANALYSIS: ACTION INITIATION TIMES (AITs) AND CEILINGS OF FOSSIL FUEL CARBON DIOXIDE FOR A 4 DEGREE CELSIUS CEILING ON AVERAGE GLOBAL TEMPERATURE CHANGE

Case	Climate Sensitivity (to 2 x CO_2, degrees C)	Other Gas Warming (% of CO_2 Warming)[a]	Airborne Fraction (%)[b]	Non-Fossil CO_2 (ppmv)[c]	Ambient CO_2 Ceiling (ppmv)[d]	Fossil CO_2 Ceiling (ppmv)	AIT[e]
Base	3	150	45	Base (105)	456	351	1985
$Base_1$	4	150	45	Base (98)	417	319	1985
$Base_2$	2	150	45	Base (105)	546	441	1985/1995
$Base_3$	3	300	45	Base (105)	411	306	1985
$Base_4$	3	50	45	Base (98)	549	451	1985/1995
$Base_5$	3	150	35	Low (70)	456	386	1985
Worst	4	300	65	High (175)	388	213	1985
Best	2	50	35	Low (58)	724	668	2005/beyond 2020
Other	2	100	55	Base (128)	612	484	1985/2000
Other	3	100	55	Base (128)	489	361	1985
Other	4	100	55	Base (121)	437	316	1985

(a) See Table 10.

(b) See Table 8.

(c) Carbon released through deforestation, cement manufacture, enhanced biotic respiration, and methane decay. For details on emissions, see Table 9. The temperature-sensitive estimates given here are recalculated for a 4 degree Celsius increase in mean global temperature. The carbon emission from methane decay is adjusted for internal consistency with the other gas warming.

(d) Accounts for the yet unrealized warming from past emissions.

(e) Estimated from Laurmann, this volume, and A. Perry, "Carbon Dioxide Production Scenarios," in *Carbon Dioxide Review: 1982*, W. Clark, ed. (New York: Oxford University Press, 1982). (For details, see ref. 95).

Action initiation times (AITs) are a useful measure of the sensitivity of energy policy to the total allowable carbon input to the atmosphere. Since there is no effective technical fix through which to control emissions of carbon dioxide after combustion, the accumulation of carbon dioxide in the atmosphere can be limited only through an abandonment of the present fossil energy system in favor of a non-carbon based system. Action initiation times designate the date at which a non-fossil energy system must begin to displace the present fossil fuel system.

From Table 13, it is clear that the various uncertainties, if properly accounted for, cannot act as a significant obstacle to a preventive strategy--at least at an assumed ceiling of 4 degrees Celsius on allowable change in mean global temperature. In most cases, the level of allowable fossil fuel carbon input is quite low. Action initiation times generally fall at, near, or before the current date; in most cases, action initiation times fall well before the year 2000. Due to the lengthy amount of time required for individual nations, and then sets of nations jointly, to take decisions about preventive action and then to develop and implement preventive programs, action initiation times that fall within the next fifteen years imply the necessity of immediate policy action. Only in the case of unlikely combinations of parameters (low climate sensitivities, low other gas contributions, low airborne fractions, etc.) do action initiation times fall outside of this time period, implying that the policy imperatives of the climate change problem are relatively invariant to the physical science uncertainties.

This analysis demonstrates the error in the contention that uncertainties in the physical science underlying our understanding of climate change, if properly accounted for, can act as a significant obstacle to a preventive response--at least at an assumed ceiling on the rise in mean global temperature of 4 degrees Celsius. Only in the fairly unlikely event that the most optimistic estimate for all the governing parameters were in fact realized could one sustain the opposing position.

This analysis also makes it clear that a wait-and-see response is inconsistent with an ultimate warming of less than 4 degrees Celsius. This is a substantially different conclusion from those that have been arrived at in the past.[96] Raising or lowering the ceiling level only marginally affects the results.*

THE ROLE OF OTHER CONSIDERATIONS

Future Generations

Social and time discounting techniques constitute the principal mechanism for the differential valuation of generations in contemporary public decision-making. Under the terms of social and time discounting, future generations are valued at a rate that is substantially lower than the rate at which present generations are valued. This makes it difficult for society to respond to any impacts of present activities other than those that are very proximate in time.

But to what degree must such techniques make irrelevant any effort to control present-day releases of the greenhouse gases? Social and time discounting is premised upon an assumed consensus across generations of the

*Evaluated against a ceiling of 3.5 degrees Celsius, action initiation times in the case of the most optimistic assessment of parameters would fall into the period beyond 2030. Base and worst case action initiation times would, in the case of ceilings in the range of 5 to 6 degrees Celsius, fall before or at the present date.

essential rightness of such discounting. It requires that we know that such a consensus will hold over very long periods of time. However, like the theological truths of the past, the time-scales of economic thought are historical in nature. They come and go with changes in the material and social bases of society. Thus, we cannot at present know that discounting can be extended to the greenhouse problem. At present at least, the assumption that it can be so extended is unwarranted.[97]

Aspects of Scale

Not all climate changes are acceptable. Some changes are of such intensity that they are manifestly unacceptable. In this vein, ceilings of 3 to 5 degrees Celsius on mean global temperature change have been offered.[98]

The argument for limiting the average global surface temperature rise to less than 4 degrees Celsius is comprised of three components. The rate of global surface warming in the case of any rise in temperature greater than 4 degrees Celsius implies that later in the next century the rate of warming will begin to approach 0.5 to 1 degrees Celsius per decade. This is almost certainly too rapid a pace to be sustained by society.

At such a rate of change, climate would, at warmings in excess of 4 or 5 degrees Celsius, be forced through a series of fundamental changes in boundary conditions that suggest closely spaced step-changes in climate.* Since nearly all human systems have long characteristic times, a sequence of such step-changes would be difficult to accommodate.

Finally, a warming greater than 4 or 5 degrees Celsius would move climate into a climate space about which, essentially, nothing is known. The physical basis of such a change is, with few exceptions, a mystery. To this degree, such an extreme rise in mean global surface temperature would enormously expand the set of possible climate outcomes to which society might need to adapt. The impact of a 6 to 9 degree warming must be assumed to be at least as bad as, and probably a good deal worse than, the impact of a 4 degrees Celsius change. Tropical heat effects would place lowland conditions somewhere near the tolerance level;[100] initial modeling efforts suggest an intensification of middle latitude drying; a warming of around 7 degrees Celsius appears to be intense enough to result in tropical or near-tropical climates in Western Europe.[101] But beyond this, little can be said.

Thus bounded only at the lower end of the range of possible effects, where one finds at best a bad situation, but not at all on the high end, the situation is one of nearly complete uncertainty. It can be only ill-advised to allow the climate to move off into such unknown territory.

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*At such rates of warming, a rapid succession of one qualitatively different climate by another, and then by a third, might reasonably be expected, associated with change from a fully ice-covered Arctic, to a summer Arctic melt, to annually ice-free Arctic.[99] Somewhere in a warming of 4 to 7 degrees Celsius, these successive changes should be realized.

The context of likely future conditions (e.g., global population reaching 8 to 10 billion, and extreme pressure on land and biotic resources) assures us of the reasonableness of this assessment.

Feasibility Aspects

An effective preventive response can be affected only through a gradually declining rate of fossil fuel combustion. The means by which the rate of combustion might be constrained include: increased energy end-use efficiency; the incorporation of environmental costs into the costs of energy services; the elimination of subsidies to fossil fuel production; subsidization of non-carbon fuels; the taxation of combustion; and coal export restrictions. Society's ability to significantly reduce the rate of atmospheric accumulation is estimated either through the use of energy-economy models or through more intuitive estimates of what might possibly be achieved through different energy use arrangements than presently prevail.

Various estimates of the technical potential for long-term limits on the rate of accumulation are given in Table 14. These establish a lower bound on what could potentially be achieved. The table also shows the estimated effects of enhanced end-use efficiencies. As a point of reference, end-use efficiency increased by 1 to 2 percent per year in the decade subsequent to the 1973 oil embargo.[102] Also shown are results gleened from energy-economy models. Taken together, these results suggest that in 2050 the atmospheric concentration of carbon dioxide could be constrained to 400 to 440 ppmv. These are in sharp contrast to the projected levels in the uncontolled case, 510 to 550 ppmv.[103]

These estimates are taken from a wide variety of approaches to underline the apparent potential that exists for a successful interventionist response. Other estimates could as easily be substituted for those included in Table 14.[104]

Probabilistic Reasoning

Given the parameters governing the rate of future warming, different rates of warming have different probabilities of occurrence. A limited warming, for example 2 or 3 degrees Celsius, is rather improbable. Policy cannot be based on such improbably low estimates. It is possible to do so only upon a willingness to play long odds with regard to the physical description of the problem. As others have pointed out, probabilistic reasoning ought to form the principal basis for decision-making with regard to the climate change problem. This approach suggests that policy respond to impacts at the much higher levels of warming that, in absence of preventive action, would accompany the realization of the base case parameters of Table 13. There is but one exception to this rule: that extra weight be given to worst case events to express our aversion to high-risk outcomes.

If we use this reasoning as a guide to policy formulation, the basis for an inactive response, which, again, assumes relatively minor changes in climate, effectively disappears.

Table 14
ESTIMATES OF FEASIBLE LIMITS ON FUTURE CARBON DIOXIDE LEVELS

	Carbon Dioxide (ppmv)[a]			Cost (percent of GDP)
	2020	2050	Ultimate	
Technical potential				
Williams 11 TW Case[b]	388	--	--	?
Lovins 8 TW Case[c]	370	370	--	?
Fossil fuel limitation				
Coal, oil shale, tar sands	--	--	431-491[d]	?
Oil and natural gas	--	--	1,489-7,455[e]	?
Energy efficiency gain[f]				
High gain (1.8 % per year)	408	--	--	?
Base gain (1.2 % per year)[g]	412	--	--	?
Full cost coal pricing[h,i]	400	468	--	1[j]
Alternative OECD/LDC development model[k]	405	--	--	?
$150/mtce tax (1975 $)[l]	--	414-440	--	?
Energy-economy scenarios				
Rose et al. Case E[i,m]	383	428	--	2
Rose et al. Case J[i,n]	379	410	--	2
Edmonds and Reilly[o]	402-410	452-482	--	?

(a) Assumes an airborne fraction of 0.56.

(b) See R. Williams et al., this volume.

(c) See A. Lovins, "Economically Efficient Energy Futures," in *Interactions of Energy and Climate*, W. Bach, J. Pankrath, and J. Williams eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1980).

(d) The carbon content of remaining conventional oil and natural gas is taken from W. Haefele et al., *Energy in a Finite World* (Cambridge, Mass.: Ballinger Publishing Co., 1981).

(e) Coal resources are estimated after World Energy Conference, *World Energy Resources 1985-2020: An Appraisal of World Coal Resources and Their Availability* (Guildford, U.K.: IPC Science and Technology Press, 1978). Best guess and upper limit speculations for the carbon content of oil shale and tar sands are from R. Rotty and G. Marland, "Constraints on Fossil Fuel Use," in Bach, Pankrath, and Williams, note (c) above.

(f) W. Chandler, *Energy Productivity: Key to Environmental Protection and Economic Progress*, Worldwatch paper 63 (Washington, D.C.: Worldwatch Institute, 1985).

(g) 1.8 percent per year from 1985 to 2000, and 1.2 percent per year from 2000 to 2025.

(h) Incorporating the full environmental costs of coal combustion into the sale price.

(i) See D. Rose, M. Miller, and C. Agnew, *Global Energy Futures and CO_2-Induced Climate Change*, MITEL 83-015 (Cambridge, Mass.: Massachusetts Institute of Technology Energy Laboratory, 1983).

(j) Incorporating the full environmental costs of fossil fuel combustion into the selling price should result in no economic costs to society. The given value does not fully represent environmental costs as a determinant of the rate of future economic growth.

(k) Assumes the present ratio of rural to urban populations and much enhanced efficiency of energy end-use in Organization for Economic Cooperation and Development (OECD) economies. See U. Columbo and O. Bernardini, "A Low Energy Growth 2030 Scenario and the Perspective for Western Europe," report prepared for the Commission of the European Communities, Panel on Low Energy Growth, European Economic Community, Brussels, 1979. The atmospheric carbon dioxide levels associated with the Colombo and Bernardini modeling effort are taken from W. Bach, *Our Threatened Climate: Ways of Averting the CO_2 Problem Through Rational Energy Use* (Dordrecht, Netherlands: D. Reidel Publishing Co., 1984).

(l) Assumes an average decadal response of 0.1 to 0.136 ppmv per dollar per metric ton coal equivalent (mtce) taxation, and that permanent taxation is implemented in the year 2000. See W. Nordhaus and G. Yohe, "Future Carbon Dioxide Emissions from Fossil Fuels," in *Changing Climate*, Carbon Dioxide Assessment Committee, National Research Council (Washington, D.C.: National Academy Press, 1983), taxation experiments (permanent 1980 tax, and permanent stringent year 2000 tax).

(m) Low solar electric costs ($2.05/watt), full-cost coal pricing, and an oil and gas tax of about 50 percent.

(n) Case E plus higher end-use efficiency improvements (1 percent per year), and the embargo of Middle East oil exports.

(o) See J. Edmonds et al., *Uncertainty in Future Global Energy Use and Fossil Fuel CO_2 Emissions 1975 to 2075*, DOE/NBB-0081 (Washington, D.C.: U.S. Department of Energy, 1986).

Time to Much Better Information

Given the time-scales of required action, under nearly any set of parameters, a delay in the effort to initiate action may foreclose the possibility for action. By contrast, the amount of time required for society to significantly improve its understanding of the regional climate response may be long. Significantly improved information depends on the development of a realistic ocean GCM. Further, it depends on greatly enhanced resolution of the atmospheric GCMs. Given the physical dimensions of storms and clouds, it is probably necessary to reduce the distance between grid points by at least one-half. We will also need, somehow, to be able to discount the effects of potential surprises arising from our limited understanding of much of nature.[105]

A good ocean GCM is at least two decades away.[106] Better resolution with regard to some weather parameters may come more quickly. But detailed, reliable physical descriptions of precipitation changes depend on local cloud responses. Current descriptions of these are primitive. The long-term program of research suggests that several decades or more of research will be involved.[107] The past rate of progress on cloud responses suggests that the resolution of unknowns here might take a like amount of time.[108] It may never be possible to resolve the unknowns at warmings greater than 5 degrees Celsius.

A MORE REASONABLE RESPONSE

Given the above analysis, it can be shown that an inactive response to the climate change problem does not fit the physical and time dimensions of global warming. Inaction depends on the ultimate rightness of action initiation times decades into the future. This cannot be shown. It depends on the employment of time and social discounting techniques, and, as D'Arge et al. have shown,[109] distributional issues are probably best treated through an equal valuation of present and future generations. Finally inaction requires an unreasonable treatment of the probability of the occurrence of a warming.

A better approach might involve the employment of a provisional response. In order to effectively respond to global warming over the short-term, society can act with long-term resolution to restrict emissions; it can do nothing; or it can act to preserve society's long-term options with regard to the release of the greenhouse gases. Since a warming in the range of 4 to 5 degrees Celsius appears to introduce us to the margin of change at which catastrophic events become an important consideration, a provisional response designed to preserve our options must also be a preventive response. To implement such a response, initial actions to limit the long-term rate of accumulation must be taken soon.

A provisional response has the virtue of allowing scope for future revision of the parameter estimates given above. Provisional responses can be reversed, but there can be no recouping of ground lost through inaction.

But beyond this, a better approach might involve some effort to meld present actions into the longer-term logic of global energy supply. The transition from petroleum to another energy base is inevitable. In the long-term, a coal-based system is not an option. The discussion over the future of coal is fundamentally constrained by the dilemma of a changing climate; the issue is not whether coal constitutes a long-term option but only when a transition away from it can be affected. Given this, it is only reasonable, in considering the long-term imperative for a movement from coal, to fold-in our concern for the timeliness of that movement. It makes little sense, from a strategic point of view, to continue our present coal use, knowing that, in the end, it will have to be discontinued, and that, in addition to high capital costs, the cost of transition, if delayed, will also include the climate impact costs of a warming.

Regardless of whether we reason from the present forward on the basis of risk or from the future backward, it is impossible to escape the imperative of a preventive response. In a sense, the sheer physical scale of the problem assures this. At what seem to be likely parameter estimates, if we are to avoid warmings that no one thinks we can live with, an enormous reduction in carbon dioxide emissions is necessary. If we look at the worst case, large amounts of carbon have to be withdrawn from the atmosphere. The degree of intervention that is required is a measure of the enormity of the problem. The estimated response of global temperatures to industrialization is now so large as to require wholesale transformation of the energy base of industrial society. Or, stated another way, the scale of possible changes is now so large that, in order to assess the sign of the impacts, we need not even be able to describe individual impacts; the scale of the change virtually ensures that the sign will be negative. Estimated against any standard benefit-cost calculus (assuming no social and time discounting), this must convince us of the logic of the preventive response.

The only question that arises relates to the time of action. At many of the parameter combinations given in Table 13, each and every year that passes without action makes it less likely that the rise in average global temperature could be limited to even as high a level as 6 to 7 degrees Celsius. This is not the type of changes that we should will to future generations.

The most efficient preventive response involves the proper pricing of energy services and enhancement of the efficiency of energy end-use. This might be pursued first. Over the longer term, in order to roll the emission's curve over, it may be necessary to resort to taxation. This can be determined as the long-term emissions response becomes clear.

Objections

Cost Constraints: It has been suggested that the costs of action constitute an irresistible constraint to action.[110] There is, however, little evidence to support this contention. Estimated with global energy-economy models, the costs of the policies noted in Table 14 might serve to lower gross world product on the order of 1 or 2 percent by 2050 (or at an average rate of -0.02 to -0.04 percent per year) and, hence, are are small in comparison to the costs of climate change.[111] The costs of significantly enhanced end-use efficiency are consistent with the estimates of Nordhaus.[112] The postulated annual increase in end-use efficiency is thought to be attainable with moderate stimuli and good information. The costs of full-cost coal pricing are known axiomatically: full-cost pricing is an expression of the polluter-pays principle, which, in theory at least, maintains efficiency in energy and other markets. As a point of reference, historical subsidies to energy production in the United States have been estimated at about $44 billion per year (in 1984 dollars), or about 1.5 percent of gross national product.[113]

Ability to Set a Threshold: As noted elsewhere, below the 4 degrees Celsius level of change, it is difficult to establish a particular threshold of unacceptable change. There is no way to distinguish between different levels of warming in any believable way. Below this level of change, the history of the greenhouse problem suggests that it is exceedingly difficult to convince the body politic that action is necessary.

But, although this is true, the case for a preventive response at a warming of 7 or 9 degrees Celsius is, nonetheless, manifest. No one has suggested that such a warming could be sustained. And, since a 6 degree Celsius warming is largely indistinguishable, in a qualitative sense, from the slightly more intense warmings, the same can be said of this type of warming. Hence, while some approaches do founder in confusion at the 2 to 3 degree Celsius range of change,[114] no fundamental constraint to the analysis leading to the establishment of a ceiling on permissible mean global temperature change is in fact evident.

International Aspects of Control: It has been suggested that the international requirements of the preventive response render it infeasible.[115] Due to the wide geographical distribution of fossil fuel consumption, long-term limits on combustion demand some sort of cooperative agreement. This, it is suggested, is unlikely.

We have no doubt that it will be difficult for the international community to agree to limit fossil fuel use. However, at present, emissions from the industrialized West account for about 50 percent of all carbon added to the atmosphere, which gives the West a controlling influence on future atmospheric carbon dioxide concentrations so long as rates of growth in fossil fuel use remain below 1 or 1.5 percent per year elsewhere (see Table 15). Since Western nations do often act in concert, it is not inconceivable that OECD action could form the basis for a long-term preventive response.

Effects of Long Time-scales on Rates of Accumulation: The feasibility of longer-term limits on atmospheric carbon dioxide concentrations is often questioned on the grounds of the long time-scales of the problem.[116] An enormous amount of carbon could potentially be released through the combustion of the world's coal resources. Over long periods of time, this must accumulate in the atmosphere.

However, the future atmospheric level of carbon dioxide is very sensitive to a host of assumptions about the structure and the long-term rate of maturation of the global economy, the price of presently exotic liquid and gaseous fuel sources, the degree of environmental degradation with which a post-industrial society would be willing to live, and other factors.* At present,

*For instance, the results of the Edmonds and Reilly model (1983) depend to a degree on the estimated cost of shale oil and synthetic oil, which, according to the model together will contribute about 20 percent to the net atmospheric carbon dioxide increase between 1980 and 2100. No shale oil and synoil would be produced according to the model were the prices for these fuels in the next century to be lower by just one-sixth to one-third.[117]

only speculative assessments or estimates can be offered for most of these. Our understanding of the long-term relations between energy use and future developments in the global economy is limited.[118] The energy-economy models have been consistently wrong over the last fifteen years, and those projecting high energy growth rates continue to yield results for future use that diverge widely from recent experience.[119] Although releases during only the next fifty years could be as much as 400 to 450 GT carbon (resulting from 12,000 gigawatt years per year of coal consumption[120]), it is also possible that enactment of environmental legislation to control the worse effects of combustion activities will limit long-term coal use, or that over the long-term the coal export trade will fail to develop.[121]

Therefore, we do not believe that the results of such models can be taken as particularly demonstrative of the inevitability of a high future atmospheric level of carbon dioxide but only as illustrative of the degree to which our present mode of projecting future conditions is mismatched to problems which have very long time horizons.

Table 15
ATMOSPHERIC LEVELS OF CARBON DIOXIDE IN 2050 WITH VARIATIONS IN FOSSIL FUEL GROWTH RATES FOR VARIOUS OECD NATIONS
(in ppmv)

Annual Percent Change in Emissions	USWE	USWEJ	USWEJC[a]
+2	539	542	541
+1	510	509	506
0	492	490	485
-1	481	477	472

Note: It is assumed that trends in fossil fuel use outside of the OECD are based on historic trends. See R. Rotty, G. Marland, and N. Treat, *The Changing Pattern of Fossil Fuel CO_2 Emissions*, DOE/OR/21400-2 (Washington, D.C.: U.S. Department of Energy, 1984). For Council on Mutual Economic Assistance (CMEA) nations, emissions would increase initially 1.8 percent per year, but the rate of increase would itself decline about 6 percent per year. For China, emissions would initially increase annually 3.25 percent per year, but the rate of increase would decline 6 percent per year until it reaches 1.5 percent per year, where it is assumed to stabilize. Emissions from the developing market economies would increase 4 percent per year, consistent with the average annual rate of increase in fossil fuel use from 1972 to 1983. Present rates of increase in emissions from Canada, Japan, and Australia and New Zealand are 1.9, 1.17, and 2.7 percent per year, respectively.

(a) US = United States; WE = Western Europe; J = Japan; C = OECD Commonwealth Nations.

Other Releases: Finally, it has been suggested that sources of climate change other than carbon dioxide from energy use might be the targets of an effective preventive response. Carbon dioxide could be controlled by controlling deforestation. Likewise, controls could be imposed on surface emissions of the other greenhouse gases. Finally, society could employ various technical fixes that might allow a fossil fuel-based economy to go forward with limited effects on climate.

At present, none of these alternatives appears to hold much promise. Net emissions of carbon from the biosphere are principally related to demographic pressures in developing tropical and subtropical regions and to the need for land for agriculture and wood for fuel.[122] Of the various pressures leading to the emission of the greenhouse gases, demographic pressure is by far the most difficult with which to deal, since, for political reasons, controls on population growth seem the least likely of any controls to be implemented. This, along with the pace of present demographic pressures, suggests that long-term emissions from biospheric sources are inevitable.

Temperature-related emissions of methane and carbon dioxide can be controlled only to the degree that the overall rate of global warming is controlled. No intervention outside of such long-term control is possible.

The surface sources of the chlorofluorocarbons, methyl chloroform, methylene chloride, carbon tetraflouride, and carbon tetrachloride are mainly related to manufacturing activities (see Table 16). As noted above, long-term trends in global industrialization may make control of these releases exceedingly difficult. The feasibility of emissions control has been demonstrated with regard to the chlorofluorocarbons.[123] However, even at constant present-day rates of release of CFC-11 and CFC-12, concentrations will still approach 3 parts per billion (ppbv) in the long term. (At a 15 percent reduction, concentrations would approach 2.5 ppbv.[124]) And although it is possible to control CFC-11 and CFC-12, other infrared active gases like methyl chloroform and CFC-22 are believed likely to be introduced as substitutes. Hence, although some measure of control can be purchased, only a part of the future effects of these gases can in fact be forestalled.

To the degree that some of the emissions of these gases result from combustion, long-term limits on combustion will help to limit the long-term accumulation of gases like methane and ozone. At present, about 15 to 20 percent of surface methane emissions result from activities associated with the production, transportation, and combustion of coal and natural gas.[125] Tropospheric ozone is produced in situ in the atmosphere consequent to the surface emission of carbon monoxide and methane. Anthropogenic emissions of carbon monoxide result from incomplete combustion of fossil fuels and from wood burning in deforestation.[126] Although the former should increase in importance with the gradual disappearance of the tropical forests, it now accounts for no more than half of the observed increase in concentrations.

Table 16
SOURCES OF SOME OTHER GREENHOUSE GASES

Gas	Sources of Increase[a]
CFC-11, CFC-12, CFC-22	Use as aerosol propellants, leakage from refrigerator units, foam blowing
Methyl chloroform	Industrial solvent use, landfills
Methylene chloride	Industrial solvent use
CFC-13, CFC-113, CFC-114, CFC-115	Industrial solvent use
Carbon tetrafluoride	Aluminum refining, steel production
Carbon tetrachloride	Chlorofluorocarbon production
CFC-116	Aluminum industry
Nitrous oxide	Combustion, fertilizer use
Tropospheric ozone	Carbon monoxide, NO_x, methane emissions
Stratospheric water vapor	Tropical tropopause warming from presence of chlorofluorocarbons

(a) See V. Ramanathan et al., "Trace Gas Trends and Their Potential Role in Climate Change," *Journal of Geophysical Research* 90 (1985): 5,547.

If we account for limited contribution of combustion activities to future rates of increase, then the level of possible control is quite minor. We estimate the other gas-induced warming by 2070 at 2.2 to 6.2 degrees Celsius.[127] Levels of potential control are estimated in Table 17 for the other gases. Estimates for some other measures of control are also included.

There is no economically feasible way of removing carbon dioxide either from the effluent streams of power plants or directly from the atmosphere.[128] It has been suggested that, in response to climatic change, society will generate a technical fix.[129] However, it has yet to be demonstrated that the physical potential for any single technological remedy exists. To base policy on the hope that one day a technological fix will be developed is to go beyond the bounds of credibility.[130]

Table 17
FEASIBILITY FOR LIMITING WARMING FROM OTHER SOURCES
(degrees Celsius)

	Potential Limitation	Warming, No Control
Other gases by 2070[a]	0.3-2.2	2.2-6.2
Temperature sensitive releases[b]	--	0.4-0.8
Deforestation carbon in 2070[c]	?	0.2-0.5
Carbon dioxide removed through stack scrubbing by 2050[d]	0.1-0.4	1.6-5.1[e]

(a) Chlorofluorocarbon, nitrous oxide, methane, and tropospheric ozone levels in the uncontrolled case are estimated at 2.7 to 7.8 ppbv, 400 ppbv, 6 to 7.5 ppmv, and double present tropospheric ozone level, respectively. Chlorofluorocarbon levels are taken from R. Dickinson and R. Cicerone, "Future Global Warming from Atmospheric Trace Gases," *Nature*, 319 (1986): 109. In the controlled case, CFC-11 and CFV-12 levels are assumed to stabilize at about 2.5 ppbv.

(b) Assumes a 20 ppmv increase of carbon dioxide through respiration and a net methane increase of 2.2 to 3.5 ppmv.

(c) Assumes a net addition of 50 to 70 ppmv of carbon dioxide to the atmosphere.

(d) Assumes that control is limited to the electrical sector and that, due to the distance of much electrical capacity from coastal regions, half of electrical generation capacity would be affected; control is forseen only in the case of capacity added after 1995.

(e) An equilibrium carbon dioxide-induced warming assuming a 1.5 to 2 percent per year increase in fossil carbon emissions.

CONCLUSION

The past few years have seen increasingly sophisticated scientific descriptions of the warming that will result from present and future releases of the greenhouse gases. As a result of these, it is no longer reasonable to employ relatively minor global warmings of 1 or 2 degrees in estimating the importance of future warming. In conjunction with the emissions of the other gases, unrestricted combustion of the fossil fuels will result in a warming three to four times greater than this.

As a result, it is possible to demonstrate that, if global warming is to be limited to less than 4 degrees Celsius, action to restrict the expansion of fossil fuel combustion is necessary in the very near future. Further, it is possible to show that, under the changed conditions of the problem, the usual imperatives of uncertainty no longer hold sway in the policy calculus. At realistic estimates of change, we can define something of a lower limit to the broad scale of climatic and environmental disruption, and this suggests that at best the situation is a bad one. But no upper limit can be described. In such a situation, only a safety-first preventive response is reasonable.

Past assessments have failed to appreciate the degree to which changes in the physical dimensions of the greenhouse problem have, since the late 1970s, transformed it. As a result, many people have come to the conclusion that at this stage intervention is not warranted. These conclusions have lost much of their past relevance.

Uncertainties certainly exist, and will continue to exist long into the future. But in those cases where uncertainties do exist, they can be bounded, and in the process can be shown not to constitute an insurmountable barrier to policy intervention. In conjunction with the effect that the projected intensity and rate of future warming has had on our perception of the importance of global warming, this should bias policy toward a more interventionist response.

NOTES

1. Carbon Dioxide Assessment Committee, National Research Council, *Changing Climate* (Washington, D.C.: National Academy Press, 1983).

2. For a review of the problem, see P. Ciborowski and D. Abrahamson, "The Global Greenhouse Problem," this volume.

3. V. Ramanathan et al., "Trace Gas Trends and Their Potential Role in Climate Change," *Journal of Geophysical Research* 90 (1985): 5,547.

4. See note 1 above.

5. See the climate sensitivities cited in M. Schlesinger and J. Mitchell, "Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide," in *Projecting the Climatic Effects of Increasing Carbon Dioxide*, M. MacCracken and F. Luther, eds., DOE/ER-0237 (Washington, D.C.: U.S. Department of Energy, 1985).

6. See note 1 above.

7. J. Trabalka et al., "Atmospheric CO_2 Projections With Globally Averaged Carbon Cycle Models," in *The Changing Carbon Cycle: A Global Analysis*, J. Trabalka and D. Reichle, eds. (New York: Springer-Verlag, 1986).

8. See note 3 above.

9. North American conditions during the Altithermal (6,000 years before the present), the most often cited analogue to a 1 to 1.5 degrees Celsius warming, included: lower midwestern precipitation levels; a 100 to 200 kilometer eastward advancement of the prairie; lower lake levels; and a higher frequency of drought. See J. C. Bernabo and T. Webb III, "Changing Patterns in the Holocene Pollen Record of Northeastern North America: A Mapped Summary," *Quaternary Research* 8 (1977): 64; W. Watts and R. Bright, "Pollen, Seed and Mollusk Analysis of a Sediment Core from Pickerel Lake, Northeastern South Dakota," *Geological Society of America Bulletin* 79 (1968): 855; F. Street-Perrott and S. Harrison, "Lake Level Fluctuation," in *Paleoclimate Analysis and Modeling*, A. Hecht, ed. (New York: J. Wiley and Sons, 1985); P. Bartlein, T. Webb III and E. Fleri, "Holocene Climatic Change in the Northern Midwest: Pollen-Derived Estimates," *Quaternary Research* 22 (1984): 361; M. Winkler, A. Swain, and J. Kutzbach, "Middle Holocene Dry Period in the Northern Midwestern United States: Lake Levels and Pollen Stratigraphy," *Quaternary Research* 25 (1986): 235; W. Watts, "Late Quaternary Vegetation of Central Appalachia and the New Jersey Coastal Plain," *Ecological Monographs* 49 (1980): 427; and J. King and W. Allen Jr., "A Holocene Vegetation Record from the Mississippi River Valley, Southeastern Missouri," *Quaternary Research* 8 (1977): 307.

10. N. Shackleton et al., "Oxygen Isotope Calibration of the Onset of Ice-Rafting and the History of Glaciation in the North Atlantic Region," *Nature* 307 (1984): 620.

11. For a seasonal disappearance of the Arctic ice, see S. Manabe and R. Stouffer, "Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration," *Journal of Geophysical Research* 85 (1980): 5,529. For a discussion of complete disappearance, see H. Flohn, "Reply," in *Carbon Dioxide Review: 1982*, W. Clark, ed. (New York: Oxford University Press, 1982). For some questions about the degree of mean global surface warming required to melt the Arctic pack ice, see A. Semtner, "On Modelling the Seasonal Thermodynamic Cycle of Sea Ice in Studies of Climatic Change," *Climatic Change* 6 (1984): 27.

12. The generalized response of ecological regions in the middle latitudes is estimated at several hundred kilometers per degree Celsius change in mean global surface temperature. See P. Ciborowski and D. Abrahamson, "The Global Greenhouse Problem," this volume, ref. 10.

13. E. Dorf, "Climatic Changes of the Past and Present," *American Scientist* 48 (1960): 341.

14. F. Lotze, "Distribution of Evaporites in Space and Time," in *Problems in Paleoclimatology*, A. Nairn, ed. (London: Interscience Publishers, 1964).

15. J. Hansen et al., "Climate Sensitivity: Analysis of Feedback Mechanisms," in *Climate Processes and Climate Sensitivity*, J. Hansen and T. Takahashi, eds. (Washington, D.C.: American Geophysical Union, 1984).

16. The time trends in Figure 1 are calculated to account for two different sets of concerns: that a lower limit to the likely effect be estimated and that a reasonable upper limit that accounts for the other gases and the potential high emissions effects of long-term technological change and spreading worldwide industrialization be estimated.

Parameter Estimates for Figure 1

Parameters	Case A	Case B	Case C
Fossil fuel CO_2 emissions' growth rate (%/yr.)	2	2	1.5
Initial airborne fraction	65	65	40
Climate sensitivity (degrees C/2 x CO_2)	4.2	3.5	2
Other gases (% of CO_2)	150	100	--
Other carbon (ppmv)	150	150	65
Lag in response (yrs.)	45	40	12

Growth rates in fossil fuel use are taken from A. Perry, "Carbon Dioxide Production Scenarios," in Clark in note 11 above; and H.-H. Rogner, "Long-term Energy Projections and Novel Energy Systems," in Trabalka and Reichle in note 7 above. The estimates for climate sensitivity are taken from Table 12, this paper. The estimates for the other gas parameter are taken from the "best" estimate category of Table 10, this paper.

Other Gas Warming, Case C, 2070 (degrees C)

Gas	Warming
Ozone	0.6
Methane	0.8
CFC-11, CFC-12	0.3
Nitrous oxide	0.2
Others	0.3
Total	2.2

Sources for the net emission of "other carbon" include: deforestation, methane decay, cement production, oceanic out-gassing, and an enhanced rate of biotic respiration. A range of possible emissions is given in Table 9, this paper. The values given above are rounded and adjusted for the appropriate airborne fraction. Values for the present airborne fraction are taken from Table 8, this paper. The airborne fraction can be expected to rise about 10 percent over the time period of interest. See S. Seidel and D. Keyes, *Can We Delay a Greenhouse Warming?* (Washington, D.C.: U.S. Environmental Protection Agency, 1983). Also see the rise in the airborne fraction from 2020 to 2070 in the model results for four models and thirteen scenarios presented in J. Trabalka et al., "Human Alterations of the Global Carbon Cycle and the Projected Future," in *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, J. Trabalka, ed., DOE/ER-0239 (Washington, D.C.: U.S. Department of Energy, 1985), table 10.6.

The delay in the climate response is for a 100 percent delay, estimated by the difference in timing between the transient response at 2030 and 2070 and the corresponding point earlier in the time trend of atmospheric CO_2 accumulation at which the equilibrum warming from that accumulation (calculated at that point) would yield an equivalent warming. The pattern of estimated delay for Case C is taken from K. Bryan et al., "Transient Climate Response to Increasing Atmospheric Carbon Dioxide," *Science* 215 (1982): 56. For Cases A and B, the pattern of response is approximated from Hansen et al., note 15 above.

No carbon dioxide-induced increase in photosynthesis is assumed in the calculations. For the highly uncertain nature of this term, see Trabalka et al., this note. In the low case, we assume an initial airborne fraction of 0.4, which takes into account any net flux of carbon into an otherwise expanding biosphere. An airborne fraction of 0.4 assumes an emission of about 8 GT from fossil fuel use and deforestation, of which some 3.5 GT remains in the atmosphere, while 2.25 to 3 GT moves into the oceans, and the rest is assumed to move into some missing sink. This could be the biosphere. If we explicitly incorporate a growing biosphere and use for the present airborne fraction the apparent airborne fraction (0.56), with a B factor of 0.2, atmospheric carbon dioxide concentrations would be about 600 ppmv at 2070, or roughly similar to those calculated for Case C.

17. These changes are roughly similar to those reported in recent studies.

Projected Changes in Mean Global Surface Temperature

	End Date of Projection		
Projection	2050	2075	2100
Seidel and Keyes 1983[a]			5.0
Hansen et al. 1986[b]			2.7-23.5
Dickinson 1985[c]			3.4-6.9
Mintzer 1987 [d]		3.2-6.7	
Dickinson and Cicerone 1986[e]	1.0-7.5		
MacDonald 1982[f]	3.4-7.0		
Hansen et al. 1988[g]	3.4		

Note: Where equilibrium estimates are given, they are adjusted to climate sensitivities of 2 and 4.2 degrees Celsius (per doubled atmospheric carbon dioxide).

(a) Seidel and Keyes in note 16 above.

(b) J. Hansen et al., "The Greenhouse Effect: Projections of Global Climate Change," in *Effects of Changes in Stratospheric Ozone and Global Climate*, vol. 1., *Overview*, J. Titus, ed. (Washington, D.C.: U.S. Environmental Protection Agency, 1986).

(c) R. Dickinson, "Impact of Human Activities on Climate--A Framework," in *Sustainable Development of the Biosphere*, W. Clark and R. Munn, eds. (Cambridge, U.K.: Cambridge University Press, 1985).

(d) I. Mintzer, *A Matter of Degrees: The Potential for Controlling the Greenhouse Effect*, research report 5 (Washington, D.C.: World Resources Institute, 1987).

(e) R. Dickinson and R. Cicerone, "Future Global Warming from Atmospheric Trace Gases," *Nature* 319 (1986): 109.

(f) G. MacDonald, ed., *The Long-Term Impacts of Increasing Atmospheric Carbon Dioxide Levels* (Cambridge, Mass.: Ballinger Publishing Co., 1982).

(g) J. Hansen et al., "Global Climate Changes as Forecast by Goddard Institute for Space Studies Three-Dimensional Model," *Journal of Geophysical Research* 93 (1988): 9,341.

18. R. Rotty and G. Marland, "Constraints on Fossil Fuel Use," in *Interactions of Climate and Energy*, W. Bach, J. Pankrath, and J. Williams, eds. (Dordrecht, Netherlands: D. Reidel Publishing Company, 1980).

19. See R. Bacastow and A. Bjorkstrom, "Comparison of Ocean Models for the Carbon Cycle," in *Carbon Cycle Modelling*, B. Bolin et al., ed., Scope 16 (Chichester, U.K.: John Wiley and Sons, 1981) chap. 2, figs. 13-16.

20. R. Loomis, "CO_2 and the Biosphere," in *Workshop on the Global Effects Carbon Dioxide from Fossil Fuels*, W. Elliot and L. Machta, eds., CONF-770385 (Washington, D.C.: U.S. Department of Energy, 1979).

21. For a 75 to 140 GT emission from ocean out-gassing with an ocean warmer by 2 to 5 degrees Celsius, see C. F. Baes, Jr. and G. Killough, *A Two Dimensional CO_2-Ocean Model Including the Biological Processes*, DOE/NBB-0070 (Washington, D.C.: U.S. Department of Energy, 1985). For an apparent release of about 200 GT during the last interglacial age, see J.-C. Duplessy and N. Shackleton, "Carbon-13 in the World Ocean during the Last Interglacial and the Penultimate Glacial Maximum: Reevaluation of the Possible Biosphere Response to the Earth's Climatic Change," *Progress in Biometeorology* 3 (1984): 48. For a 100 to 200 GT emission per degree Celsius increase in temperature, see Loomis in note 20 above.

22. C. F. Baes Jr. and G. Killough, "Chemical and Biological Processes in CO_2-Ocean Models," in Trabalka and Reichle, note 7 above.

23. The components of the 300-year sea level rise are estimated as follows:

300-Year Sea Level Rise

Source of Increase	Sea Level Rise (in meters)
Water column expansion[a]	2.5-4.5
Small glaciers[b]	0.3-0.6
Permafrost[c]	0.1
Greenland[d]	1.1-2.6
Antarctica[e]	0.6-1.7

(a) The generalized water column response to temperature is from S. Savin and R. Douglas, "Sea Level, Climate and the Central American Bridge," in *The Great American Biotic Interchange*, F. Stehl and S. Webb, eds. (New York: Plenum Press, 1985).

(b) M. Kuhn, "Reactions of Mid-Latitude Glacier Mass Balance to Predicted Climatic Changes," in *Glaciers, Ice Sheets, and Sea Level: Effects of a CO_2-Induced Climatic Change*, Committee on Glaciology, National Research Council, ed., DOE/ER/60235-1 (Washington, D.C.: U.S. Department of Energy, 1985).

(c) R. Barry, "Snow Cover, Sea Ice and Permafrost," in Committee on Glaciology, National Research Council, note (b) above.

(d) R. Bindschadler, "Contribution of the Greenland Ice Cap to Changing Sea Level: Present and Future," in Committee on Glaciology, National Research Council, note (b) above.

(e) R. Thomas, "Responses of the Polar Ice Sheets to Climatic Warming," in Committee on Glaciology, National Research Council, note (b) above; and C. Lingle, "A Model of a Polar Ice Stream and Future Sea Level Rise Due to Possible Drastic Retreat of the West Antarctic Ice Sheet," in Committee on Glaciology, National Research Council, note (b) above.

24. See Ciborowski and Abrahamson in note 12 above, table 8; and R. Thomas, "Future Sea Level Rise and Its Early Detection by Satellite Remote Sensing," in Titus, note 17 (b) above, vol. 4, *Sea Level Rise*. For sea level during the last period in which mean global surface temperature was 1 degree Celsius warmer, see H. Lamb, *Climate, History and the Modern World* (London: Methuen, 1982), p. 107, fig. 39.

25. R. Sorenson, R. Weisman, and G. Lennon, "Control of Erosion, Inundation, and Salinity Intrusion," in *The Greenhouse Effect and Sea Level Rise: A Challenge for this Generation*, M. Barth and J. Titus, eds. (New York: Van Nostrand Reinhold, 1984).

26. J. Titus, "The Causes and Effects of Sea Level Rise," in Titus, note 17 (b) above.

27. R. Bradley, "Conceptualization of Esthetic Damages Induced By Climatic Change," *Economic and Social Measures of Biologic and Climatic Change*, Climatic Impact Assessment Program, CIAP monograph 6 (Washington, D.C.: U.S. Department of Transportation, 1975). Bradley concludes that any average annual temperature increase in the United States will result in net annual economic losses in terms of the compensation which must be offered in order to induce present populations to remain in warmer climates. Presumably, this will affect tourism.

28. M. Gibbs, "Economic Analysis of Sea Level Rise: Methods and Results," in Barth and Titus, note 25 above.

29. S. Ben-David, and W. Schulze, "Economic Impact of Climatic Change on World Agriculture: Benefit-Cost Analysis for Cotton and Corn," in Climatic Impact Assessment Program, note 27 above; and E. Cooter, "An Assessment of the Potential Economic Impacts of Climate Change in Oklahoma," in Titus, note 17 (b) above, vol. 3, *Climate Change*. For the generalized impact, see R. Warrick, R. Gifford, with M. Parry, "CO_2, Climatic Change and Agriculture," in *The Greenhouse Effect, Climatic Changes and Ecosystems*, B. Bolin et al., eds. (Chicester, U.K.: John Wiley and Sons, 1986).

30. I. Hoch, "Climate, Energy Use, and Wages," in *The Economics of Managing Chlorofluorocarbons*, J. Cumberland, J. Hibbs, and I. Hoch, eds. (Baltimore: John Hopkins University Press, 1982).

31. Development and Resources Corporation, "Economic Impact of Water Resources as a Result of Climatic Change," Climatic Impact Assessment Program, note 27 above.

32. P. Sasson, "Public Sector Costs of Climate Change," in Climatic Impact Assessment Program, note 27 above.

33. W. Riebsame, "Social Adaptation to Climate Change: Research and Policy Issues," this volume.

34. For these conditions, see note 14 above. For a generalized review of the evidence, see Ciborowski and Abrahamson in note 12 above, table 9.

35. Summer temperatures tend to vary with the availability of surface moisture. A drying will tend to accentuate the surface temperature response. See D. Rind, "The Influence of Ground Moisture Conditions in North America on Summer Climate as Modeled in the GISS GCM," *Monthly Weather Review* 110 (1982): 1,487; also J. Shukla and Y. Mintz, "Influence of Land-Surface Evapotranspiration on the Earth's Climate," *Science* 215 (1982): 1,498. For the surface temperature response under drier model conditions, see S. Manabe and R. Wetherald, "Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide," *Science* 232 (1986): 626.

36. Ciborowski and Abrahamson in note 12 above, table 9; D. Rind and S. Lebedeff, *Potential Climatic Impacts of Increasing Atmospheric CO_2 with Emphasis on Water Availability and Hydrology in the United States*, EPA 230-04-84-066 (Washington, D.C.: U.S. Environmental Protection Agency, 1984); and Manabe and Wetherald in note 35 above.

37. See J. Callaway and J. Currie, "1985: Water Resource Systems and Changes in Climate and Vegetation," in *Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health*, M. White, ed., DOE/ER-0236 (Washington, D.C.: U.S. Department of Energy, 1985); or P. Gleick, "Regional Water Resources and Global Climatic Change," in Titus, note 17 (b) above, vol. 3, *Climate Change*.

38. T. Wigley and P. Jones, "Influences of Precipitation Changes and Direct CO_2 Effects on Streamflow," *Nature* 314 (1985): 149.

39. W. Langbein et al., *Annual Run-off in the United States*, U.S. Geological Survey circular 52 (Washington, D.C.: U.S. Department of Interior, 1949).

40. This assumes the use of the median value given in Wigley and Jones, note 38 above. The values there are for a doubling of the present atmospheric carbon dioxide level to 700 ppmv. By the time mean global surface temperature rises 2 to 3 degrees Celsius, the carbon dioxide level will probably be well below this, due to the effects of the other gases. This suggests the use of a value for the estimated reduction in evapotranspiration one-half the maximum value that is given.

41. T. Wigley, K. Briffa, and P. Jones, "Predicting Plant Productivity and Water Resources," *Nature* 312 (1984): 102.

42. S. Manabe, R. Wetherald and R. Stouffer, "Summer Dryness Due to an Increase of Atmospheric CO_2 Concentration," *Climatic Change* 3 (1981): 347.

43. R. Revelle and P. Waggoner, "Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States," in Carbon Dioxide Assessment Committee, note 1 above.

44. U.S. Council on Environmental Quality, *Environmental Trends* (Washington, D.C.: Council on Environmental Quality, 1981).

45. A. Barnston and P. Schickedanz, 1984: "The Effect of Irrigation on Warm Season Precipitation in the Southern Great Plains," *Journal of Climate and Applied Meteorology* 23 (1984): 865.

46. See Warrick, Gifford with Parry in note 29 above. For a summary of crop requirements, present constraints to production, and effects, see P. Ciborowski and D. Abrahamson, "The Granary and the Greenhouse Problem," in *The Future of the North American Granary: Politics, Economics, and Resource Constraints in North American Agriculture*, C.F. Runge, ed. (Ames, Iowa: Iowa State University Press, 1986). For effects on the corn belt, see T. Blasing and A. Solomon, "Response of the North American Corn Belt to Climatic Warming," *Progress in Biometeorology* 3 (1984): 31. For the crop response under conditions like those of the 1930s, which Manabe and Wetherald, note 35 above, suggest are likely, see R. Warrick, "The Possible Impacts on Wheat Production of a Recurrence of the 1930s Drought on the U.S. Great Plains," *Climatic Change* 6 (1984): 5. For yield effects on Great Plains corn, see W. Terjung, D. Liverman, and T. Hayes, "Climatic Change and Water Requirements for Grain Corn in the North American Great Plains," *Climatic Change* 6 (1984): 193. For the generalized corn belt and soybean yield response, see the National Defense University model response given in R. Shaw, "Climate Change and the Future of American Agriculture," in *The Future of American Agriculture as a Strategic Resource*, S. Batie and R. Healy, eds. (Washington, D.C.: Conservation Foundation, 1980). For the generalized Great Plains wheat response, see R. Stewart, "Climatic Change - Implications for the Prairies," in Titus, note 17 (b) above, vol. 3, *Climate Change*. For the economic implications, see Cooter in note 29 above; and J. Niedercorn, "The Capital Costs of Climatically Induced Shifts in Agricultural Production: The Example of the American Corn Belt," in *The Urban Costs of Climatic Modification*, T. Ferrar, ed. (New York: John Wiley, 1976).

47. For the critical threshold for agroclimatically injurious daily maximum temperature, see R. Shaw, "Estimates of Yield Reductions in Corn Caused by Water and Temperature Stress," in *Crop Reactions to Water and Temperature Stresses in Humid, Temperate Climates*, C. Raper and P. Kramer, eds. (Boulder, Colo.: Westview Press, 1983); and A. Bauer, *Effects of Water Supply and Seasonal Distribution on Spring Wheat Yields*, Agricultural Experiment Station Bulletin 490 (Fargo, N. Dak.: North Dakota State University, 1972). For an estimate of the change in corn belt extreme

summer temperature events, see L. Mearns, R. Katz, and S. Schneider, "Extreme High-Temperature Events: Changes in Their Probabilities with Changes in Mean Temperature," *Journal of Climate and Applied Meteorology* 23 (1984): 1,601. For a similar estimate, see Hansen et al., note 17 (b) above. It is possible that, due to an increase in cloud cover, the regional temperature response may be reduced. For the yield response with less available sunlight, see Terjung, Liverman, and Hayes in note 46 above.

48. For instance, see the forest response given in A. Solomon et al., *Response of Unmanaged Forests to CO_2-Induced Climate Change: Available Information, Initial Tests, and Data Requirements*, DOE/NBB-0053 (Washington, D.C.: U.S. Department of Energy, 1984).

49. For instance, see the economic effects on the agricultural sector in Cooter in note 29 above.

50. In theory, society might adapt at no cost to changes in climate through sequential changes in capital stocks, or society might sustain losses if such sequential deployment of capital to meet changing climatic conditions is not possible. See W. Nordhaus, *Thinking About Carbon Dioxide: Theoretical and Empirical Aspects of Optimal Control Strategies*, discussion paper 565 (New Haven, Conn.: Yale University, 1980).

51. See note 43 above.

52. The ability to generate such results depends on, among other things, the development of atmospheric and oceanic GCMs with adequate resolution. The time required to develop such models is measured in decades.

53. A reduction in western streamflow of 40 to 70 percent is projected by the NAS-CDAC. See note 43 above.

54. J. Thompson, "The Economic Value of Improved Long Range Weather Forecasts--Some Implications for Predictions of Climatic Change," in *Proceedings of the Symposium on Living With Climatic Change: Phase II* (McLean, Vir.: The MITRE Corp., 1977).

55. For the initial work, see Solomon et al. in note 48 above; and H. Shugart et al., "Assessing the Response of Global Forests to Climatic Change and Direct Effect of Increasing CO_2," in Bolin et al., note 29 above.

56. H. A. Tucker, *Effects of Climate Change on Animal Agriculture*, DOE/EV/10019-11 (Washington, D.C.: U.S. Department of Energy, 1982).

57. For a significant increase in the destructive force of hurricanes, see K. Emanuel, "The Dependence of Hurricane Intensity on Climate," *Nature* 326 (1987): 483. For the response of hurricane incidence to temperature, see W. Wendland, "Tropical Storm Frequencies Related to Sea Surface Temperatures," *Journal of Applied Meteorology* 16 (1977): 480.

58. D. de Sylva, "Increased Storms and Estuarine Salinity and Other Ecological Impacts of the 'Greenhouse Effect,'" in Titus, note 17 (b) above, vol. 4, *Sea Level Rise*.

59. For an initial consideration, T. Sibley and R. Strickland, "Fisheries: Some Relationships to Climate Change and Marine Environmental Factors," in note 37 above.

60. For the lake level response, see S. Cohen, "Impacts of CO_2-Induced Climatic Change on Water Resources in the Greats Lakes Basin," *Climatic Change* 8 (1986): 135.

61. R. Park, T. Armentano, and C. L. Cloonan, "Predicting the Effects of Sea Level Rise on Coastal Wetlands," in Titus, note 17 (b) above, vol. 4, *Sea Level Rise*.

62. See, for instance, the effects of the 1980 heat wave on ground water availability, in Assessment and Information Services Center, *U.S. Impacts of the Great 1980 Heat Wave and Drought* (Washington, D.C.: Assessment and Information Service, 1980).

63. For the suggested effects on capital lifetimes, see L. Lave, "Mitigating Strategies for Carbon Dioxide Problems," *American Economic Review* 72 (1982): 257.

64. Economic losses due to flooding constitute the largest single annual expense relating to weather and climate events. See note 44 above.

65. For example, it has been noted that one can describe the present population centers of the United States according to an objective function which is temperature-based, with the critical requirement being the least-cost maintenance of a constant 65 degree Fahrenheit environment year-round. Presumably, population will shift with changes in average conditions. See F. Hassler, "Transportation and Climate," in Mitre corp., note 54.

66. For instance, see masonry productivity and temperature shown in A. Eddy, ed., *The Economic Impact of Climate* vol. 4 (Norman, Okla.: Oklahoma Climatological Survey, 1980).

67. L. Harris and W. Jetter, "Natural Ecosystem Response to Climatic Change: Wildlife," in *Impacts of Climatic Change on the Biosphere*, Climatic Impact Assessment Program, CIAP monograph 5. Part 2. Climate Effects (Washington, D.C.: U.S. Department of Transportation, 1975).

68. If conditions during previous warm periods are any indication, for a mean global warming of 1 to 1.5 degrees Celsius, the boundaries defining the southern extent of the Arctic permafrost, Arctic air masses, and the boreal and other forest regions would migrate northward about 200 to 300 km. See J. Ritchie and F. K. Hare, "Late-Quaternary Vegetation and Climate Near the Arctic Tree Line of Northwestern North America," *Quaternary Research* 1 (1971): 331.

69. B. Frenzel, "The Pleistocene Vegetation of Northern Eurasia," *Science* 161 (1968): 637.

70. International Food Policy Research Institute, *Food Needs of Developing Countries: Projections of Production and Consumption to 1990*, research

report 3 (Washington, D.C.: The International Food Policy Research Institute, 1977).

71. F. Mattei, "Climatic Variability and Agriculture in the Semi-Arid Tropics," *Proceedings of the World Climate Conference*, Secretariat of the World Meteorological Organization, WMO 537 (Geneva: World Meteorological Organization, 1979).

72. For the effects with large increases (4 to 6 degrees Celsius) in dry bulb temperatures, see J. Russell et al., "Industrial Operations Under Extremes of Weather: The Problem, Method and Conclusions," *Meteorological Monographs* 2, no. 9 (1957): 1. These authors also comment on productivity changes (5 to 20 percent) with ambient warmings of 4 to 6 degrees Celsius. These are the averages of cases with beginning dry bulb temperatures and relative humidities of 80 degrees Fahrenheit and 50 to 80 percent, respectively, or the values for Singapore and for Ibadan and Kaduna, Nigeria.

For threshold effective temperatures required for large declines in productivity, see R. Pepler, "Performance and Well-Being in Heat," in *Temperature: Its Measurement and Control in Science and Industry*, J. Hardy, ed. (New York: Reinhold Publishing Co. 1963); A. Carpenter, "A Comparison of the Influence of Handle Load and Unfavorable Atmospheric Conditions on a Tracking Task," *Quarterly Journal of Experimental Psychology* 2 (1950): 1; C. Wyndham et al., "Studies on the Effects of Heat on Performance of Work," Applied Physiology Laboratory report 1-3, (Johannesburg, South Africa: Transvaal and Orange Free State Chamber of Mines, 1959); N. Mackworth, "Effects of Heat on Wireless Telegraphy Operators Hearing and Recording Morse Code Messages," *British Journal of Industrial Medicine* 3 (1946): 143. All of these sources report significant productivity declines with effective temperatures (ETs) of 27 to 30 degrees Celsius. For reference, the workday (7 a.m.-7 p.m.) effective temperatures at Singapore, and Ibadan and Kanuda, Nigeria are about 26, 25.1 and 25.1 degrees Celsius, respectively. Assuming no change in the relative humidity, a 4 degree Celsius increase in dry bulb temperature would produce an increase to about 29.2 and 28.5 degrees Celsius in ET in Singapore and Ibadan, respectively; a 6 (8) degree Celsius increase in dry bulb temperature would increase the ET to about 31.3 (33) and 30 (32) degrees Celsius in Singapore and Ibadan, respectively. For changes in productivity (15 to 50 percent) with effective temperature raised to 28 to 31 degrees Celsius, see Mackworth, this note. See also A. Caplan and J. Lindsay, "An Experimental Investigation of the Effects of High Temperatures on the Efficiency of Workers in Deep Mines," *Bulletin of the Institute of Metallurgy* 480 (1946).

For smaller reported (1 to 2 percent) declines in productivity with small warmings (1 to 1.5 degrees Celsius), see E. Roth, ed., *Compendium of Human Responses to the Aerospace Environment*, NASA-CR-1205 (Washington, D.C.: National Aeronautics and Space Administration, 1968); and R. Pepler, "Warmth and Performance: An Investigation in the Tropics," *Ergonomics* 2 (1958): 63.

73. W. Terjung et al., "Yield Responses of Crops to Changes in Environment and Management Practices: Model Sensitivity Analysis. I. Maize," *International Journal of Biometeorology* 28 (1984): 261; and W. Terjung et al., "Yield Responses of Crops to Changes in Environment and Management Practices: Model Sensitivity Analysis. II. Rice, Wheat, and Potato," *International Journal of Biometeorology* 28 (1984): 279. Also see the tropical crop response in National Defense University, *Crop Yields and Climate Change to the Year 2000*, vol. 1 (Fort Lesley J. McNair, Washington, D.C.: National Defense University, 1980). For the effect in a hot subtropical climate, see C. Rosenzweig, "Potential CO_2-Induced Climate Effects on North American Wheat-Producing Regions," *Climatic Change* 7 (1985): 367.

74. J. Edmonds et al., *An Analysis of Possible Future Atmospheric Retention of Fossil Fuel* CO_2, DOE/OR/21400-1 (Washington, D.C.: U.S. Department of Energy, 1984).

75. The effects of slow chemical saturation of the upper layer of the ocean with dissolved carbon dioxide will raise the rate of atmospheric retention by 5 to 15 percent from 1985 to 2080. See the model estimates given in Trabalka et al., note 7 above, table 10.6; and Seidel and Keyes in note 16 above. For estimates similar to those of Seidel and Keyes at a rate of emissions increase of less than 1.4 percent per year, see Baes and Killough in note 21 above, Case D, preindustrial carbon dioxide at 270 ppmv. Takahashi and Azevedo suggest a 1.5 to 3 percent increase per 10 percent increase in the size of the pool of warm oceanic water. The pool of subtropical water was about 8 degrees latitude further toward the pole during the Eem Interglacial when mean global temperature was 1 degree Celsius warmer than now. This suggests a rise in the airborne fraction of 3 to 6 percent. See T. Takahashi and A. Azevedo, "The Oceans as a CO_2 Reservoir," in *Interpretation of Climate and Photochemical Models, Ozone and Temperature Measurements*, R. Reck and J. Hummel, eds. (New York: American Institute of Physics, 1982).

76. For an increase in the airborne fraction of 3 to 15 percent from 1985 to 2075, the rise in the cumulative fraction would be about 3.5 to 7 percent. These are calculated from the pattern of emissions and rates of atmospheric retention presented in Seidel and Keyes, note 16 above.

77. Ciborowski and Abrahamson in note 12 above.

78. See note 3 above.

79. Gases variously dependent upon the OH chemistry of the troposphere include: nitrogen oxides, carbonyl sulfide, sulfur dioxide, hydrogen sulfide, CFC-22, CFC-1342, dichloroethane, methyl chloroform, methylene chloride, chloroform, methyl chloride, methyl bromide, methane, ethane, propane, butane, acetylene, benzene, carbon monoxide, formaldehyde, and methanol.

80. S. Hameed and R. Cess, "Impact of a Global Warming on Biospheric Sources of Methane and its Climatic Consequences," *Tellus* 35 (1983): 1.

81. Ciborowski and Abrahamson in note 12 above, ref. 23.

82. See note 80 above; and R. Revelle, "Methane Hydrates in Continental Slope Sediments and Increasing Atmospheric Carbon Dioxide," in Carbon Dioxide Assessment Committee, National Research Council, note 1 above.

83. This assumes a 2 percent per year growth in emissions and an airborne fraction of 0.6.

84. See Dickinson and Cicerone, note 17 (e) above.

85. Methane levels are assumed to increase to more than double the present level due to emissions related to agricultural practices and temperature sensitive releases. The nitrous oxide level is assumed to increase to 368 ppbv. The tropospheric level of ozone is assumed to rise about 40 percent as a result of a four-fold increase in methane, carbon monoxide, and NO_x emissions. CFC-11 and CFC-12 levels are assumed to increase to 2 ppbv from emissions reduced by 25 percent through regulation. See M. Khalil and R. Rasmussen, "Causes of Increasing Atmospheric Methane: Depletion of Hydroxyl Radicals and the Rise of Emissions," *Atmospheric Environment* 19 (1985): 397; Revelle in note 82 above; Hameed and Cess in note 80 above; S. Hameed, R. Cess, and J. Hogan, "Response of the Global Climate to Changes in Atmospheric Chemical Composition Due to Fossil Fuel Burning," *Journal of Geophysical Research* 85 (1980): 7,537; W. Hao et al., "Sources of Atmospheric Nitrous Oxide from Combustion," *Journal of Geophysical Research* 92 (1987): 3,098; and Office of Technology Assessment, "An Analysis of the Montreal Protocol on Substances that Deplete the Ozone Layer," Washington, D.C., December 1987.

86. See note 77 above.

87. R. Dickinson, "Modeling Climate Changes Due to Carbon Dioxide Increases," in Clark, note 11 above.

88. M. Schlesinger and J. Mitchell, "Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide," in MacCracken and Luther, note 5 above.

89. R. Somerville and L. Remer, "Cloud Optical Thickness Feedbacks in the CO_2 Climate Problem," *Journal of Geophysical Research* 89 (1984): 9,668.

90. See note 88 above. For a more empirically based estimate of climate sensitivity, see Hansen et al. in note 15 above.

91. F. Luther and R. Cess, "Review of the Recent Carbon Dioxide-Climate Controversy," in MacCracken and Luther, note 5 above.

92. For the misfit of market time-scales to climatic change, see "Introduction to Section 3," this volume. For the bureaucratic and political constraints to anticipatory adaptation, see W. Riebsame, this volume; the author observes that programs established ostensibly for the amelioration of future impacts are, in fact, often captured by private interests or entrenched bureaucracies, leading to maladaptation. Also see Riebsame

for constraints arising from the poor present understanding of the operation of human systems. For a broader discussion of the inefficiencies of administered programs, see C. Lindblom, *Politics and Markets: The World's Political and Economic Systems* (New York: Basic Books, 1977). For a discussion of the shortcomings of the type of policy analysis and intervention that would be required to effect much of an anticipatory response, see D. Braybrooke and C. Lindblom, *A Strategy of Decision* (New York: Free Press, 1963).

93. The unrealized warming is estimated as the difference between the equilibrium warming expected as a result of past releases and the observed change. Assuming a climate sensitivity of 2 degrees Celsius, the equilibrium warming from past releases would be 1.09 degrees Celsius; the observed warming is 0.5 degrees Celsius; and the difference, 0.59, is the unrealized warming. For a similar estimate of the unrealized warming, see Hansen et al., note 17 (b) above. With a climate sensitivity of 3 and 4 degrees Celsius, the unrealized warming would be 0.87 and 1.16 degrees Celsius, respectively. With a climate sensitivity of 4.2 degrees Celsius, Hansen et al. (note 15 above) estimate an unrealized warming of 1.25 degrees Celsius.

For past releases of the chlorofluorocarbons, chlorocarbons, and fluorocarbons, see D. Wuebbles, M. MacCracken, and F. Luther, *A Proposed Reference Set of Scenarios for Radiatively Active Atmospheric Constituents*, DOE/NBB-0066 (Washington, D.C.: U.S. Department of Energy, 1984). Time histories for methane and nitrous oxide are taken from the model estimates of Khalil and Rasmussen (1985), and Weiss (1981), respectively, presented in G. Pearman et al., "Evidence of Changing Concentrations of Atmospheric CO_2, N_2O and CH_4 from Air Bubbles in Antarctic Ice," *Nature* 320 (1986): 248. The preindustrial level of carbon dioxide is estimated at 275 ppmv. The water vapor contribution is taken from D. Wuebbles, F. Luther, and J. Penner, "Effect of Coupled Anthropogenic Perturbations on Stratospheric Ozone," *Journal of Geophysical Research* 88 (1983): 1,444.

The surface heat emission is calculated from the estimates of Kellogg, who gives a surface heat emission of 1 degree Celsius for an increase in energy use to 400 TW (from the present 11 TW). Based on this estimate, a 1.9 percent per year increase in energy use would result at 2100 in a warming of about 0.25 degrees Celsius (with a range of 0.125 to 0.5 degrees Celsius), and a 1.5 percent per year increase would result in a 0.15 degree Celsius increase (0.08 to 0.3 degrees Celsius). In those cases of high allowable fossil fuel combustion (e.g., the best case), we assume a 0.2 degree Celsius increase in mean global temperature from surface heat emission, and in the case of low allowable combustion, a 0.1 degree Celsius warming. See W. Kellogg, *Effects of Human Activities on Global Climate*, WMO 486 (Geneva: World Meteorological Organization, 1977).

94. With the atmospheric methane concentration increasing between 1.29 and 1.89 percent per year, and assuming a residence time of four to nine years, methane would decay to carbon dioxide approximately as follows:

Net Carbon Dioxide Added (in ppmv) to the Atmosphere for Different Rates of Increase in Methane Levels and Different Airborne Fractions

	Annual Rate of Increase		
Airborne Fraction (%)	1.29	1.63	1.89
35	14-29	17-35	20-40
45	18-36	22-45	--
65	26-52	31-65	--

The atmospheric methane concentration is increasing about 1.1 percent per year, and the long-term rate of increase could be 1.7 percent per year in the long term. See B. Stauffer, et al., "Increase of Atmospheric Methane Recorded in Antarctic Ice Core," *Science* 229 (1985): 1,386. Based on the fit of surface emissions to the historic population expansion, Khalil and Rasmussen (note 85 above) suggest a 0.8 percent per year future increase from agricultural expansion. Rice paddy agriculture is an important source of the historic rise in the atmospheric methane level. It can be expected that, as mean global temperature rises, the area climatically suited for rice cultivation will expend. See J. Stansel and R. Huke, "Agricultural Implications of Climatic Change: Rice," in Climatic Impact Assessment Program, note 67 above. Additional methane can be expected from emissions from ocean sediments (1 to 2 ppmv) (see Revelle in note 82 above) and an increasing rate of anaerobic respiration (1 ppmv) (see note 80 above).

In Table 13, the long-term rate of increase in the atmospheric level of methane is scaled to the aggregate other gas warming and the climate sensitivity to make the methane-induced warming reasonably consistent with the parameters chosen for each case. A tripling (quadrupling) by 2070 in the methane level corresponds to a 1.29 (1.63) percent per year increase; a five-fold increase corresponds to a 1.89 percent per year increase to 2070. A 1.63 percent per year long-term rate of increase is assumed for the combinations of 2 to 3 degrees Celsius climate sensitivities and other gas contributions of 100 to 200 percent; and a 1.29 percent per year rate of increase is assumed for combinations of 2 to 3 degrees Celsius climate sensitivities and an other gas contribution of 50 percent. A 1.89 percent annual rate of increase is assumed for a 2 degrees Celsius climate sensitivity and an other gas contribution of 300 percent. The calculated atmospheric input of carbon dioxide is for the period from 1985 to 2100. Methane concentrations are assumed to stabilize by 2070.

The remainder of the non-fossil "other carbon" is taken from Table 9. For an airborne fraction of 0.56, in ppmv it would be:

Deforestation	45-72
Cement	8-17
Respiration	17

In Table 13, the net rise in the atmospheric carbon dioxide concentration (in ppmv) is assumed as follows:

Best Case (airborne fraction 0.35)	43
Worse Case (airborne fraction 0.65)	123
Base Case (airborne fraction 0.45)	71

95. See J. Laurmann, "Market Penetration as an Impediment to Replacement of Fossil Fuels in the CO_2 Environmental Problem," this volume; and Perry in note 16 above. The total amount of carbon (in GT) that might be added for the different cases is calculated and evaluated against the carbon input implied by the action initiation times and associated carbon dioxide levels given in Laurmann and Perry. A fifty-year market penetration time is assumed. For comparison, the historic market penetration times for coal, oil, and natural gas have been estimated at, depending on geographical scale, between thirty and seventy-five years. An initial 2 percent per annum increase in the emission of carbon dioxide is also assumed.

The values given in Perry are based on an assessment of the physical constraints to the rapid development of new energy sources. At least some failure to consistently follow the optimal paths of decline in fossil fuel use specified through this approach must be expected for the very long period of interest (1995 to 2100). Short-term downward price instability, arising from cartel conditions in oil markets, can slow the short-term rate of transition. To be non-disruptive and efficient, a long-term transition to another energy system will also require that planning and policy measures be taken decades in advance, if only because infrastructure and capital stocks cannot be quickly scrapped and replaced without high economic costs. This will slow the rate of transition. See J. Ausubel and W. Nordhaus, "A Review of Estimates of Future Carbon Dioxide Emissions," in Carbon Dioxide Assessment Committee, National Research Council, note 1 above. Presently unknowable developments in the technology of fossil energy production can also be a factor. Although no empirical estimate for either of these effects is available, it is possible that a decade should be added to the action intiation times given in Perry.

96. The principal difference between the estimates given in this paper and past estimates reflect the add-on warming of the other gases and the effect of the other carbon parameter. Of the published analyses, only Perry 1986 ("Possible Changes in Future Use of Fossil Fuels to Limit Environmental Effects," in Trabalka and Reichle, note 7 above) treats the effects of the other gases. Also, those estimates that are derived from economic optimization models fail to consider the effects of market penetration time lags. See A. Perry et al., "Energy Supply and Demand Implications of CO_2," *Energy Journal* 7 (1982): 991; Council on Environmental Quality, *Global Energy Futures and the Carbon Dioxide Problem* (Washington, D.C.: Council on Environmental Quality, 1981); and W. Nordhaus, *Strategies for the Control of Carbon Dioxide*, Cowles Foundation discussion paper 443 (New Haven, Conn.: Yale University, 1977).

97. R. D'Arge, W. Schultze, and D. Brookshire, "Carbon Dioxide and Intergenerational Choice," *American Economic Review* 72 (1982): 251.

98. Perry in note 95 above; J. Laurmann, "Assessing the Importance of CO_2-Induced Climatic Changes Using Risk-Benefit Analysis," in Bach, Pankrath, and Williams, note 18 above; W. Bach, "Carbon Dioxide/Climate Threat: Fate or Forebearance?" in *Carbon Dioxide: Current Views and Developments in Energy/Climate Research*, W. Bach et al., eds. (Dordrecht, Netherlands: D. Reidel Publishing Co., 1983); and W. Nordhaus, *The Efficient Use of Energy Resources* (New Haven, Conn.: Yale University Press, 1979). For others see H. Flohn, *Major Climatic Events Associated With a Prolonged CO_2-Induced Warming*, ORAU/IEA-81-8(M) (Oak Ridge, Tenn.: Oak Ridge Associated Universities, 1981); W. Haefele et al., *Energy in a Finite World* (Cambridge, Mass.: Ballinger Publishing Co., 1981); D. Rose, M. Miller, and C. Agnew, *Global Energy Futures and CO_2-Induced Climate Change*, MITEL 83-015 (Cambridge, Mass.: Massachusetts Institute of Technology, 1983); and D'Arge, Schultze, and Brookshire, note 97 above.

99. For the climate state in which the pack ice melts in summer but refreezes in winter, see Manabe and Stouffer in note 11 above. For the last time the Arctic basin was ice-free, the late Tertiary, with mean global temperature about 4 degrees Celsius warmer than at present, see Schackleton et al.,note 10 above. The Arctic basin was almost certainly ice-free year-round in the Oligocene and Eocene.

100. For a tropical warming of 10 to 15 degrees Fahrenheit (5 to 8 degrees Celsius). See note 72 above. Also see the tropical warming as a percent of the mean global surface warming in the simulations of the latest generation of GCMs given in Schlesinger and Mitchell, note 88 above.

101. For the climatic situation in the Tertiary with a similar degree of mean global warmth, see S. Savin, "The History of the Earth's Surface Temperature During the Past 100 Million Years," *Annual Review of Planetary Science* 5 (1977): 319.

102. E. Hirst et al., "Recent Changes in U.S. Energy Consumption: What Happened and Why?" *Annual Review of Energy* 8 (1983): 193.

103. Calculated from 1980 with an airborne fraction of 0.56 and rates of increase in fossil fuel use of 1.5 to 2 percent per year.

104. For instance Mintzer, note 17 (d) above; and H. Cheng, M. Steinberg, and M. Beller, *Effects of Energy Technology on Global CO_2 Emissions*, DOE/NBB-0076 (Washington, D.C.: U.S. Department of Energy, 1986).

105. For an example of the surprises of nature, see W. Broecker, D. Peteet, and D. Rind, 1985: "Does the Ocean-Atmosphere System Have More than One Stable Mode of Operation?" *Nature* 315 (1985): 21; or for an example of a less dramatic nature, see R. Watts, "Global Climate Variation Due to Fluctuations in the Rate of Deep Water Formation," *Journal of Geophysical Research* 90 (1985): 8,067; or C. Hollings, "Resilience of Ecosystems: Local Surprises and Global Change," in Clark and Munn, note 17 (c) above. For the difficulties encountered in the effort to understand climates that are far different from the present climate, see S. Schneider, S. Thompson, and E. Barron, "Mid-Cretaceous Continental Surface Temperatures: Are High CO_2 Concentrations Needed to Simulate Above-Freezing

Winter Conditions?" in *The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present*, E. Sundquist and W. Broecker, eds., (Washington, D.C. American Geophysical Union, 1985). For the possibility that the climate problem may be intractable, see E. Lorenz, "Irregularity: A Fundamental Property of the Atmosphere," *Tellus* 36a (1984): 98.

106. This is based in part on the time involved in the development of sufficient computational capacity of computers. Given present trends, the required computer capacity will not be available until the turn of the century. See Joint Scientific Committee, International Council of Scientific Unions, World Meteorological Organization, *Report of the Sixth Session of the Joint Organizing Committee*, WMO/TD 54 (Geneva: World Meteorological Organization, 1985). It is also based on the amount of time involved in the development of the atmospheric GCMs. Atmospheric GCM development began in the 1950s and 1960s. For the early history, see S. Manabe, and J. L. Holloway Jr., "The Seasonal Variation of the Hydrologic Cycle as Simulated by a Global Model of the Atmosphere," *Journal of Geophysical Research* 80 (1975): 1,617.

107. See the projected lifetime of the Biosphere-Geosphere Programme of the International Council of Scientific Unions. J. Roederer, "ICSU Gives Green Light to IGBP," *EOS*, October, 14, 1986. See also Hansen et al. in note 17 (b) above.

108. The initial cloud studies related to the planetary heat balance were conducted in the early 1970s. See S. Schneider, "Cloudiness as a Global Climatic Feedback Mechanism: The Effects on the Radiation Balance and Surface Temperature of Variations in Cloudiness," *Journal of the Atmospheric Sciences* 29 (1972): 1,413.

109. See note 97.

110. G. Golubev, "Global Environmental Change: The UNEP Perspective," in Titus, note 17 (b) above.

111. See Laurmann in note 98 above.

112. W. Nordhaus, *Strategies for the Control of Carbon Dioxide*, Cowles Foundation discussion paper 443 (New Haven: Yale University, 1977), as reported in Laurmann in note 98 above.

113. H. R. Heede, R. Morgan, and S. Ridley, "The Hidden Costs of Energy," *Sunworld* 10 (1986): 4.

114. Various microeconomic models have been suggested as a means to indicate optimal levels of emissions based on welfare maximizing criteria. See W. Nordhaus, "How Fast Should We Graze the Global Commons?" *American Economic Review* 72 (1982): 242.

115. T. Schelling, "Climate Change: Implications for Welfare and Policy," in Carbon Dioxide Assessment Committee, National Research Council, in note 1 above; K. Meyer-Abich, "Socioeconomic Impacts of CO_2-Induced Climatic

Changes and the Comparative Chances of Alternative Political Response: Prevention, Compensation and Adaptation," *Climatic Change* 2 (1980): 156; and L. Lave, "The Carbon Dioxide Problem: A More Feasible Social Response," *Technology Review* 84 (1981): 23.

116. J. Edmonds and J. Reilly, "A Long-Term Global Energy-Economic Model of Carbon Dioxide Release from Fossil Fuel Use," *Energy Economics* 5 (1983): 74.

117. Estimated from the base case model runs given in Seidel and Keyes in note 16 above.

118. See H. Landsberg, "Commentary," in Clark in note 11 above.

119. From 1975 to 1984, world energy use increased 1.5 percent per year. World oil use, world coal use, and OECD and CMEA (Council for Mutual Economic Assistance) energy use increased at annual rates of 0.6, 2.6, 0.4, and 2.6 percent, respectively. (The long-term rate of increase in use in CMEA countries has declined, and continues to decline, about 6 percent per year, and, at that rate of decline, would approach 0.15 percent per year in fifty years.) By contrast, the high and medium energy growth studies suggest typical annual rates of growth (in percent) of:

World energy use	1.8 to 3.5
OECD energy use	1 to 2.5
CMEA energy use	1 to 2.5
World oil use (1975 to 2000)	1 to 2
World coal use	2 to 3

See Haefele et al. in note 98 above; Edmonds and Reilly, note 116 above; Seidel and Keyes in note 16; Rotty and Marland in note 18; and U.S. Department of Energy, *National Energy Policy Plan Projections to 2010*, DOE/PE-0029-3 (Washington, D.C.: U.S. Department of Energy, Office of Policy, Planning, and Analysis, 1985). See also Ausubel and Nordhaus in note 95 above. For the historic data, see United Nations Department of International and Social Affairs, *Statistical Yearbook* (New York: United Nations, 1973-1986).

120. Haefele et al. in note 98 above.

121. The amount of fossil fuels in the non-OECD, non-CMEA world, China excluded, amounts, in the case of coal, to the equivalent of a net addition of about 50 ppmv of carbon dioxide to the atmosphere and, in the case of oil shale and heavy oil, to the equivalent of a net addition of 19 and 24 ppmv, respectively. For the oils, see Haefele et al. in note 98 above. The estimate for coal assumes that 100 percent will be exploited. Rotty and Marland, note 18 above, suggest that 50 to 90 percent is a more reasonable estimate. Since of the developed countries, only the United States, Canada, Australia, and South Africa appear to be in a position to expand coal export activities, a preponderant Western influence on coal-related emissions can be assumed. See C. Wilson, *Coal: Bridge to the Future* (Cambridge, Mass.: Ballinger Publishing Co., 1980).

122. G. Woodwell et al., "Global Deforestation: Contribution to Atmospheric Carbon Dioxide," *Science* 222 (1983): 1,081.

123. A. Miller and I. Mintzer, *The Sky is the Limit: Strategies for Protecting the Ozone Layer*, research report 3 (Washington, D.C.: World Resources Institute, 1986).

124. CFC-12 levels are estimated after J. Hoffman, "The Importance of Knowing Sooner," in J. Titus in note 17 (b) above. Steady-state CFC-11 levels are assumed to be one-half of the steady state CFC-12 levels. For the buildup with constant 1977 CFC-11 and CFC-12 emissions, see D. Ehhalt, "The Effects of Chlorofluoromethanes on Climate," in Bach, Pankrath and Williams in note 18 above.

125. H. Bolle, W. Seiler, and B. Bolin, "Other Greenhouse Gases and Aerosols," in B. Bolin et al. in note 29 above.

126. J. Logan et al., "Tropospheric Chemistry: A Global Perspective," *Journal of Geophysical Research* 86 (1981): 7,210.

127. The mean global surface warming in the uncontrolled case would be as follows:

Uncontrolled Case (degrees C)

Gas	Warming
CFC-11, CFC-12	0.4-1.2
Nitrous oxide	0.2
Tropospheric ozone	0.6
Methane	0.7-0.8
Others	0.3

CFC-11 and CFC-12 levels are taken from the 2050 values suggested by Dickinson and Cicerone in note 17 (e) above. For nitrous oxide, see Hao et al. in note 85 above. The suggested tropospheric ozone levels assume a long-term rate of increase slightly less than the observed rate, after G. MacDonald, *Climate Change and Acid Rain* report MP8600010 (McLean, Vir.: The Mitre Corp., 1985). The suggested methane levels assume a continuation of the present rate of increase due to agricultural activities, a four-fold increase in NO_x emissions (and a corresponding reduction in the base 1985 methane level of perhaps 15 percent), and an additional 2.3 to 3.7 ppmv increase in the methane level as a result of increased anaerobic respiration from flooded fields (1.2 to 1.5 ppmv) and methane release from clathrates (1.1 to 2.2 ppmv).

For the close historic fit of population growth to methane levels, and a suggested 0.8 percent per year increase in the atmospheric methane level from continued population growth, see Khalil and Rasmussen in note 85 above. For the influence of climatic warming on the area climatically suitable for rice cultivation, see Stansel and Huke in note 85 above. For methane release as a result of increased rates of anaerobic respiration, see Hameed and Cess in note 80 above, and P. Guthrie, "Biological Methanogenesis and the CO_2 Greenhouse Effect," *Journal of Geophysical Research* 91 (1986): 10,847. For methane emission from clathrates, see Revelle in note 82 above. For the NO_x influence, see Hameed, Cess, and Hogan in note 85 above.

In the controlled case, the accumulation of nitrous oxide is assumed to be about half of the uncontrolled case, or equal in percent to the accumulation of carbon dioxide in the controlled case as a percent of the uncontrolled accumulation (see Table 14). In the case of tropospheric ozone, surface emissions leading to in situ production are only partially accounted for by combustion activities. From Hameed, Cess, and Hogan, this note, methane and NO_x might account for perhaps half of the increase. NO_x emissions will continue to increase even at low rates of energy growth. See M. Kavanaugh, "Estimates of Future CO, N_2O, and NO_x Emissions from Energy Combustion," *Atmospheric Environment* 21 (1987): 463. No control is envisioned for methane release. Of the remainder of the increase suggested for the uncontrolled case, perhaps half--that part associated with carbon monoxide released as a result of fossil energy consumption--might be controlled. For the percent of anthropogenic carbon monoxide emissions resulting from fossil energy consumption, see Logan et al., note 126 above.

128. M. Steinberg and A. Albanese, "Environmental Control Technology for Atmospheric Carbon Dioxide," in Bach, Pankrath, and Williams in note 18 above; and M. Steinberg, *An Analysis of Concepts for Controlling Atmospheric Carbon Dioxide*, DOE/CH/00016-1 (Washington, D.C.: U.S. Department of Energy, 1983).

129. Schelling in note 115 above.

130. For discussion of intentional aerosol loading of the stratosphere to reduce the amount of incoming radiation, and some of its consequences, see W. Broecker et al., "SO_2: A Backstop Against a Bad CO_2 Trip?" unpublished manuscript, Lamont Doherty Geological Observatory, Columbia, University, 1983. For a discussion of the infeasibility of other technical "biospheric" fixes, see F. Dyson and G. Marland, "Technical Fixes for the Climatic Effects of CO_2," in Elliot and Machta in note 20 above.

SECTION 5: THE INDUSTRIALIZED NATION RESPONSE

INTRODUCTION TO SECTION 5

The position of the individual nation in the policy calculus is the subject of Section 5. Decisions will be made about emissions or other responses to climate change by individual nations, acting alone. Always anxious for unbridled freedom of decision and action, states gravitate toward individual action. Action is tied to internal necessity. Decisions about the future life of society are taken with the interests of the individual state in mind, and they rarely depart from those interests. In a word, public action is effected through the individual state, which seeks to alienate none of its sovereignty and arrogates all action to itself. It avoids multilateral action and allows no long-term international planning to structure the life of its society. It acts alone.

The fit of policy responses to climate change to such a world is ambiguous. To the degree that they are feasible, adaptive responses fit well. Action is assumed to follow from the individual decisions of nations. No international cooperation is assumed, and each nation, no matter its condition, is assumed to be best able to fit its own resources to climatic conditions. But adaptation also sets up severe informational needs, and, as can be inferred from Riebsame, these cannot now be met.

By contrast, the preventive response is technically plausible but stands contrary to the realities of individual action. Due to the distribution of fossil fuel consumption, the actions of one nation can only partially effect a preventive response. No one nation has a large enough share of the present global consumption of fossil fuel to noticeably limit the long-term atmospheric accumulation of carbon dioxide. Preventive action by single actors can swing the increase in long-term carbon dioxide levels but a few percentage points. Even dramatic action, after Williams et al., by the world's largest emitter, the United States, would result in only marginal reductions (7 to 15 percent) during the period from 1980 to 2070. Unilateral actions affecting supply would be equally ineffectual. Only in the case of oil are the remaining deposits reasonably concentrated among a few nations, and since the economics of production and consumption favor complete combustion, even here no limiting action is foreseen. The distribution of the global demand for oil is such that the exit of any one consumer from the market would be followed by the entry of another, resulting in little net change in consumption.

The heart of the problem can be found in the disparity between the large costs of action and its meager effects. To have an effect anywhere near that possible for the United States, the typical Western European democracy would need to abandon the combustion of fossil fuel altogether, and do so immediately. Having foregone the benefits of its fossil fuel sector, it would be parent to at best a miniscule reduction in the rate of warming.

The situation is somewhat redeemed by the smallness of the set of states that would need to act under the terms of a cooperative response. Due to the present dominance of the developed world in global energy markets, a preventive response at present would only need to involve the industrialized nations. At present, these nations control the rate of atmospheric accumulation of carbon dioxide. In the period relevant to current decision-making, the next few decades, this should continue to be the case. The atmospheric effects of industrialization in the developing world will be felt only later, if they are felt at all. About two-thirds of all present energy consumption takes place in eleven countries--France, West Germany, the United Kingdom, Italy, the United States, Canada, Japan, Australia, Poland, East Germany, and the Soviet Union--a fact that would vastly simplify any effort at cooperative action.

But the situation is complicated by the effect of nations that do not participate in multilateral action but still benefit from it. These "free riders" breed resentment and an unwillingness on the part of the other nations to participate. Given the enormous disparity between the costs of action to any one nation and its limited benefits, preventive action carries a built-in incentive to cheat.

The preventive option thus leaves the individual nation in an ambiguous position. Confronted with the likelihood that action to limit its own emissions will be without result, the individual nation, if it is to act, must act cooperatively. But, although it might be possible for a limited number of states to take effective preventive action, factors like the free rider problem limit the ease with which multilateral action might be implemented. More important, as a strategy, multilateral action violates the canons of individual state action. To the degree that no means is found to work around this, multilateral action will be unworkable and preventive action will be a dead letter.

The literature suggests several such means. The most interesting of these, and certainly those with the greatest potential for effect, stress the market and the importance of actions that make good economic sense in their own right above and beyond any use to which they might be put in controlling carbon dioxide emissions. Actions that make sense in their own right need involve no direct action of a multilateral nature. The market is increasingly international. Measures with an obvious economic appeal will be taken up by the market. Measures taken by one economy because they make economic sense often spread rapidly to other similar economies, and, to the degree that the operation of the market is independent of the state, require no individualized or other governmental action.

Measures that might possess such dual appeal include actions that, in an era of resource depletion, facilitate more efficient use of resources, and the use of competitive substitutes for the chlorofluorocarbons and chlorocarbons. In many cases, major investments would be required to develop such substitutes or the technology of more efficient use. But there is evidence for the evolution of the latter under conditions of sharply rising prices, and the technology for the more efficient use of energy seems likely to continue developing for sound economic reasons.

Measures with a somewhat different effect, but which may also help society to avoid the hurdle posed by national sovereignty, include actions taken in response to environmental problems that are more properly domestic in scope and that result from the combustion of fossil fuels or from related industrial releases. Responses that are of particular interest are those in which little net cost accrues to society and for which a case for successful intervention can be made on the basis of domestic impacts in rich industrialized countries. Ameliorative action on acid precipitation and forest death is one such response. It seems unlikely that action will not be taken on this problem in the next decade. The same may be true of measures to limit the depletion of the stratospheric ozone column. Ameliorative action by the major industrialized nations would result in reduced greenhouse emissions.

Finally, one finds the pyramiding of problems, like the climate change problem and the petroleum and energy security problems. Nations may need to intervene in the fossil energy sector for reasons relating to energy, rather than environmental, policy. The petroleum and energy security problems, along with the larger energy problem, which will soon require a transition to a fuel other than petroleum and natural gas regardless of the decisions that are taken as a result of climate change, present persuasive arguments for action that will be before the industrialized West for a long time. Together with the reasons for action already noted, they offer a slim chance that the industrialized world may yet maneuver around the sovereignty constraint to action.

In this section, Johansson and Williams provide the technical information that forms the basis of this chain of reasoning. Their paper investigates the energy policy response of the individual industrialized nation. Their work is represented as an existence theorem, making it clear that the technical potential for preventive action among individual industrialized nations indeed exists.

Concentrating on the potential for energy efficiency improvements, the authors find a significant potential for large reductions in total energy use. Some of this potential results from structural changes in the Western economies, which have shifted increasingly toward services, and, within the goods-producing sectors of their economies, toward fabrication and finishing. These activities use much less energy than basic industries. The potential for significantly improved energy efficiency within the industrial sector is considered, as is the potential for energy savings through the deployment of the most energy efficient existing technology in the residential, commercial, and transportation sectors. Building from a set of examples involving energy use in Sweden and the United States, the authors estimate that per capita energy use in Western industrialized nations could be reduced up to 50 percent in 2020 over what it is projected to be even with a doubling of per capita income.

As the authors indicate, some of this potential will be exploited through the natural operation of the market. But some directed governmental action will be needed. Action will be needed to ensure energy price stability, thereby providing a stable investment climate. Change will be needed in energy pricing policies to ensure that energy prices reflect the marginal costs of bringing forth new supply. There is also a role for government in the provision of information about efficiency improvements, the regulation of energy performance, and the support of private sector firms that market energy efficiency improvements. None of these changes needs to be draconian in nature. To the degree that they move the state out of the energy supply business, they would have the opposite effect, reducing governmental intervention and presumably making policy change a more digestable, feasible alternative.

AN END-USE ENERGY STRATEGY FOR INDUSTRIALIZED COUNTRIES

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INTRODUCTION

In this paper, we describe an end-use oriented energy strategy for industrialized countries which takes into account the implications for future energy demand of both ongoing economic structural changes and opportunities for more cost-effective provision of energy services.

Following a general analysis along these lines, we illustrate the quantitative implications of an end-use energy strategy with long-range projections of Swedish and United States energy demand. We show in both cases that the end-use approach to energy can lead to future levels of energy demand far below both official forecast levels and present levels, even with greatly increased economic output.

STRUCTURAL CHANGES

A discussion of future energy use should be carried out in the context of expected future levels of social welfare or well-being. This necessarily entails some discussion of likely future structural changes in the economy that might significantly affect future energy use. The mix of economic activities contributing to gross domestic product (GDP),* a common measure of social welfare, can be expected to differ markedly in the future from what it has been in the past as industrialized countries continue to develop into post-industrial economies.

This continuing development has major implications for future energy use levels. In particular, a sharp departure from the historical trends of the last few decades, in which energy consumption increased dramatically with the prosperity of the industrialized world, can be expected as levels of consumer services associated with especially energy-intensive activities approach saturation. The approach to saturation in consumer services is reflected in continuing shifts from goods to services production and, within the goods-producing sector, from basic materials production to production involving emphasis on fabrication and finishing. Both changes imply continued long-term reductions in energy demand per dollar of value added.

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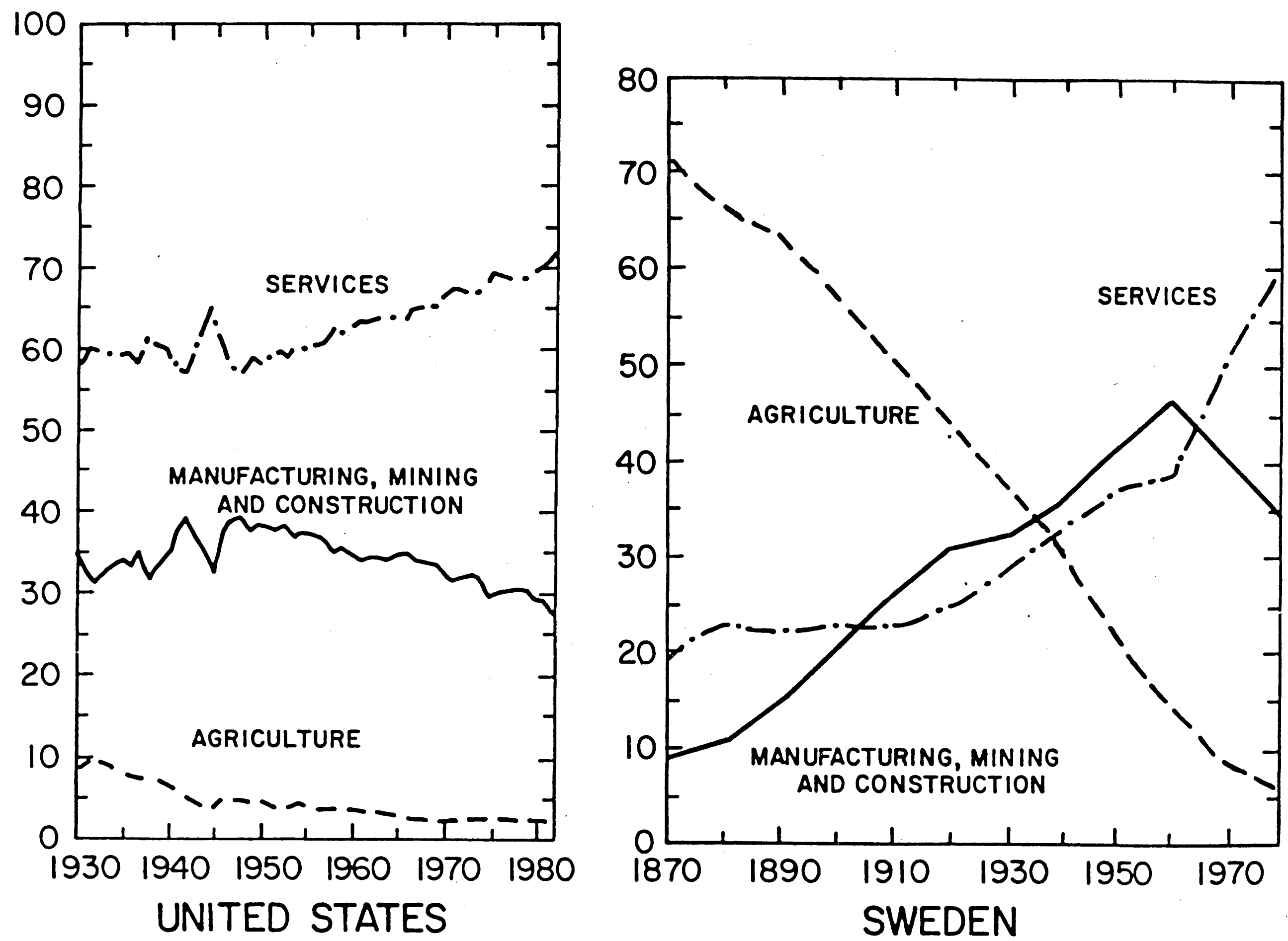
*Total added value of goods and services plus gross investment. Although there is no simple relationship between energy use and social welfare, or even between true social welfare and various existing measures of material well-being, we shall occasionally use the GDP as a measure of social welfare, essentially because it is the only measure available.

The Growing Importance of the Service Sector

The shift to services (e.g. finance, insurance, education, communications, marketing, information, medical, and recreational services) has been underway for decades, as is evident from long-term trends in employment in Sweden and the United States (see Figure 1). In the early years of industrialization, the shares of employment accounted for by manufacturing and services grew at the expense of employment in agriculture. More recently, services have grown at the expense of manufacturing, mining, and construction.

The increasing importance of services is also reflected in the slower growth of goods production. The output of the goods-producing sector (measured by gross product originating [GPO] or value added) grew just 0.83 and 0.60 times as fast as the gross national product (GNP) in the period from 1970 to 1980 in the United States and Sweden, respectively.

Figure 1
DISTRIBUTION OF EMPLOYMENT BY SECTOR IN THE UNITED STATES AND SWEDEN*
(in percents)



*For the United States, the employment measure is the number of full-time equivalent employees. For Sweden, it is the number of employees working more than half-time.

The Growing Importance of Fabrication and Finishing

A shift is also evident within the goods-producing sector, away from the extraction and processing of basic materials to fabrication and finishing activities, which involve much lower inputs of energy per dollar value added than the processing of basic materials (see Figure 2).

Consider the situation in the United States, which has a largely closed economy, with the consumption of goods and services approximately equal to production in most sectors. The industrial sector here can be disaggregated into: mining, agriculture, and construction (MAC); the basic materials processing (BMP) subsector of manufacturing; and other manufacturing. In 1978, these sectors accounted for about 25, 25, and 50 percent of industrial output; for 15, 73, and 11 percent of final energy use in industry; and required 3, 14, and 1 units of energy per dollar of output, respectively. In Sweden, these sectors accounted for about 35, 37, and 28 percent of industrial output; 10, 82, and 8 percent of final energy use in industry; and 1, 7.5, and 1 units of energy per dollar of output respectively. Thus while other manufacturing, which involves the fabrication and finishing of basic materials, is economically important in both countries, the BMP subsector of manufacturing dominates energy use.

Shifts in output among these sectors toward less materials-intensive activities have been pronounced. In the United States, for example, the rate of growth of industrial output (GPO) for fabrication and finishing activities averaged 2.5 percent per year from 1973 to 1984, compared to 0.5 percent per year for the BMP subsector and 0.7 percent per year for MAC. In Sweden, fabrication and finishing activities grew in the 1970s at an annual average rate of 2.0 percent per year, compared to 1.1 percent per year for industry as a whole and 1.2 percent per year for the primary metals sector, and a 1.4 percent per year rate of decline for the cement industry

There is strong evidence that the shift to fabrication and finishing is associated with a cessation of growth in the per capita consumption of materials, as indicated in a recent analysis of the long-term history and future outlook for a representative sampling of basic materials. For both traditional materials (steel, cement, paper) and modern materials (aluminum, ethylene, chlorine, and ammonia), per capita consumption stopped growing and in most cases began to decline in the United States and Western Europe in the 1970s (see Figures 3a and 3b).[1] The trends appear to be due to a combination of factors, including materials substitution, more efficient use of materials, saturation in markets for bulk materials, and a shift in consumer preferences at high income levels to value-added intensive goods. The first two factors have been important throughout the history of materials use, although they are more important now because of today's high materials and energy costs. The latter two are relatively new phenomena which signal the beginning of a new postindustrial era. That these recent trends are likely to represent permanent structural changes is indicated for the U.S. situation by market analyses which show that for nearly all materials indicated in Figure 3 the outlook for volume growth is poor and that only markets for high value-added specialty products appear promising. While it is unclear whether growth in these markets will be adequate to offset the declines in markets for high-volume bulk products, the evidence for at least a cessation of growth in per capita demand is strong.[2]

Figure 2
MARKET SHARES OF GOODS-PRODUCING SECTOR, 1947 TO 1982

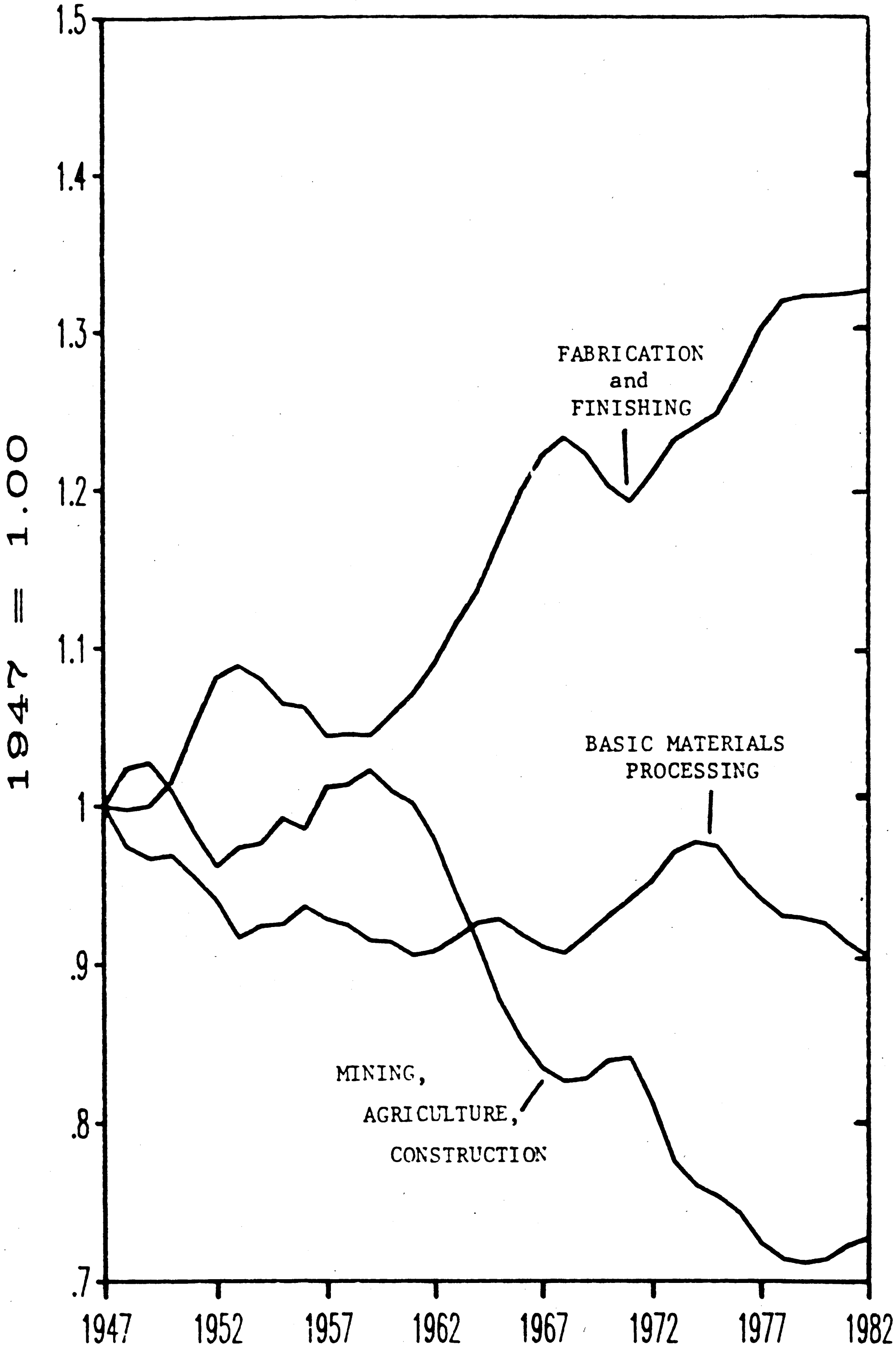
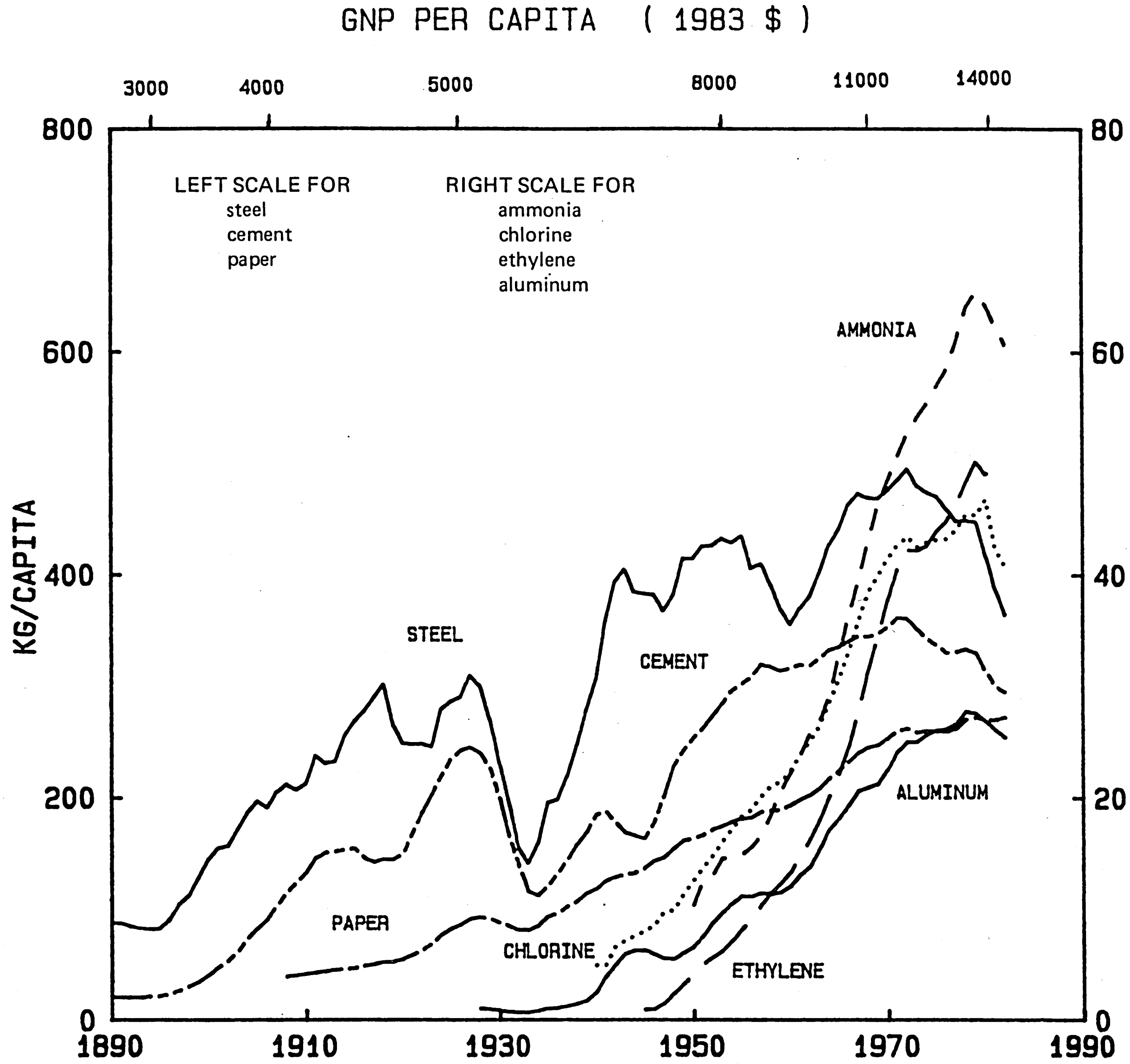


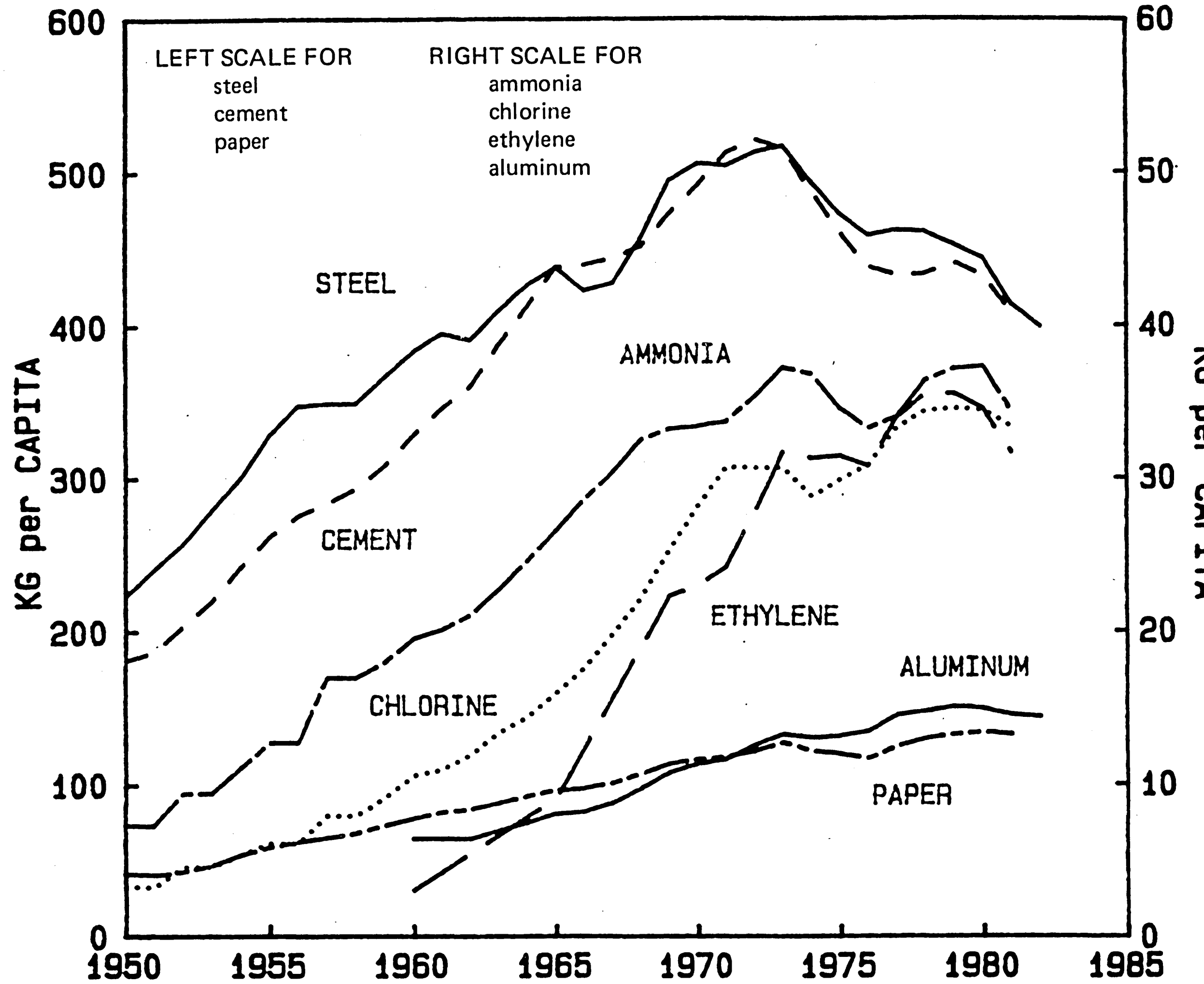
Figure 3a
TRENDS IN APPARENT CONSUMPTION (PRODUCTION PLUS NET IMPORTS)
PER CAPITA FOR THE UNITED STATES*



*The data are five-year running averages. Change in GNP per capita from 1890 to 1990 is shown as an economic referent.

From M. Ross, E. Larson, and R. Williams, "Energy Demand and Materials Flow in the Economy," Center for Energy and Environmental Studies (Princeton, N.J.: Princeton University, 1985).

Figure 3b
TRENDS IN APPARENT CONSUMPTION (PRODUCTION PLUS NET IMPORTS)
PER CAPITA FOR WESTERN EUROPE*



*These data are actually aggregate data for Germany, France, and the United Kingdom, except in the case of ammonia, where the data are for France and Germany only. The data are three-year running averages.

From M. Ross, E. Larson, and R. Williams, "Energy Demand and Materials Flow in the Economy," Center for Energy and Environmental Studies (Princeton, N.J.: Princeton University, 1985).

Shifts to fabrication and finishing, which typically require an order of magnitude less energy per unit of output than the processing of basic materials, can have profound effects on industrial energy use. For the United States, such shifts accounted for an annual rate of decline in industrial energy use per dollar of GNP of 1.6 percent from 1973 to 1984, out of a total rate of decline of 3.6 percent per year in this period.[3]

These ongoing trends, which began well before the energy crises of the 1970s, can be expected to continue, and perhaps also to accelerate, in response to sharply increased energy prices.

OPPORTUNITIES FOR ENERGY PRODUCTIVITY IMPROVEMENT BY SECTOR

The shift to less energy-intensive economic activities might be complemented by increased use of technologies that make more efficient use of energy supplies in providing energy services. The energy price increases of the 1970s have encouraged the commercialization of new, more energy-efficient technologies, as well as research and development efforts that will lead to even more efficient technologies in years to come. Opportunities exist for major improvements in energy productivity for all major energy-intensive activities in buildings, transport, and industry. We illustrate the possibilities with examples from each energy-using sector.

Residential Buildings

Space heating, accounting for between 60 and 80 percent of final energy use in residential buildings in industrialized countries, warrants especially close attention and indeed has been the focus of ongoing residential energy conservation programs. Higher energy productivity for space heating can be achieved through improvements in both the building shell and in the heating equipment.

Shell Modifications in New Houses: Heat losses can be reduced by increasing insulation, adding more glazing (extra panes of glass) to the windows, and reducing natural air infiltration. Good indoor air quality can be maintained in a "tight house" through forced ventilation with heat recovery instead of natural ventilation; a heat exchanger can be used to transfer heat from stale exhaust air to incoming fresh air or to other useful purposes.

Table 1 lists the energy performances of various groups of new houses having major energy-saving features. (Here energy performance is measured by the energy output required of a house's heating system, corrected for floor area and climate variation.) While typical new houses use much less energy than houses in the existing stock, much more can be accomplished with attention to energy-conserving design features. Well-built new houses with such features in both Sweden and the United States require less than one-third as much energy for space heat as existing houses, while very energy efficient "superinsulated houses" being built require an order of magnitude less energy.

Table 1
SPACE HEAT REQUIREMENTS IN SINGLE FAMILY DWELLINGS
(In Kilojoules per Square Meter per Degree Day)

United States	
Average housing stock[a]	160
New (1980) construction[b]	100
Mean measured value for 97 houses in Minnesota's Energy Efficient Housing Demonstration Program[a]	51
Mean measured value for 9 houses built in Eugene, Oregon[c]	48
Calculated value for a Northern Energy Home, New York City area[d]	15
Sweden	
Average housing stock[e]	135
Homes built to conform to the 1975 Swedish Building Code[f]	65
Mean measured value for 39 houses built in Skane[g]	36
House of Mats Wolgast[h]	18
Calculated value for alternative versions of the prefabricated house sold by Faluhus[i]	
Version 1	83
Version 2	17

Note: Space heat requirement is the required output of the space heating system (i.e., heat losses less internal heat gains less solar gains) per unit floor area per heating degree day.

(a) See R. Williams, G. Dutt, and H. Geller, "Future Energy Savings in U.S. Housing," *Annual Review of Energy* 8 (1983): 269.

(b) As reported by the National Association of Home Builders. See J. Ribot et al., "Monitored Low-Energy Houses in North America and Europe: A Compilation and Economic Analysis," in *What Works: Documenting Energy Conservation in Buildings: Proceedings of the Second Summer Study of Energy Efficient Buildings at Santa Cruz, California, August, 1982*, J. Harris and C. Blumstein, eds. (Washington, D.C.: American Council for an Energy Efficient Economy, 1983) pp. 242-256.

(c) One-story houses with an average floor area of 103 square meters, 15 square meters of double-paned windows, 15 centimeters (30 cm) of fiber-glass insulation in the walls and floor (ceiling), and an average air infiltration rate of 0.25 air changes per hour. The energy performances are adjusted to standardized conditions: an internal heat load of 1.0 kilowatts (kW) and an indoor temperature of 20 degrees Celsius. See Ribot et al., in note (b) above.

(d) The Northern Energy Home (NEH) is a superinsulated home design which is sold in the Northeast. The NEH design is based on modular construction techniques. The house is constructed of factory-built wall and ceiling sections (120 x 240 cm x 23 cm) which are mounted on a post and beam frame. The calculations presented here were carried out by Dan McMillan of the American Council for an Energy Efficient Economy using the Computerized Instrumented Residential Audit computer program for a house with the following features: 120 square meters of floor area; 12 percent of wall area (14 square meters) in windows, with 60 percent on the south side; triple-glazed windows with night shutters; 20 cm of polystyrene insulation in walls, 23 cm in ceiling; 0.15 air changes per hour (ACH) natural ventilation plus 0.35 ACH forced ventilation plus 70 percent efficient air-to-air heat exchanger; internal heat load of 0.65 kW, corresponding to the most energy-efficient appliances available in 1982 plus 3.06 occupants on average. The indoor temperature is assumed to be 21 degrees Celsius in the daytime, set back to 18 degrees at night. The New York climate is characterized by 2,700 degree days.

(e) Average 1980 fuel consumption for space heating, floor area, and number of heating degree days of 98.5 gigajoules (GJ), 120 square meters, and 4,474 degree days, respectively, for oil-heated single family dwellings. Here a 66 percent average furnace efficiency is assumed. See L. Schipper, "Residential Energy Use and Conservation in Sweden," Lawrence Berkeley Laboratory, Berkeley, Calif., 1982.

(f) A single-story house with 130 square meters floor area, no basement, electric resistance heat, an indoor temperature of 21 degrees Celsius, and 4,010 degree days should consume this much for space heating. See Schipper in note (e) above.

(g) Average for thirty-nine identical, four-bedroom, semi-detached houses (112 square meters of floor area; 3,300 degree days).

(h) Heated floor space, 130 square meters; 27 and 45 cm of mineral wool insulation in the walls and ceiling, respectively; quadruple glazing; low natural ventilation plus forced ventilation through air preheated in ground channels. Heat from the exhaust air is recovered through a heat exchanger. The local climate is characterized by 3,800 degree days. See P. Steen et al., *Energy: For What and How Much?* (Stockholm: Liber Forlag, 1981), in Swedish. Summarized in Johansson et al., "Sweden Beyond Oil--The Efficient Use of Energy," *Science* 219 (1983): 355.

(i) Floor area of 112 square meters. Version 2 (with extra insulation and heat recuperation) costs 3,970 SEK (U.S. $516) per square meter compared to 3,750 SEK (U.S. $488) per square meter for Version 1. The annual electricity savings for the more efficient house would be 8,960 kilowatt hours (kwh) per year. The cost of saved energy (assuming a 6 percent discount rate--the value used by the Swedish Energy Commission for assessing alternative energy technologies--and a thirty-year life for extra investment) would be 0.20 SEK per kwh (U.S. $0.026 per kwh). Electricity rates for residential consumers in Sweden consist of a large fixed cost independent of consumption level (about 1,200 SEK [U.S. $156] per year) plus a variable cost of 0.25 SEK per kwh ($0.032 per kwh).

The costs of improved energy performance tend to vary with the builder and the experience of the builder, but for a wide range of circumstances, the cost of saved energy (CSE) is less than the price of the energy supply displaced by investments in energy efficiency.*

Even for superinsulated houses, which one might expect to be very expensive, there is a growing body of evidence suggesting that the net extra cost may not be very large in comparison to the cost of conventional houses because of synergisms whereby the added costs of extra insulation can be offset to a considerable degree by savings in the heat generation and distribution systems.[4] Some particularly good data on the cost of superinsulated houses are provided by the prefabricated houses offered by Faluhus in Sweden. The more energy-efficient version, one of the most energy-efficient houses available, has an associated CSE less than the present Swedish electricity price, even though present hydropower-based Swedish electrical rates are exceedingly low and far below marginal costs for new electricity sources (see Table 1, note i).

<u>Shell Modifications for Existing Houses</u>: Attention to existing houses is important, since such houses will dominate the housing stocks of industrialized countries for many decades, both because of the long life of existing structures and because of the expected slow net growth of the housing stock. However, since many features cannot be readily changed once a house is built, thermal design improvements are generally more costly for existing than for new houses.

Nevertheless, there are a number of cost-effective conservation measures widely available to homeowners today, including extra insulation, storm windows, clock thermostats, etc. The opportunities in this area are evident in the Swedish government's ten-year plan for the retrofit of buildings, which has targeted about a one-third reduction in the energy use of the 1978 building stock. The plan was initiated in 1978 and is optimized for an energy price 30 percent below 1981 energy prices.

The Modular Retrofit Experiment (MRE) conducted by gas utilities in the state of New Jersey demonstrated state-of-the-art possibilities that go beyond such conventional measures and exploit low-cost opportunities that can be identified through the use of sophisticated diagnostic equipment.[5] In the MRE, which was based on a "house doctor" concept, the measured savings associated with the one-day, two-person house doctor visit were, on average, equal to 19 percent of gas use associated with space heating. Subsequent

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*The cost of saved energy is an index in units of energy price which permits a ready economic comparison between investments in energy efficiency and energy supply alternatives. For a typical situation in which energy saved is financed through banks or other loans, the CSE is the annual repayment cost (principal plus interest), with the term of the loan equal to the expected lifetime of the equipment or structure being financed. Investments in energy efficiency improvement are cost-justified up to the point where the CSE is equal to the cost of the extra energy supply that would otherwise have to be purchased.

more conventional shell modification retrofits bring the total fuel savings to an average of 30 percent, for an average total investment of about $1,300; the associated real internal rate of return in fuel savings was nearly 20 percent, for an assumed life cycle gas price equal to $8 per gigajoule (GJ), which is equal to the heating oil price in 1982.[6]

The achievements demonstrated in the MRE do not represent the limit of what can be achieved with shell improvements of existing dwellings. One important experiment exploiting additional unconventional opportunities resulted in an energy savings of two-thirds in a U.S. house which prior to modification was regarded as thermally tight by U.S. standards.[7] Also, over a period of several decades, the energy savings potential from retrofits should be much greater than that which can be achieved immediately. Some important energy-reducing shell improvements are much more cost effective if carried out in conjunction with other needed structural changes (e.g., the installation of energy-efficient windows at the time of the scheduled retirement of old windows). Moreover, new technical opportunities for energy demand reduction can be expected to be developed continually.

Space Heating Equipment: The efficiencies of space-heating equipment can be much improved.[8] For gas furnaces, conversion efficiencies have increased in the U.S. from an average of about 69 percent for new units sold in 1980 to more than 90 percent for new condensing furnaces, so called because heat is extracted from flue gases past the point where the water vapor condenses out. Heat pumps with coefficients of performance (COP) up to 2.5 for air-to-air units and up to 3 for water-to-air or water-to-water units have also become available on the market. For comparison, the average COP of heat pumps in the existing U.S. stock is less than 2 and that of resistive electric heating units is 1 or less.

Other End Uses: There are also many opportunities to improve energy productivity cost effectively for air conditioning, domestic water heaters, refrigeration, lighting, and cooking.[9] Opportunities relating to refrigerator-freezers in the United States are summarized in Table 2.

Total Residential Final Energy Use: An indication of the overall potential for energy savings is given in Table 3, which shows per capita final residential energy use, first for average households in the United States and Sweden at present and second for hypothetical all-electric households having a full set of major energy-using amenities and the most energy-efficient technologies commercially available in 1982. While these hypothetical households have a higher level of amenities than average households today, they would use only about 300 watts per capita, which is only about one-fifth of the present level of final energy use (fuel plus electricity) and is even less than the present level of electricity use. With more efficient technologies under development, energy use could be reduced even further.

Table 2
ELECTRICITY SAVINGS POTENTIAL FOR TWO-DOOR
REFRIGERATOR-FREEZERS WITH AUTOMATIC DEFROST IN THE UNITED STATES

Electricity use by the average unit in the existing stock	1,700 kwh/year
Average electricity requirements for new models, 1983	1,200 kwh/year
Electricity requirements for the most efficient model commercially available as of April, 1984[a]	880 kwh/year
Electricity requirements of 500-liter (18 cubic foot) prototype that has been field tested	650 kwh/year
Number of baseload power plants (@ 1,000 megawatts [MW] each) required to drive U.S. refrigerators in 1980[b]	31
Number of power plants (@ 1,000 MW each) saved if instead every unit in the United States were replaced with the most efficient unit available on the market in 1984[c]	15
Extra first cost per unit associated with top-rated models (relative to conventional, less efficient units with similar features)	$ 50 - $ 100
Annual electricity savings with top-rated models	300 - 500 kwh
Cost of saved energy[d]	$0.01 - 0.03 per kwh
Average residential electricity price	$0.07 per kwh

(a) A 490-liter (17 cubic foot) Kenmore 86377*0 or Whirlpool ET17HKXM. See American Council for an Energy Efficient Economy, "The Most Energy Efficient Appliances: Fall-Winter 1984-1985," Washington, D.C., 1984.

(b) Electricity requirements for 93 million refrigerators and refrigerator-freezers in the United States of 156 billion kwh in 1980. Assuming 11 percent transmission and distribution losses, this corresponds to the output of 30.8 gigawatt electricity (GW[e]) of generating capacity operated at 65 percent capacity factor. See R. Williams, G. Dutt, and H. Geller, "Future Energy Savings in U.S. Housing," *Annual Review of Energy* 8 (1983): 269.

(c) If all 93 million units had instead consumed 880 kwh each in 1980, the savings would have been 14.7 GW(e) of baseload generating capacity operated at a 65 percent capacity factor.

(d) Assuming a nineteen-year lifetime and a 10 percent real discount rate.

Table 3
FINAL ENERGY USE IN THE RESIDENTIAL SECTOR
(In Watts per Capita)

	Average Household at Present		All Elect., 4-Person Hshlds. with the Most Efficient Technology Available in '82/83[a]	
End Use	U.S. 1980[b]	Sweden 1978/82[c,d]	U.S.	Sweden[c]
Space heat	890	900	60[e]	65[f]
Air cond.	46	--	65[g]	--
Hot water	280	180	43[h]	110[i]
Refrigerator	79	17	25	8
Freezer	23	26	21	17
Stove	62	26	21	16
Lighting	41	30	18[j]	9[j]
Other	80	63	75	41
Total	1,501	1,242	328	266

(a) With 100 percent saturation for the indicated appliances plus dishwasher, clothes washer, and clothes dryer.

(b) The total consists of 360 watts (w) of electricity and 1,140 w of fuel.

(c) For details, see Johansson et al., *Perspectives on Energy: On Possibilities and Uncertainties in the Energy Transition*, Report to the Swedish 1981 Energy Commission, Ministry of Industry, DsI 1983: 18 (Stockholm: Liber Forlag, 1983), in Swedish.

(d) This total consists of 350 W of electricity and 890 W of fuel; 50 percent of the electricity is for appliances and 50 percent is for heating purposes.

(e) For an average-sized, detached, single family house (150 square meters of floor space); average U.S. climate (2,600 degree days); a net heating requirement of 50 kilojoules (kj) per square meter per degree day (see Table 1); and a heat pump with a seasonal average coefficient of performance (COP) = 2.6 (the highest efficiency for new air-to-air units).

(f) For a Faluhus (see Table 1) in a Stockholm climate (3,810 degree days). This house uses a heat exchanger to transfer heat from the exhaust air stream to the incoming fresh air.

(g) For the average cooling load in air-conditioned U.S. houses (27 gj per year) and a COP = 3.3 (the COP on the cooling cycle for the most efficient heat pump available in 1982).

(h) For 59 liters per capita per day of hot water (at 49 degree Celsius or 910 kwh per year per capita) and the most efficient (COP = 2.2) heat pump water heater available, 1982.

(i) For 1,000 kwh per year per capita hot water energy use through resistive heat. Ambient air-to-water heat pumps are not competitive at the low Swedish electricity prices.

(j) Savings achieved by replacing incandescents with compact fluorescents.

Commercial Buildings

The commercial buildings sector is comprised of a heterogeneous mix of office and public buildings, schools, hotels and motels, retail stores, restaurants, hospitals, assembly buildings, churches, warehouses, etc. The energy budgets of commercial buildings, like those of residences, are dominated by the requirements for space conditioning; but for these buildings, shell improvements other than for day lighting and sun control are much less important. Most of the opportunities for improved energy performance involve the use of more energy-efficient equipment and a better matching of energy supplies to service requirements through the use of better control technology.

New Commercial Construction: While new American and Swedish commercial buildings are less energy intensive than the existing stock, the energy performance of some new buildings is far better than that for typical new construction (see Table 4).

The Folksam Building in Farsta, near Stockholm, is perhaps the most energy-efficient commercial building constructed in the late 1970s. With an ordinary design, this building in winter would require heating at night but cooling in the daytime to compensate for overheating by lights and other internal heat loads. But with the Folksam design, excess heat produced in the daytime is stored for use at night, when heating is needed, or for morning warm-up of the building. Storage is accomplished through the Thermodeck concept, which involves the movement of office ventilation air through long tubular cores in the massive concrete floor slabs on its way to the offices. With this storage scheme, the air temperature rise in the offices during the day is only about 2 degrees, so that cooling is unnecessary. In summer, the system stores heat in the slabs during the day, as in winter, but the slabs are cooled with outside air at night.

At the time of this writing, the most energy-efficient commercial building in Sweden was the Harnosand Building in northern Sweden, constructed in 1981. By utilizing the Thermodeck principle, preheating ventilation air with solar panels, and using microprocessor controls for better matching energy supply and demand, the structure's builders and operators were able to reduce its energy use to a value about half as large as that of the Folksam Building (see Table 4).

Table 4
SITE ENERGY INTENSITY FACTORS FOR COMMERCIAL BUILDINGS
(In GJ per Square Meter per Year)

	Fuel	Electricity	Total
United States			
Average 1979 building stock[a]	0.82	0.49	1.31
Current U.S. practice[b]	0.16	0.57	0.73
American Institute of Architects Research Corporation Redesigns[b]	0.07	0.40	0.47
American Institute of Architects Minimum Lifecycle Cost Designs[b]	0.04	0.28	0.32
Enerplex South, Princeton, N.J.[c]	--	0.31	0.31
Sweden			
Average 1982 building stock[d]	0.66	0.38	1.04
Swedish norm for new construction[b]	0.57	0.19	0.76
Folksam Building, Farsta[e]	0.07	0.39	0.46
Harnosand Building, Harnosand[f]	0.12	0.13	0.25

(a) For an average of 2,700 heating degree days. See Energy Information Administration, U.S. Department of Energy, *Non-residential Buildings Energy Consumption Survey: 1979 Consumption and Expenditures; Part 2: Steam, Fuel Oil, LPG, and all Fuels* (Washington, D.C.: U.S. Government Printing Office, 1983).

(b) See Solar Energy Research Institute, *A New Prosperity: Building a Sustainable Energy Future* (Andover, Mass.: Brickhouse, 1981), Table 1.12 and Figure 1.61.

(c) For 2,700 heating degree days. These are calculated, not measured values. See L. Norford, "An Analysis of Energy Use in Office Buildings: The Case of Enerplex," Phd. thesis, Department of Aerospace and Mechanical Engineering, Princeton University, Princeton, N.J., 1984.

(d) Consumption corrected to normal weather (4,010 heating degree days). L. Carlsson, National Energy Administration, Sweden, personal communication to T. Johansson, March, 1984.

(e) Measured values for the representative period from December, 1978, to December, 1979 (3,810 heating degree days). "Fuel consumption" is the energy actually delivered by the district heating system. See K. Welmer, "A Method to Make use of a Building's Heat Storage Capacity in a Controlled Manner to Save Energy," Swedish Building Energy Council, BFR report R104:1981, Stockholm, 1981, in Swedish.

(f) Measured values for 4,600 heating degree Celsius days. See personal communication K-Konsult to T. Johansson, February, 1984.

Existing Commercial Buildings: Improved energy management involving little or no capital investment (e.g., night setbacks of thermostats, adjustments in ventilation to better match needs, etc.), typically results in savings of 20 to 30 percent in existing commercial building in Sweden.[10] In the United States, the average measured savings in 184 buildings was 23 percent, and the corresponding cost of saved energy for fifty-six buildings for which cost data were available was $2.8 per GJ (1982 dollars), assuming a ten-year retrofit life and a 10 percent real discount rate.[11] These savings fall short of the economic potential, however, since there is probably much more that can be done for a cost of saved energy less than the average price of energy, some $8 per GJ for U.S. commercial buildings in 1979.[12] In a survey of experienced architects and engineers conducted by the Solar Energy Research Institute, the consensus judgment was that a 50 percent reduction in energy use per square meter was an achievable target for exising U.S. commercial buildings by the year 2000.[13]

Transportation

In 1982, transportation accounted for 53 percent of all oil consumption in the Organization for Economic Cooperation and Development (OECD) nations.[14] Accounting for over 60 percent of all oil use in transport, automobiles and light trucks warrant special attention.

Light Vehicles: It is feasible to improve the fuel economy of automobiles and light trucks from present average values of 12 to 8 liters per 100 kilometers (km) (20 to 30 miles per gallon [mpg]) to the range 4 to 2.3 liters per 100 kilometers (km) (60 to 100 mpg) in the decades immediately ahead by increasing engine/drive train efficiency and reducing vehicle weight and aerodynamic and rolling resistances.

Engine efficiencies are typically low. For example, the model year 1981 gasoline-powered Volkswagen (VW) Rabbit with manual transmission has an average engine/drive train efficiency in converting fuel to mechanical energy at the wheels of only 13.5 percent.[15] One possibility for improving efficiency involves use of a diesel engine. The diesel version of the Rabbit has an energy performance on the U.S. Environmental Protection Agency (EPA) combined driving cycle of 5.3 liters per 100 kilometers (km) (45 mpg), compared to 7.9 liters per 100 kilometers (km) (30 mpg) for the gasoline version. The cost of saved energy for this $525 engine switch, assuming a 10 percent real discount rate and an annual average driving distance of about 16,000 kilometers (about 10,000 miles) per year, would be just $0.22 per liter ($0.78 per gallon) of gasoline equivalent.

While the addition of energy-saving features can result in increased initial investment, energy efficiency improvement does not necessarily imply higher first costs. Just as there are often synergisms at work to keep down the first costs of superinsulated houses, so too synergisms can work to keep down the first cost of energy-efficient cars. For example, by emphasizing the use of lightweight materials, it is possible, without sacrificing acceleration, to use a less powerful and less costly engine, which in turn requires even less materials for the supporting structure.[16]

Additional improvements in the VW Rabbit, based on proven technology, such as reduced aerodynamic drag and rolling resistance, use of a direct-injection diesel rather than a prechamber diesel, use of a continuously variable transmission, weight reduction, and addition of an engine-off feature during coast and idle, would improve its fuel economy to 2.6 liters per 100 kilometers (km) (89 mpg).[17] Many of these features have been incorporated into prototypes, of which the Volvo Light Component Project 2000 (LCP 2000) car and the VW Experimental Car 2000, with fuel economies of 3.6 and 3.8 liters per 100 kilometers (km) (65 and 62 mpg), respectively, are notable examples (see Table 5).

Among further improvements possible with advanced technology, the efficient adiabatic diesel engine is especially promising. The Volvo LCP 2000, with a three-cylinder, heat-insulated, direct-injection, turbocharged engine is an advance in this direction.[18]

Researchers at Ford Motor Company, in describing what an "average" vehicle in the late 1990s could be like, describe it as "a four- or five-passenger vehicle in the 2,000-pound (900 kilogram [kg]) inertia weight class with an aerodynamic drag coefficient of 0.2 or less....Electronics would control a turbocharged, ceramic, adiabatic diesel engine and continuously variable transmission to provide smooth effortless performance and fuel economy in excess of 100 miles per gallon on the highway."[19]

Concern has been raised about the safety of super-mpg cars. However, a lightweight car need not be unsafe, as is indicated by the safety features built into Volvo's LCP 2000.[20] Also, lightweight cars can be built with large bodies that provide crush space, thereby giving the occupants some protection in the event of collision. This idea is a key feature of the design for the Pertran car, which has been proposed by automotive researchers at the Battelle Memorial Institute in Columbus, Ohio. The diesel version of the Pertran would be a 545 kg, five-passenger car, comparable in length and height with the General Motors X-Car or Chrysler K-Car (current designs) but somewhat narrower. The estimated fuel economy of this car on the U.S. EPA urban driving cycle is 2.3 liters per 100 km (100 mpg).[21] Lastly, super-mpg cars are not necessarily lightweight. Researchers at the Cummins Engine Company and the NASA Lewis Research Center have described the design of a 1,360-kg (3,000-pound) passenger car having an adiabatic diesel engine with a turbo-compound bottoming cycle which would have a fuel economy of 3.0 liters per 100 kilometers (km) (79 mpg) and would thus be a "heavy" super-mpg car.[22]

Diesel air pollution is another concern. However, spark-assisted versions of diesels would be able to use clean-burning methanol fuel[23] without loss of efficiency.[24] The engine in the Cummins/NASA Lewis vehicle thus would be able to use methanol as fuel.[25]

<u>Truck Freight</u>: For trucks, it appears feasible to reduce energy use per ton-km by 50 percent relative to the present U.S. average for long-haul trucks through a combination of measures such as the development of adiabatic diesel engines and bottoming cycles, reduction in aerodynamic drag, and tire improvements.[26] Additional savings might be achieved through increased load factors.

Table 5
FUEL ECONOMY FOR FOUR-PASSENGER AUTOMOBILES

Car	Status	Fuel Economy (in liters per 100 km [mpg])	Power (kw)	Curb Wgt. (kg)	Drag Coef.
1981 VW Rabbit					
Gasoline	commercial	7.9 (30)	55	945	0.42
Diesel	commercial	5.3 (45)	39	945	0.42
Honda City Car					
Gasoline	commercial	5.0 (47)	46	655	0.40
VW Experimental Car 2000[a]	prototype	3.8 (62)	33	786	0.25
Volvo LCP 2000[b]	prototype	3.6 (65)	66	707	0.27
Volvo LCP Potential[c]	design	2.75 (85)	--	--	--
Cummins/NASA Lewis Car[d]	design	3.0 (79)	51	1360	--
Diesel Pertran[e]	design	2.3 (100)	--	545	0.25

Note: The world 1978 average automobile fuel economy was 13 liters per 100 km (18 mpg).

(a) Three-cylinder, direct-injection, turbocharged diesel engine; more interior space than the Rabbit; engine off during idle and coast.

(b) Two-passengers plus cargo or four-passengers; three-cylinder, heat-insulated, direct-injection, turbocharged engine with multi-fuel capability. See Volvo, "Volvo LCP 2000--Light Component Project," Volvo Personvagnar AB, S-405 08, Gothenburg, Sweden, 1984.

(c) The Volvo LCP 2000 features plus continuously variable transmission (CVT) and engine off during idle and coast. See R. Mellde, Volvo Car Corporation, personal communication to F. von Hippel, February, 1985.

(d) Four to five passengers; four-cylinder, direct-injection, spark-assisted, multi-fuel capable, adiabatic diesel with turbo-compounding; CVT; 1984 model Ford Tempo body. See R. Sekar, R. Kamo, and J. Wood, "Advanced Adiabatic Engine for Passenger Cars," SAE Technical Paper series 840434, International Congress and Exposition, Detroit, Mich., 1984.

(e) Pre-chamber diesel engine with supercharger; CVT; flywheel for energy storage in braking. See S. Fawcett and J. Swain, "Prospectus for a Consumer Demonstration of a 100 MPG Car," Battelle Memorial Institute paper, Columbus, Ohio, 1983.

Air Passenger Travel: For passenger aircraft, the high cost of fuel, accounting for as much as 30 percent of the operating costs of U.S. commercial airlines, provides a strong incentive for seeking fuel economy improvements. It appears feasible to reduce fuel intensity in the United States by 50 percent relative to 1977 levels through a combination of measures such as completing the shift to wide-bodied jets with high-bypass turbofan engines, improved wing design, reduced weight through use of composites, and other factors.[27]

Industry

The energy price shocks of the 1970s resulted in much larger relative price increases in the industrial sector than in other energy-consuming sectors. Within the industrial sector, the energy-intensive basic materials processing industries, which accounted for 70 percent of industrial energy use in OECD countries in 1979, experienced much larger relative price increases than the average for all industry. A measure of the relative economic impact of high energy prices on different manufacturing activities is the ratio of energy costs to value added, which in the United States in 1980 ranged from 15 to 76 percent for various basic materials processing sectors and subsectors but averaged only 3 percent for other manufacturing activities.[28]

Economic conditions thus provide a powerful motivation for the pursuit of improvements in energy productivity. As in other sectors, there is a wide range of technical opportunites for making such improvements. It is useful to classify these opportunities in terms of good housekeeping measures, fundamental process changes, product changes, and new energy conversion technologies.

Good Housekeeping: During the era of low-priced energy, little attention was given to the details of energy use in industry, and as a consequence there was often widespread energy waste.

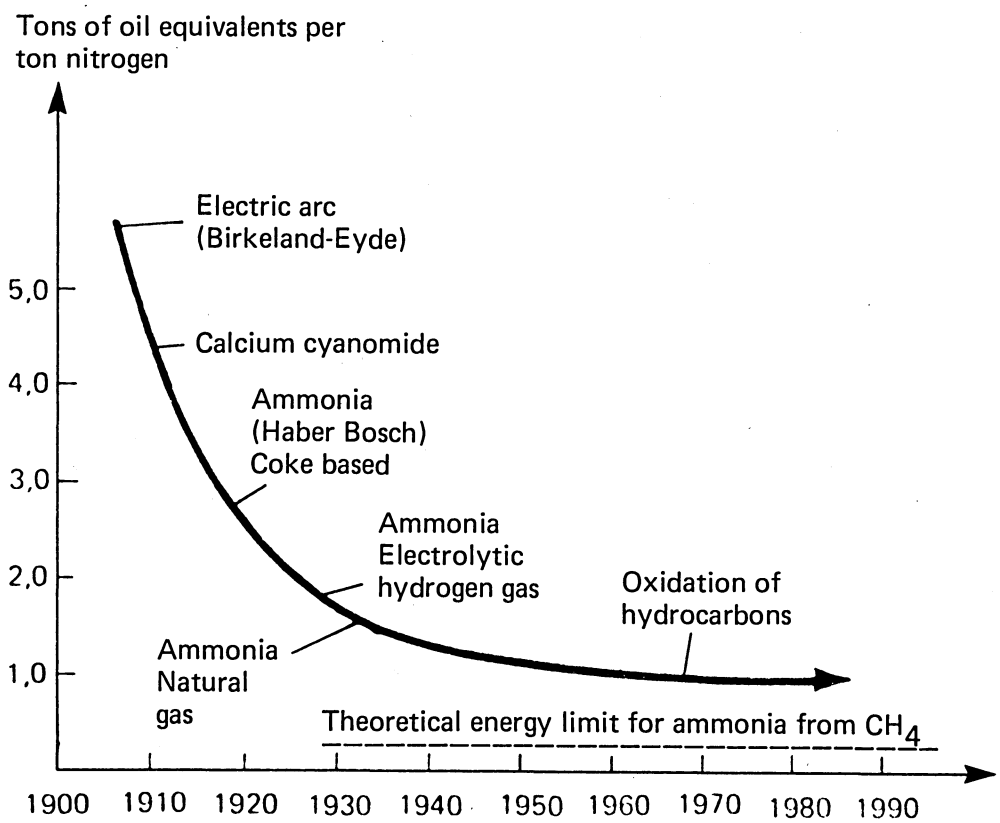
However, much can be accomplished simply through the elimination of leaks in and the insulation of steam lines, the turning off of energy supply systems when not in use, etc. Simple good housekeeping measures such as these can be promoted effectively, for instance, by: the direct metering of major energy-using sections of industrial facilities; charging energy costs to production departments instead of to general overhead; using sophisticated inspection and maintenance equipment, such as infrared scanners; establishing training programs in energy conservation techniques for the operation of energy-intensive equipment; and using automatic control systems for energy-intensive equipment. The potential for energy savings here are typically on the order of 10 to 20 percent at little or no capital cost.

Process Innovation: The history of modern industry tells us that new processes are most likely to overcome resistance to technical change and displace existing processes if they offer opportunities for simultaneous improvements in several factors of production--for instance, reduced labor, capital, materials, and energy requirements.[29] This has been a powerful phenomenon, resulting in reduced energy requirements through technological innovation even during periods of declining energy prices.

The goal of process innovation is not to minimize the cost of providing energy services, but rather to minimize the total cost of production. Nevertheless, energy requirements are typically reduced in process innovation, and the energy savings are often much greater than what can be achieved by simply retrofitting existing processes with energy conservation devices such as heat recuperators.

One example of the importance of process change is illustrated in Figure 4, which shows that the energy required to produce a ton of ammonia has been reduced by about a factor of 5 since the turn of the century. Another example is the recent introduction of the float-glass process, which by now has captured most of the market for flat glass. Previously, the manufacture of high-quality flat glass involved extensive grinding and polishing, which consumed 10 to 20 percent of the glass. The elimination of these steps not only reduced costs but also saved the energy that formerly was used in grinding and polishing and in the production of the glass that was ground into waste.

Figure 4
THE ENERGY REQUIREMENTS FOR PRODUCING AMMONIA AS ALTERNATIVE PROCESSES WERE INTRODUCED OVER TIME



New processes are being continuously developed. Important research and development areas from which industrial process innovations are likely to emerge include powder metallurgy, plasma metallurgy, computer-assisted design and manufacturing, laser processing of chemicals, biotechnology, membrane separation technology, and the use of microwaves for localized rather than volumetric heating. Improvements in all such areas will make it possible to produce more with fewer inputs of the various production factors, including energy. We now illustrate the possibilities with two examples.

Steel: About five-sixths of all steel is produced in industrialized countries, where it accounts for a major fraction of all manufacturing energy use, for instance, one-sixth in Sweden and one-seventh in the United States. The minimum energy theoretically required to produce a ton of steel is 7 GJ from iron ore[30] and 0.7 GJ from scrap. At present, steel-making in Sweden and the United States is based on a fifty-fifty mix of iron ore and scrap, so that the theoretical minimum is about 3.9 GJ per ton of raw steel. For comparison, the actual energy used to produce raw steel was 27 GJ per ton in 1980 in the United States and 22 GJ per ton in 1976 in Sweden.

The markedly better energy performance of the Swedish steel industry arises from the need of this relatively small industry to be innovative to secure its niche in the global steel market. However, the Swedish steel industry is not the most energy efficient. The Japanese are probably the leaders in this regard, since a ton of their steel in 1978 required only about 17 GJ of energy inputs.[31]*

The potential for increased energy productivity in steel production is illustrated in Table 6 with four alternative technological structures for the Swedish steel industry. Structure I is based on current plans of Swedish industry for the 1980s. In structure II, presently commercial technology for heat recovery is fully exploited, mostly through the use of combustible gases in cogeneration. Structures III and IV are based on iron-making processes now under development in Sweden. In both cases, the objective is to reduce overall costs and ameliorate environmental problems through: the use of powdered ores (concentrates) directly, without agglomeration of the ore into sinter or pellets; the use of ordinary steam coal instead of coke derived from much more costly metallurgical coal; and the integration of the various individual operations.

The Plasmasmelt process may be especially appealing to coal-poor, hydro-rich countries, while in countries where electricity prices are high (e.g., the United States), it may be preferable to focus on less electricity-intensive processes like Elred or iron-making processes that produce solid, direct-reduced iron and not molten metal. Direct reduction processes convert iron ore in various forms into sponge iron at temperatures much below the melting point, using a wide variety of reductants other than metallurgical coke.

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*The performance of the Japanese industry relative to Sweden's is better than indicated by these numbers, because the ore fraction in Japanese steel was 75 percent.

Table 6

UNIT ENERGY REQUIREMENTS FOR RAW STEEL PRODUCTION IN SWEDEN, WITH A COMPARISON TO PRESENT U.S. PRACTICE

(In gj per ton)

			Alternative New Technologies			
			I	II	III	IV
	Sweden 1976, Average[a]	U.S. 1980, Average[b]	Modern Technology[c]	Maximum Energy Recovery[d]	Elred[e]	Plasma smelt[f]
Electricity[h]	2.9	2.0	1.8	1.8	1.3	4.2
Oil and gas	7.6	7.5	4.3	2.2	1.3	1.3
Coal	11.9	17.5	9.0	9.0	9.4	3.3
Total	22.3	27.0	15.1	13.0	11.9	8.7

Note: The data in this table assume a fifty-fifty mix of iron ore and scrap feedstocks, approximately the present average for both Sweden and the United States.

(a) See Johansson et al., "Sweden Beyond Oil: The Efficient Use of Energy," *Science* 219 (1983): 355.

(b) For 108 million tons of produced raw steel. For energy consumption by energy carrier see Energy and Environmental Analysis, "The Iron and Steel Industry," in *Industrial Energy Productivity Project Final Report*, vol. 4, prepared for the Assistant Secretary for Conservation and Renewable Energy, DOE/CS/40151-1 (Washington, D.C.: Department of Energy, 1983).

(c) These are consistent with changes planned for the mid-1980s by the Swedish steel industry.

(d) Same as "Modern Technology" except that the potential for energy recovery with presently commercial technology has been fully exploited.

(e) Same as "Modern Technology" except that the blast furnaces are replaced by a process called Elred, which is under development by Stora Kopparberg A.B. See S. Eketorp et al., "The Future Steel Plant," National Swedish Board for Technical Development, Stockholm, 1980.

(f) Same as "Modern Technology" except that the blast furnaces are replaced by a new process called Plasmasmelt, which is under development by SKF Steel A.B. See S. Eketorp et al., in note (e) above.

(g) Here electricity is evaluated at 3.6 megajoules (mj) per kwh (i.e., losses in generation, transmission, and distribution are not included).

The various new iron-making processes at or near commercialization are by no means the end of the line as to what might eventually be achieved in terms of energy and total productivity improvements in the steel industry. Other promising advanced processes that integrate now-separate operations to save on capital, labor, and energy costs include direct casting, direct steel-making, and dry steel-making. The dry steel-making process, which ends up with the final product in powder form (i.e., there would be no melting), holds forth the promise of very low capital costs, suitability for small-scale operations, and a potential 40 percent energy savings relative to conventional processes.[32]

Chemicals: The chemical industry, which accounts for about one-fourth of industrial energy use in OECD countries, is an energy-intensive industry characterized by a broad diversity of products and continuing process innovations, spurred in recent decades by rapid demand growth. There have been continual reductions in the energy intensity of chemicals production throughout the history of the chemical industry (see Table 7). The energy intensity of the U.S. chemical industry declined at a rapid average annual rate of 3.8 percent from 1972 to 1979; even when feedstocks are included in the calculation of energy inputs, the result is an impressive annual average rate of improvement of 2.8 percent in this period. The efficiency improvements achieved in this period were due largely to improved housekeeping. Very little of the improvement can be attributed to major capital investment and fundamental process change.

Table 7
HISTORICAL ENERGY REQUIREMENTS PER UNIT OF OUTPUT FOR SELECTED CHEMICALS PRODUCED IN THE UNITED STATES

Soda Ash (Solvay process)		Ammonia (Haber-Bosch process)		Chlorine (diaphragm cells)	
Date	Energy (in gj/ton)	Date	Energy (in gj/ton)	Date	Electricity (in kwh/ton)
1868	60	1917	93.0	1916	4,400
1894	31	1923-50	81.0	1947-73	3,300
1911	28	1965	52.0	1980	2,400
1925	17	1972	46.5		
1942	15	1978	41.2		
1970	14				

Ethylene Dichloride		Ethylene Oxide		Polyethelene	
Date	Index	Date	Index	Date	Index
1967	100	1970	100	1956	100
1973	15	1973	85	1973	40
		1974	79	1975	18

Source: R. Ayers, "Final Report on Future Energy Consumption by the Industrial Chemicals Industry," SIC 28, prepared for the Energy Productivity Center, Mellon Institute: Appendix to vol. 5.

While the diversity of the chemical industry makes a thorough discussion of the technical opportunities for process improvement very difficult, some insights into the future possibilities can be gleaned from a discussion of generic opportunities in two areas: reaction chemistry and separation and concentration processes.

To drive a chemical reaction, enough energy must be supplied to break existing chemical bonds and/or to form new ones. Typically, however, far more energy is used than is theoretically required. Much energy is wasted in exciting the wrong bonds, and often reactants must be heated to very high temperatures before the desired reaction will take place. There is much that can be done to better direct energy inputs to the targeted reactions using catalysis, laser chemistry, and biotechnology. An example f such an innovation, now exploited, involves the use of catalyzed ammonia production in place of an old non-catalyzed process and has resulted in a three-fold improvement in energy efficiency.[33] The laser holds forth the promise of selective control over chemical reactions by making it possible to provide electromagnetic energy inputs at discrete wavelengths chosen to match the energy required to weaken or break specific bonds as needed to achieve a desired chemical result.[34]

For typical chemical reactions, 70 percent of the capital costs and 80 percent of the energy consumed are in separation and concentration processes.[35] Often these separation processes are energy-intensive and incomplete, involving "brute force" techniques. Some of the more promising alternative approaches involve membrane separation,[36] supercritical fluid extraction,[37] and freeze crystallization. Membrane separation requires much less energy than do "brute force" methods. For example, desalinating seawater requires some 280 megajoules (MJ) per ton of fresh water produced through distillation but only 60 MJ per ton through reverse osmosis.[38]

<u>Product Change</u>: One way product design can lead to reduced energy use if it facilitates materials recycling; this is especially important for metals. Only 35 percent as much energy is consumed in the production of finished steel from recycled steel as from iron ore; recycled aluminum uses less than 10 percent as much. Product design can also lead to reduced energy use if it extends product life, facilitating repair, remanufacture, and reuse.

Significant energy savings are possible through product weight reduction. But sometimes the use of lightweight materials can increase manufacturing energy use--for example, when aluminum is substituted for steel in cars. But such increases are usually offset by the much greater reduced operational energy use, as would be the case with the Volvo lightweight car, the LCP 2000.[39]

Some of the most exciting possibilities for energy-saving substitutions involve entirely new primary materials. One candidate is a "super cement" now under development, which, like ordinary concrete, has a relatively low energy intensity (a cubic meter of ordinary concrete requires six times and twenty-nine times less energy to produce than a cubic meter of polystyrene and stainless steel, respectively) and hence would constitute a desirable substitute for more energy-intensive materials. To date, the substitution possibilities have been quite limited, largely because cements tend to have low tensile strength and low fracture toughness. However, the new super cement under development is a macro-defect-free (MDF) cement, which differs from ordinary cement in that the pores in the cement are reduced from millimeter to micrometer size. This dramatically increases tensile strength and fracture toughness; super cement can be made highly resistant to impact through reinforcement with fibers. These fibers can be inexpensive organic materials because cement is manufactured at low temperatures. Strips of fiber-reinforced MDF cement can be made pliable and bent like strips of metal.[40]

New Energy Conversion Technologies: More efficient energy conversion technologies also can help reduce the industrial use of energy. These technologies typically yield savings on the order of 20 to 50 percent. While such relative savings tend to be less dramatic than that which can often be achieved with process innovation or product change (where two- to four-fold or even larger savings are sometimes possible), the savings opportunities associated with many improved energy conversion devices are often widely applicable throughout industry, so that the aggregate savings can be significant. The measures and devices here include better insulation of furnaces, the use of radiation reflectors, heat recovery devices, induction heating of metals, microwave heating, better mechanical drive systems, and cogeneration.

To illustrate the possibilities, in what follows we discuss mechanical drive technology and industrial cogeneration.

Mechanical Drives: In both the United States and Sweden, industrial motor drives account for about three-fourths of total industrial electricity use. A superficial inquiry into the opportunities for energy efficiency improvements indicates that most industrial motors are fairly efficient, so that only modest electricity savings are possible through the use of high-efficiency motors. A 1976 study estimated that if all new and replacement motors in the United States were high-efficiency devices, savings could be realized by 1990 equivalent to about 7 percent of all electricity used by motors.[41]

Far greater savings are achievable, however, through efforts to better match motor output to load through the use of new semiconductor motor control technology for variable-load situations involving pumps, compressors, fans. For example, constant-speed, overpowered motors are typically used to move gases, and the gas flow is regulated by baffles; similarly, throttling valves are used to control liquid flows. An alternative to throttling involves the use of an alternating current (AC) variable-speed drive (VSD).[42] With VSD, the voltage and frequency are varied simultaneously, maintaining a constant voltage-to-frequency ratio, so as to efficiently modulate a standard induction motor. The VSD thus allows a motor-drive process to be controlled by reducing the energy input to the motor rather than by dissipating the unwanted portion of the motor's output. Energy savings of 20 to 50 percent or more can be realized with the VSD technology. Important VSD applications exist not just in industry but throughout the energy economy. It has been estimated that half of AC motor usage in the United States could be economically affected by the use of VSD controls by 1990, with an average savings of 30 percent for the motors affected.[43] The attraction of VSDs for both new and retrofit applications is cost. Paybacks of one to three years are possible in a wide variety of applications. Even in applications where the savings are modest (on the order of 20 percent or less), good rates of return can often be achieved. Due to improvements in solid state technology, the reliability of VSD devices has improved in recent years, costs have tumbled, and they can be expected to continue falling.[44]

Industrial Cogeneration: Cogeneration involves the combined production of heat and electricity. Cogeneration can be an effective way to efficiently provide space heating for buildings or clusters of buildings through district heating. However, the cogeneration application with the largest fuel savings potential is in the steam-using, basic materials processing industries such as the pulp and paper, chemical, and petroleum refining industries. Since these industries typically have large steam loads which are fairly constant, day and night and year-round, the electricity they produce tends to be base-load electricity. Thus, industrial cogenerators can produce power which is similar in quality to baseload electricity produced by large central station coal or nuclear power plants. The extra fuel required to produce cogenerated electricity typically amounts to only about one-half of the fuel required to produce electricity at conventional thermal electric power plants. In addition to fuel savings, cogeneration installations often require less capital per unit of electrical output than central station power plants.

Although historically utilities have discouraged the development of cogeneration systems,* industrial cogeneration offers distinct advantages in the new era of high-cost central station power and uncertain future demand. The lead-time for cogeneration facilities is only two to three years, compared to the eight to twelve years for conventional power plants. If utilities were involved with cogeneration projects, they could plan the addition of new capacity in small increments as they see how demand is evolving. Cogeneration thus offers utilities a means through which to escape dependence on dubious long-term electricity demand forecasts, and hence the risk of having the excess generating capacity--the situation at present in many industrialized countries--which results from overbuilding large plants with long lead times.

The amount of electricity that might be produced through cogeneration depends on the technology deployed. With the steam turbine system, the most familiar cogeneration technology, the power-generating potential of industrial cogeneration is quite limited. However, with alternative electricity intensive cogeneration technologies such as the gas turbine, the gas turbine/steam turbine combined cycle, or the diesel engine, the potential can be quite large.[45] For the United States, the cogeneration potential based on these technologies in six basic materials processing industries characterized by relatively steady process steam loads has been estimated to be equivalent to about one-quarter of total 1980 electricity generation.[46] The recent commercialization of steam-injected gas turbines for cogeneration applications, which extends the economic advantages of gas turbine cogeneration to

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*Through excessive rates charged for backup power, refusal to provide backup power, and/or refusal to purchase at fair rates electricity produced in excess of on-site needs.

variable steam load applications, could significantly increase the overall cogeneration potential.[47]

TWO INTEGRATED EXAMPLES: SWEDEN AND THE UNITED STATES

In this section, we describe what the ongoing structural changes and exploitation of opportunities for energy productivity improvement could mean for Sweden and the United States, two highly industrialized but quite different modern economies.

Sweden is a small, affluent country with a cold, northern European climate. It has an open economy with a sizable basic materials-processing sector dominated by steel and paper. It is often regarded as a very energy-efficient country. The United States, on the other hand, is a large, affluent country with diverse climates that range from essentially subtropical climates to climates as cold as those of the northernmost reaches of Europe. The United States also has one of the world's most energy-intensive economies, measured in terms of either per capita energy use or energy use per dollar of GNP. Yet, despite the wide differences in these economies, our analysis indicates that in each case it would be feasible, through end-use oriented energy strategies, to reduce per capita energy use by about a factor of two, even with continued economic expansion.

An End-Use Oriented Energy Future for Sweden

In 1982, 60 percent of all energy used in Sweden was imported oil; hydro power supplied 14 percent; biomass, 12 percent; nuclear power, 9 percent; and coal, 5 percent. Primary and final energy use per capita were 5.5 kilowatts (kW) and 4.7 kW, respectively; and per capita GDP was $11,900 in 1982 dollars. Swedish energy policy follows from a 1981 energy policy decision of the Swedish Parliament, which calls for reduced dependence on oil and no use of nuclear power after the year 2010. The energy supply system, according to the decision, should be based on sustainable domestic, and preferably renewable, energy sources, with the least possible environmental impact; energy demand should be at the lowest possible level compatible with economic and social goals.

A study published in 1981 explored what might be meant by lowest possible energy demand compatible with economic and social goals.[48] While the use of different task definitions and fuller exploitation of the technical opportunities for energy efficiency improvements might have led to projections of lower energy demand levels for the long term, the results of this 1981 study nevertheless suggest future energy demand levels far below those indicated by conventional wisdom, with far-reaching implications for investments in the energy system. In this section, we summarize the demand analysis presented in the 1981 study, the results of which, it should be stressed, are not forecasts of what will happen but of what could happen.

Methodology: The analysis was separated into three parts to facilitate the identification and understanding of the most important factors that bear on future energy demand. First, the overall development of society was described and structural changes that might have a major influence on future energy demand were identified. Here, physical and economic parameters for energy-intensive activities were treated explicitly, so that the reader could more easily grasp the implications of changing these parameters. Next, the potential impacts of new energy-efficient and now cost-effective end-use technologies were explored. Finally, consideration was given to the amount of time required for such technology to come into common use.

The total energy demand under different assumptions was obtained by multiplying the activity levels in all sectors by their corresponding energy intensities and then summing up to cover all activities in society. The overall volume of activity was treated as an exogenous variable. A twenty-four-sector, input-output model of the Swedish economy was used to associate a specific level and mix of private and public consumption with output from different production sectors in society, thereby resulting in a consistent description of the economy. The model was extended to cover the total economy, including investments and foreign trade.

Energy intensities for 1975 were identified for the twenty-four sectors. To quantify the impact of the use of new energy-efficient and now cost-effective technology, two sets of specific energy demand numbers were identified. One set refers to presently known best technology, or technology that is, or is judged to be, economical in the present marketplace. (Presently known best technology is not the most energy-efficient existing technology in the narrow engineering sense. Less energy demand could always be achieved, but at an extra cost.) The other set refers to advanced technology where some success is assumed in the ongoing research and development efforts to improve end-use efficiency. Again, advanced technology is judged to be in a cost bracket of economic interest and does not represent a technological limit. In both cases, estimates of cost effectiveness are based on energy prices fixed at present levels.

Since the level of future economic growth is uncertain, calculations of total energy use were performed for various combinations of end-use technologies and different levels and mixtures of final demand for goods and services. Attention was focused on those cases in which the overall volume of goods and services is 50 percent and 100 percent higher than in 1975, with a mix of activities similar to that of 1975.

In areas in which saturation effects are apparent, activity levels are expected to increase, but not to the same degree (in percentage terms) as the overall volume of goods and services. The same is true for cases in which obvious physical limitations constrain activity. Specifically, it is assumed that for a 50 percent (100 percent) increase in the overall volume of goods and services: commercial floor space would increase 30 percent (60 percent); automobile travel would increase only 25 percent (50 percent), because of time constraints on auto travel; the volume of truck freight would increase only 12.5 percent (25 percent), owing to the ongoing shift away from materials-intensive production; the production of paper and pulp would be limited to a 50 percent increase, because of the limited availability of the required feedstock from Swedish forests; iron and steel output would increase only 23 percent (44 percent), because of stiff foreign competition to the export-oriented Swedish iron and steel industry.

Energy-Efficient Technology: In this section, we highlight some of the energy-efficient end-use technologies assumed in the Swedish study.

Buildings: The government's 1978 ten-year retrofit plan provides the basis for the assumed presently known best retrofit technology. The level of energy use achieved in a single family home (the house of Mats Wolgast, Table 1) outside the city of Uppsala was taken as an example of presently known best technology for new residential buildings. Comparable energy performance is now achieved with some commercially available prefabricated houses (e.g, version two of the Faluhus, Table 1). The energy performance of the Folksam building in Stockholm, completed in 1977, is taken to be representative of presently known best technology for new office buildings, although much better performance has been demonstrated in the Harnosand building, constructed in 1981 (see Table 4). Enhanced heat recovery in ventilation air and more efficient use of hot water was assumed for the level of advanced technology.

The results of the analysis for buildings are summarized in Table 8, which shows that associated with a 50 percent (100 percent) increase in the consumption of goods and services, final residential energy use would decline to 35 percent (43 percent) of the 1975 level were current best technology to be used, and to 25 percent (30 percent) of the 1975 level were advanced technology to be employed. Similar reductions would be realized for commercial buildings.

Table 8
SCENARIOS FOR PER CAPITA FINAL ENERGY USE
IN SWEDEN AND THE UNITED STATES (In kW)

	Sweden[a]			United States[b]		
		w/GDP per capita			w/GDP per capita	
	1975	up 50%	up 100%	1980	up 50%	up 100%
Residential	1.40	0.34	0.41	1.50	0.57	0.57
Commercial	0.53	0.15	0.16	0.88	0.34	0.34
Transportation				2.90	1.33	1.53
Domestic	0.89	0.55	0.65	--	--	--
Int'l. bunkers	0.18	0.10	0.11	--	--	--
Industry	2.40	1.60	2.00	3.70	2.01	2.16
Totals	5.30	2.80	3.30	9.00	4.20	4.60

(a) Based on advanced technology. If introduced at the rate of capital turnover, this technology could become average technology by 2015-2020. See Johansson et al., "Sweden Beyond Oil--The Efficient Use of Energy" *Science* 219 (1983): 355.

(b) Realized in the year 2020. It is assumed that as the capital stock turns over and grows, investments are made in the most energy-efficent technologies available that are judged to be cost-effective. Most of the technologies considered are commercially available today; a few are advanced technologies which could be available within about a decade. See J. Goldemberg et al., *Energy for a Sustainable World* (New Delhi: Wiley-Eastern, 1987).

Transportation: The average fuel economy of automobiles on the road in Sweden is presently 10.5 liters per 100 km (22 mpg), and 1981 models averaged 9 liters per 100 km (26 mpg). Automobiles now on the market with a fuel economy of about 5 liters per 100 kilometers (47 mpg), were selected to represent presently known best technology. Further improvements can be achieved through the use of more efficient engines, lighter materials, and more efficient transmissions, and through reduced air drag and rolling resistance and other factors. Advanced designs which achieve fuel economies of 3 liters per 100 km (79 mpg) (see Table 5) were assumed to represent advanced technology.

Based on a combination of technical and organizational improvements, the energy intensity of truck freight was assumed to be reduced 22 percent and 48 percent for best available and advanced technology, respectively.

Table 8 shows for transportation that, associated with a 50 percent (100 percent) increase in the consumption of goods and services, final energy use would decline to 80 percent (93 percent) of the 1975 level were current best technology to be used, and to 61 percent (71 percent) of the 1975 level were advanced technology to be used.

Industry: The largest industrial energy users are the paper and pulp industry and the iron and steel industry, accounting for two-fifths and one-fifth of total industrial energy use, respectively.

The analysis of the pulp and paper industry is based on a set of model Swedish plants designed in 1977.[49] These designs represent what should have been ordered for new plants at that time. Since these plants were designed before the 1979-80 energy price increases, we assume a further 12 percent reduction in the energy intensities for paper and pulp production to characterize best available technology. Energy intensities with advanced technology were taken to be 18 percent less than with best available technology. Overall, energy intensity for the pulp and paper sector would be 54 and 62 percent lower than in 1975 were presently known best technology and advanced technology to be introduced, respectively.

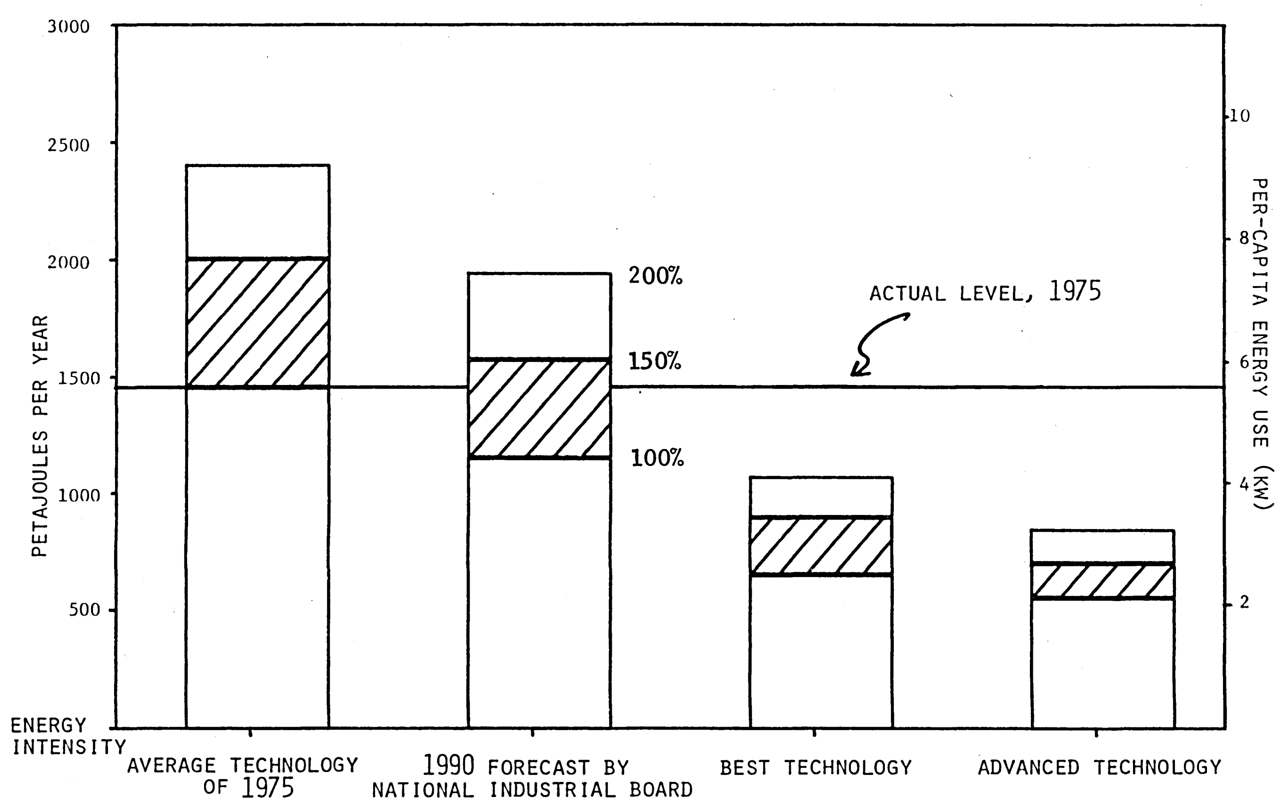
For the iron and steel industry, the analysis is based on the four alternative industrial structures described for the Swedish steel industry (see Table 6). The measure of presently known best technology was taken to be an average of the energy performances for structure I (based on current steel industry plans for the 1980s) and structure II (the same as structure I except with full exploitation of the potential for heat recovery); that for advanced technology, an average of the energy performances of structure III (Elred technology) and structure IV (Plasmasmelt technology). Energy use in the Swedish steel industry in 1976 would have been lower by about one-third and one-half had best available and advanced technology been used, respectively.

For other industries, a variety of generic energy-saving technologies (e.g., added insulation, heat recovery, heat pumps, new lighting technology, variable-speed motor control devices) were considered. For the industrial sector as a whole, a shift in the mix of output toward less materials-intensive products, along with the adoption of more energy-efficient technology, would, for a 50 percent (100 percent) increase in the consumption of goods and services, result in a reduction in final energy use by industry to 81 percent (100 percent) of the 1975 level with present best technology and to 67 percent (83 percent) with advanced technology.

Total Energy Demand: Alternative future energy demand scenarios for Sweden are summarized in Table 8 and Figure 5, which show the results in relation to the existing situation in 1975 and to a forecast for 1990 made by the National Industrial Board. Compared to a total energy use of 1,400 petajoules (PJ) in 1975, the level of annual energy use with a 50 percent (100 percent) increase in the level of goods and services production would be about 910 PJ (1,100 PJ) with best available technology and 720 PJ (870 PJ) with advanced technology. This overall reduction in energy demand would be accompanied by an increase in electricity's share of final demand from 19 percent in 1975 to 32 to 35 percent with these alternative, more energy efficient futures.

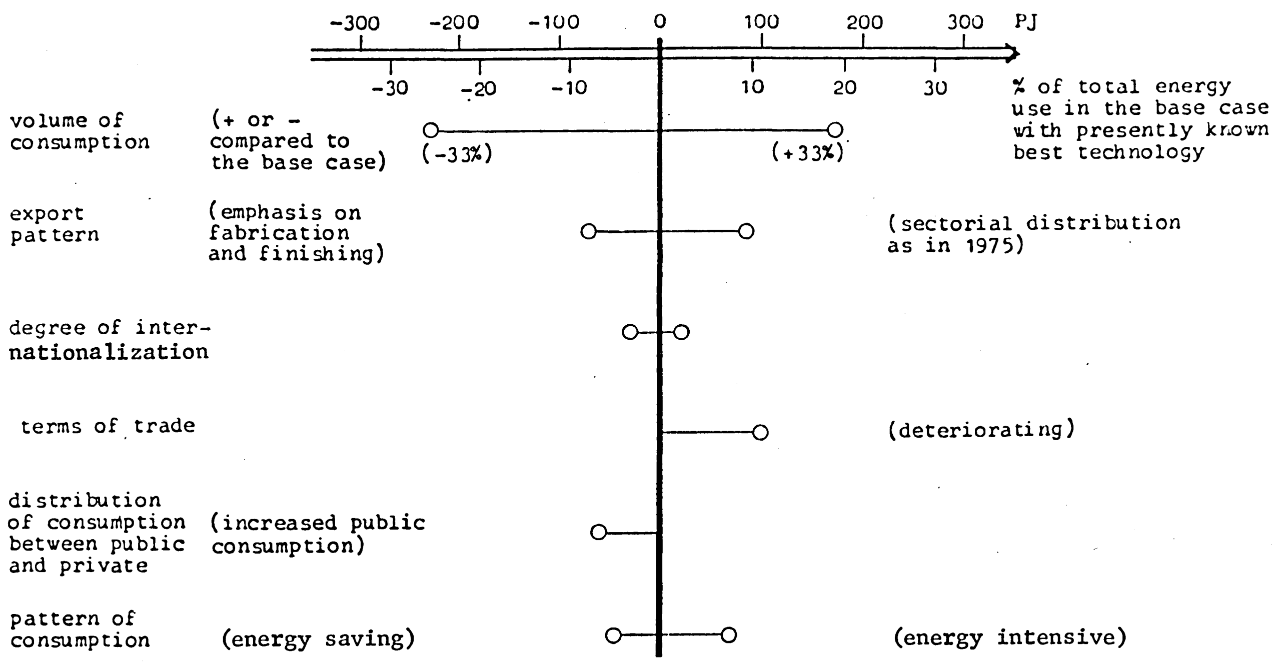
Figure 5

FINAL ENERGY DEMAND IN SWEDEN FOR FOUR LEVELS OF ENERGY INTENSITY AT 100, 150, AND 200 PERCENT OF THE 1975 LEVEL OF CONSUMPTION OF GOODS AND SERVICES



Sensitivity Analysis: The sensitivity of the level of future energy demand to changes in parameters other than the overall level of goods and services and the choice of end-use technology was explored. Figure 6 displays the results of this sensitivity analysis relative to a base case with a 50 percent increase in the overall level of goods and services and best available technology.

Figure 6
SENSITIVITY ANALYSIS SHOWING THE CHANGES IN FINAL ENERGY DEMAND FOR SWEDEN ASSOCIATED WITH ALTERNATIVE ASSUMPTIONS, RELATIVE TO A BASE CASE SCENARIO, WHERE THE OVERALL LEVEL OF CONSUMPTION OF GOODS AND SERVICES IS 1.5 TIMES THE 1975 LEVEL AND PRESENTLY KNOWN BEST END-USE TECHNOLOGY IS DEPLOYED



The mix of exports was one parameter whose effect was investigated. Sweden traditionally has been a large exporter of basic materials such as steel, iron ore, paper, and pulp. In the base case, the present contribution of each of these to total exports was assumed to change from 1975 levels: for fabrication and finishing, from 38 to 53 percent; for iron and steel, from 7.4 to 3.4 percent; for paper and pulp from 14 to 11 percent; for transportation, from 8 to 5 percent; for chemicals, from 5 to 7 percent; and for shipbuilding, from 5.5 to 1.5 percent. If instead the mix of exports were the same as in 1975, annual energy use would be about 10 percent higher. Alternatively, annual energy demand would be reduced by about 8 percent were all the increase in exports to be shifted to engineering products (i.e., products involving considerable value added in fabrication and finishing).

International economic relations, which for a small open economy like Sweden are important, also were considered. Two important indicators of these relations are internationalization and terms-of-trade. The degree of internationalization (total imports divided by total domestic demand) was assumed to be 47 percent in the base case. If this index were as low as 29 percent (the 1975 level), energy demand would be 3 percent lower; energy demand would instead be 3 percent higher than in the base case were the degree of internationalization to be 65 percent. This indicates that the energy intensities of exports and imports are roughly equal (excluding energy items). The impact of a deterioration in the terms-of-trade would be more significant, with a 1.5 percent per year decline potentially increasing energy demand by 10 percent.22* This situation would be unacceptable in the long run, since it implies that by 2000 exports of $4 in value would be required to pay for every $3 of imports.

A doubling of public expenditures (which would require that private spending be 26 percent higher than in 1975 in order to keep the overall level of economic output 50 percent higher) would reduce energy demand by 6 percent.

To illustrate the importance of the mix of household expenditures, the total increase in household expenditures was alternatively assigned to the six most and the six least energy-intensive of thirteen categories. Total energy demand was higher and lower by 8 percent in the former case and latter case, respectively.

Uncertainties: Aside from the effects of different levels of economic output and the choice of end-use technology, uncertainties relating to key assumptions in this analysis could possibly change the estimates of future energy demand presented here.

A future society with a mix of personal consumption expenditures only modestly changed from that of today was assumed. This assumption ignores the possibility that more resource-conserving life styles may become more widespread.

Constant coefficients were assumed for the input-output analysis and only very limited consideration was given to changes in the mix of industrial output (e.g., the production of the pulp and paper and iron and steel industries was assumed to be constrained). Hence, the study only partially accounts for the ongoing shift in industrial production to less materials-intensive and less energy-intensive activities.

Also, the relative prices for the factors on production were assumed to remain fixed at 1975 levels. The base year for this analysis (1975) predated the second oil price shock, and in 1975 the economy had not yet fully

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*Terms-of-trade is the ratio of the index of export prices to the index of import prices. In 1979, the Swedish government commission set up to study the consequences of dispensing with nuclear power projected that terms-of-trade would deteriorate by 1.5 percent per year during the 1980s.

adjusted to the oil price increases of 1973 and 1974. Therefore, the projected demand for energy-intensive products may not be fully consistent with today's price structure, although this shortcoming may be partially compensated for by the assumption that the growth in demand for buildings and transportation services would be less than the growth in the total volume of goods and services.

These considerations suggest that, in spite of the uncertainties and simplifications in the approach used, the calculated levels of total energy demand are likely to be high rather than low.

The Issue of When: The third step of the analysis centered on the pace of energy efficiency improvement.

Assuming that the more energy-efficient options will be chosen if they are found to be cost effective, the pace at which new technology is adopted will depend on the rate of turnover of the capital stock for major energy-using activities. Machinery and equipment in industry have economic lifetimes of ten to twenty years, depending on the sector of industry. The automobile fleet is renewed approximately every fifteen years. The structural components of buildings have very long lifetimes, fifty to one-hundred years, but many energy-related installations in buildings have shorter lifetimes, for example, ten to thirty years for furnaces, windows, ventilation systems, and facades. Using these rates of capital turnover, the impact on average specific energy demand levels was calculated for both presently known best technology and advanced technology, which were assumed to be routinely installed beginning in 1985 and 1995, respectively. It was concluded that, if this more efficient technology were introduced at the rates of normal capital turnover, best available technology might become average technology around the turn of the century and the present advanced technology might become average technology during the first decade of the next century.

While many of the new energy-efficient technologies will be introduced in this manner, it is unlikely that all the more energy-efficient technologies would be adopted solely in response to market forces, given major institutional obstacles to widespread utilization of the most cost-effective technological choices. This is especially true for energy efficiency improvements for buildings and the automobile. Hence, new government policies will be needed to overcome these obstacles and thereby realize the full potential savings.

Conclusions: Our end-use analysis shows that at the 1975 level of consumption of goods and services, per capita final energy use could be reduced cost effectively from the actual 1975 value of 5.4 kW to 2.6 kW with presently known best technology and to 2.1 kW with advanced technology. For a 50 percent (100 percent) increase in the consumption of goods and services, final energy use would instead be about 3.5 kW (4.2 kW) using best available technology and 2.8 kW (3.3 kW) using advanced technology.

These findings imply that, despite the fact that it has no known fossil fuel resources, it would be feasible for Sweden to meet its long-term energy needs largely with domestic resources (mainly biomass and hydropower), and to do so without pushing these resources to limits that precipitate significant ecological damage.[50]

An End-Use-Oriented Energy Future for the United States

With per capita primary energy use averaging 10.4 kW in 1984, two-and-one-half times that for Western Europe and Japan and ten times that for developing countries, the United States sets a global standard in energy use that would be difficult to achieve for the majority of the world's population. However, the energy price shocks of the 1970s have sharply curbed the growth in energy use in the United States. The rate of primary energy use in 1984 was 10 percent lower than the peak rate of 11.6 kW in 1973, even though per capita GNP was 17 percent higher in 1984 (see Figure 7). In what follows, we show that the potential for decoupling energy and economic growth is actually far greater than is suggested by this recent experience, taking into account both ongoing structural changes in the economy and opportunities for energy efficiency improvement.

Methodology: Total final energy demand E_f for the scenario is obtained through the sum:

$$E_f = \sum_{\text{all } j} (\text{activity level, activity } j) \times (\text{energy intensity, activity } j)$$

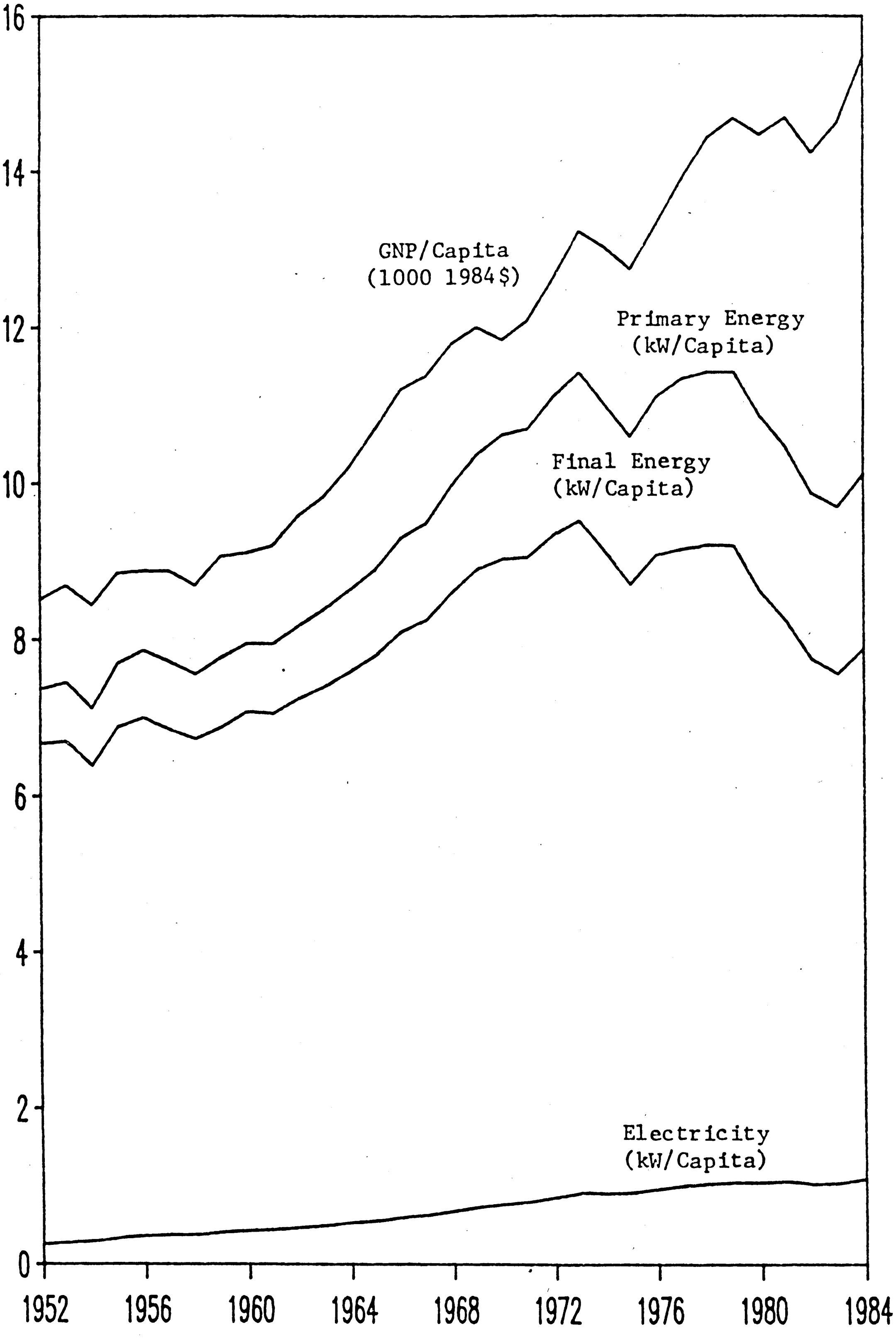
The projected activity levels for major energy end uses in this sum are based on extrapolations of recent trends, while the energy intensities assigned to these activities involve the use of energy-efficient technologies introduced at the normal rates of turnover and expansion of the energy-using capital stock.

The scenario is focused on the year 2020. That date is sufficiently far in the future that it would be feasible to bring into wide use energy-efficient technologies now available or in an advanced state of development. Yet it is sufficiently close that it has a bearing on energy decision-making today.

The resulting scenario should be regarded neither as indicating the upper limit on the potential impact of energy efficiency improvements on the U.S. economy nor as a forecast of what will happen. The improved technologies considered are either already commercially proven or are based on prototypes or advanced developments that could lead to commercial products in the near future. In all cases, efficiencies are far below thermodynamic limits, and in most instances, possibilities for further improvement are apparent.

At the same time, while the scenario is based on end-use technologies which are judged to be cost effective, the economy will not necessarily adopt these improvements automatically. The scenarios probably overstate what can be accomplished through market forces acting alone. New public policy initiatives are needed to facilitate a transition to energy-efficient technologies.

Figure 7
RECENT TRENDS IN THE UNITED STATES IN VARIOUS ENERGY USES AND IN GNP



The Economic and Demographic Context: Alternative economic scenarios are considered, involving 50 percent and 100 percent increases in per capita GNP between 1980 and 2020. In the former, the average annual growth rate for per capita GNP is 1 percent per year--the average for the period from 1973 to 1983. In the latter, it is 1.7 percent per year, which is consistent with a return to 4 percent unemployment and the average labor productivities for the goods- and services-producing sectors for the period from 1953 to 1978. If the population grows from 228 million in 1980 to 296 million in 2020 (the middle population series projected by the U.S. Census Bureau in 1982), this implies that aggregate GNP would grow for the two scenarios at average annual rates of 1.7 and 2.5 percent per year respectively between 1980 and 2020.

Modeling Future Energy-Using Activities: In the residential and transport sectors, the major energy-using activities are relatively few in number, fairly well defined, and, for the most part, well established. (Most less well defined, rapidly changing activities in these sectors contribute little to overall energy demand.) For these sectors, long-term projections are made of each of the major energy-using activities, and the associated energy intensities are indicated explicitly, based on the analysis of end-use technologies presented above and discussed in more detail elsewhere.[51] For the commercial and industrial sectors, a more aggregated approach is taken.

Future Energy Demand by Sector: Given the above assumptions, energy futures can be defined, sector by sector.

Residential Sector: We assume for both scenarios that the number of households increases from 82 million to 119 million, arising from a 30 percent increase in the population and a decline in the average household size from 2.8 persons today to 2.4 persons in 2020. Further, we assume that the average heated floor space per household remains constant at the 1980 level of 139 square meters (slightly higher than the average of 135 square meters for the period from 1980 to 1984), which implies an increase of one-sixth in the living space per capita. We also assume for both scenarios 100 percent saturation for all major household appliances except air conditioning. For air conditioning, the assumed saturation level is only two-thirds, because in most parts of the country where air conditioning is not already common, it is not needed. The assumption that the level of major energy-using amenities in the home becomes independent of GNP greatly simplifies the analysis in a manner involving little loss of generality, given the already high average level of major energy-using amenities in the home. The household amenities which are sensitive to income are characterized either by low power usage (e.g., home entertainment systems and computers) or high power usage but very low load factors (e.g, power equipment for the shop and yard) and are of minor consequence in the overall household energy budget.

Because the housing stock turns over so slowly, it is estimated that three-fifths of the housing stock built before 1981 will be standing in 2020, accounting for two-fifths of all houses at that time. For space heating retrofits in those houses that are fuel heated, a 30 percent average reduction between 1980 and 2020 is assumed for the required output of space heating systems. This norm is based on the average measured cost-effective savings achieved for the twenty-nine houses retrofitted in the 1981 utility-based Modular Retrofit Experiment described above.[52] No corresponding savings are assumed for existing electrically heated houses, which are characterized by much lower heat losses.

The space-heat load norm for new houses built after 1990 is assumed to be the average climate-adjusted measured energy performance achieved for the ninty-seven houses built under Minnesota's Energy Efficient Housing Demonstration Program, a 50 percent reduction in space-heating requirements relative to typical new construction (see Table 1).

Besides these heat load reductions, the norm for heating system performance in 2020 is assumed to be equal to that of the most efficient furnaces and heat pumps commercially available in 1982: an annual fuel utilization efficiency of 95 percent for condensing gas furnaces and a seasonal average coefficient of performance of 2.6 for electric heat pumps.[53] For end uses other than space heating, energy performance in 2020 is assumed to be that of the most efficient technology commercially available at present.[54]

With these assumptions, aggregate final residential energy use per capita would be reduced by three-fifths. Per household would be reduced by two-thirds, corresponding to an average rate of reduction of 2.7 percent per year from 1980 to 2020. While this is a rapid rate, it is much less than the average of 7.6 percent per year for the U.S. housing stock in the period from 1978 to 1982.[55]

Commercial Buildings: The growth of the commercial buildings sector is closely coupled to the expansion of the service sector. Here the linear relationship established in the period from 1970 to 1979 between commercial floor space and service sector employment is assumed to persist, so that in both scenarios the volume of commercial floor space would expand 50 percent from 1980 to 2020.

As in the residential case, it is estimated that three-fifths of the commerical building stock built before 1981 will be standing in 2020, when it would account for two-fifths of the total. For retrofits of these buildings, a 50 percent reduction in final energy use per square meter is assumed relative to 1980 levels, based on the results of a Solar Energy Research Institute survey designed to ascertain the judgments of experienced architects and engineers as to the retrofit potential by the year 2000.[56]

The assumed norm for buildings constructed after 1990 is based on the average energy performance of the three buildings designed in a life cycle cost minimization exercise of the American Institute of Architects Research Corporation (see Table 4).

With these assumptions, final energy use per capita for commercial buildings in 2020 would be less than two-fifths of that in 1980 (see Table 8).

Transportation: The potential for demand growth for automobiles and light trucks, which account for 60 percent of transport energy use in the United States, is small. Since the average American already spends an hour a day in the car, future levels of light-vehicle use are not likely to increase much with per capita GNP. Thus, it is assumed for both scenarios that the number of light vehicles per adult remains constant at the present level of 0.8 and that the average light vehicle is driven the same amount as today (17,000 km per year).

In contrast to the automotive situation, there is no evidence that air travel demand is reaching saturation levels. In accordance with a relationship to GNP established in the period from 1970 to 1979, it is assumed that air travel per capita increases between 1980 and 2020 2.1-fold (3.3-fold) as per capita GNP increases 50 percent (100 percent).

The mix of freight between truck and rail is assumed to remain fixed at the 1980 level, and the total volume of freight is assumed to grow slightly more slowly than GNP, as it did in the 1970s.

The average light vehicle on the road in 2020 is assumed to have a fuel economy of 3.1 liters per 100 km (75 mpg). This fuel economy could be achieved with present technology in lightweight cars (e.g., a VW Rabbit diesel modified with reduced aerodynamic drag, reduced rolling resistance, an open chamber instead of a prechamber diesel, a continuously variable transmission, and a 16 percent weight reduction to 775 kg[57]) or with advanced technology in heavier cars (e.g., the design for a 1,360 kg car with an adiabatic diesel engine described by Cummins Engine Company and NASA Lewis researchers--see Table 5).

For both truck and air passenger transport, it is assumed that by 2020 the energy intensity is reduced 50 percent, taking into account the opportunities for energy efficiency improvement described earlier.[58]

Under the above conditions, total energy use per capita in transportation in 2020 would be reduced to 45 percent (52 percent) of the 1980 level if per capita GNP were increased 50 percent (100 percent) (see Table 8).

Industry: Modeling the mix of future industrial activities and the energy demand associated with these activities is an especially difficult task for the United States, because the U.S. industrial base is diverse and because it is being fundamentally reshaped as the country continues the transition to a post-industrial economy. Thus, the mix of industrial activities several decades from now can be expected to be quite different from today's. Because of this difficulty, the industrial sector is modeled here with relatively aggregated descriptors.

Consider first the the growth of total industrial output. If in the future industrial output grows 0.83 times as fast as GNP, as it did in the 1970s, reflecting the ongoing shift from goods to services production, the industrial sector as a whole would expand 1.8-fold (2.3-fold) as per capita GNP increases 50 percent (100 percent) between 1980 and 2020.

Within the industrial sector, different growth paths are assumed for (1) the energy-intensive basic materials processing (BMP) and the mining, agriculture, and construction (MAC) subsectors, and (2) the value-added intensive fabrication and finishing activities that make up "other manufacturing" (OMFG). For the BMP and MAC subsectors of industry, it is assumed that output grows only as fast as population, or 30 percent from 1980 to 2020, reflecting the shift away from the use of basic materials, a shift which appears to imply saturation in the use of basic materials (i.e., zero growth in kilograms consumed per capita) in the United States.[59] Together with the assumption made about total industrial output growth, this implies that the OMFG subsector would grow 2.3-fold (3.3-fold), while per capita GNP increases 50 percent (100 percent) from 1980 to 2020.

To these assumptions about output growth is added the assumption that the energy intensity of each subsector (in megajoules [MJ] per dollar of value added) is reduced by half between 1980 and 2020. The corresponding average improvement rate of 1.7 percent per year is less than the average of 2.6 percent per year for the period from 1973 to 1984 (see Table 9). It is also well within the range of practical feasibility in light of both the large potential for energy efficiency improvement in industry discussed briefly above and in more detail elsewhere,[60] little of which has been captured to date, and the three-fold increase in the average price of final energy for industry from 1972 to 1982,[61] which provides a strong incentive to exploit the untapped potential for much greater efficiency. Moreover, even in historical periods when prices were low and falling, energy requirements per ton of typical basic materials declined at rates of the order of 1 percent per year (see Table 10), owing to the fact that industrial innovations typically improve all factors of production simultaneously.[62]

Table 9
HISTORICAL AND PROJECTED TRENDS FOR SELECTED INDUSTRIAL INDICATORS: AVERAGE ANNUAL GROWTH RATES
(Percent per Annum)

Indicator	Average Historical Rate (1973-1984)	Scenario (1980-2020)
GNP	+ 2.5	+ 2.5
Industrial GPO		
MAC	+ 0.7	+ 0.7
BMP	+ 0.5	+ 0.7
OMFG	+ 2.5	+ 3.0
Total industry	+ 1.5	+ 2.1
Final		
Fuel use[a]	- 2.0	- 1.1
Electricity use	+ 1.9	+ 1.3
Energy use[a]	- 1.6	- 0.7
Final energy use/GNP	- 4.1	- 3.2
Rate of change in final energy intensity due to efficiency improvements	- 2.6	- 1.7

(a) Includes industrial wood use.

These assumptions imply that final energy demand in industry would decline at an average rate of 0.7 percent per year (0.9 percent per year) from 1980 to 2020 were per capita GNP to increase 50 percent (100 percent) in this period. For comparison, final energy use in industry declined at an average rate of 1.6 percent per year from 1973 to 1984 (see Table 9).

If it is also assumed for both scenarios that the historical trend toward electrification continues, increasing from 11 percent in 1980 to 25 percent in 2020, then aggregate electricity demand by industry would grow at an average annual rate of 1.1 percent per year (1.3 percent per year) from 1980 to 2020 were per capita GNP to increase 50 percent (100 percent) during this period.

Table 10

TRENDS IN THE PRE-ENERGY CRISIS ENERGY INTENSITIES FOR BASIC MATERIALS PROCESSING INDUSTRIES IN THE UNITED STATES

		Average Rate of Decline in Energy Use per Ton Produced (percent per year)	
Material	Period	Final Energy[a]	Primary Energy[b]
Raw steel	1947-1971	1.41	1.19
Portland cement	1947-1971	1.17	1.09
Chlorine[c]	1947-1971	0.40	0.42
Aluminum[d]	1954-1971	2.83	1.89
Paper[e]	1954-1971	0.14	-0.11

Source: Taken from R. Williams, E. Larson, and M. Ross, "Materials, Affluence, and Industrial Energy Use," *Annual Review of Energy* 12 (1987): 99.

(a) With electricity counted as 3.6 mj per kWh of electricity consumed.

(b) Electricity is counted as that amount of fossil fuel energy required to produce it.

(c) For 1 ton of chlorine plus 1.13 tons of caustic soda in 50 percent solution.

(d) Electricity use per kilogram of primary aluminum declined 0.4 percent per year during this period.

(e) For purchased fuels and electricity only.

Integrated Results: The results of the demand analysis are summarized in Table 8, which shows that, by pursuing opportunities for energy efficiency improvement throughout the economy, per capita final energy use (at levels of per capita GDP 50 percent [100 percent] higher than 1980 levels) could be reduced between 1980 to 2020, from 9.0 to 4.2 kW (4.6 kW). This overall reduction in energy use would be accompanied by slow growth (0.3 to 0.5 percent per year) in the aggregate demand for electricity and electricity's share of final demand would increase from 12 percent in 1980 to between 21 and 22 percent in 2020.

The energy intensities assumed for commercial buildings and automobiles and the growth of the basic materials processing sector of industry are perhaps the most uncertain quantities underlying this projection.

For commercial buildings, there has been a tendency to underestimate new building loads, especially for office computers and the air conditioning systems required for their support.[63] It is uncertain whether this is a long-term problem or will become unimportant with technological advances that reduce the energy intensity of computers and other office machinery. However, if the average final energy intensity of commercial buildings were 1.0 GJ per square meter per year, two-thirds of the 1980 average and double what was assumed, aggregate U.S. energy use in 2020 would be up only 7.5 to 8 percent.

The 75 mpg fuel economy assumed for the automobile in 2020 could be achieved for large cars only with the commercial success of certain advanced technologies (e.g., the adiabatic diesel engine). With present technology, 75 mpg could be achieved only with some down-sizing. In light of uncertainties about future technologies and the American love affair with large cars, the 75 mpg target might not be achieved even with supportive new public policies. However, if the average fuel economy were 50 mpg instead of 75 mpg, U.S. energy use in 2020 would be only 4 to 4.5 percent higher.

For industry, it was assumed that the BMP and MAC sectors grow in proportion to the population. While there is good evidence that consumption will grow this fast, there are strong indications that, for at least the period to the year 2000, aggregate production of basic materials will not grow at all.[64] If this expected trend should continue, so that there would be no net growth in the BMP and MAC sectors between 1980 and 2020, the result would be aggregate energy use being 9 to 10 percent lower than that projected for 2020.

This sensitivity analysis shows that the finding that final energy use can be reduced in half at the same time that per capita GNP doubles is not very sensitive to changes in some of the boldest assumptions involved.

Since typical new energy-using buildings and equipment tend to be much more efficient than the existing stock, many efficiency improvements will be made naturally as the capital stock turns over. Accordingly, because of technological changes already set in motion, it is very likely that the recent downward trend in per capita energy use (Figure 7) will continue. But to bring about a reduction in per capita energy use of the magnitude indicated here (Table 8) new policy initiatives would be required, both to make markets work better than they do today and to correct inherent market shortcomings--issues to which we now turn.

PUBLIC POLICY ISSUES

Our analysis has shown that there are many opportunities for large and cost-effective reductions in energy use. While some of these opportunities will be exploited under present market conditions, the dramatic reductions in energy demand identified here as feasible would probably not be realized without directed government action. This is attributable to institutional obstacles to energy efficiency improvement, including improper energy price signals; inadequate consumer information about energy savings opportunities and their cost effectiveness; unavailability of capital for investments in energy efficiency; and, generally, the difficulties that arise when the industrial infrastructure needed to deliver energy efficiency improvements is not yet well established.

To overcome these problems and facilitate the adoption of cost-effective energy-saving technologies it will be necessary to implement broad-gauged policies designed to realize a more evenhanded treatment of investments in energy efficiency and energy suppy in the marketplace, and policies targeted at particular sectors or end uses. A more extensive discussion of policy options for promoting end-use energy strategies is presented elsewhere.[65] Here we merely sketch some of the highlights of what we think is called for.

Among broad-gauge policy options, economic efficiency would be improved were energy prices to properly reflect the marginal costs of bringing forth new energy supplies. It is also important to create a more predictable investment climate for investments in energy efficiency by bringing stability to the consumer oil price, which has fluctuated wildly in alternate spasms of shock and glut since the oil embargo of 1973. This might be accomplished if the governments of oil-consuming countries were to levy excise taxes on oil that would vary with the world oil price and general inflation so as to keep consumer prices constant or slowly rising in real terms. It is also desirable to eliminate the subsidies that promote energy supply expansion. Such market-distorting subsidies facilitate the flow of capital resources to energy supply, making it scarcer for alternative investments.

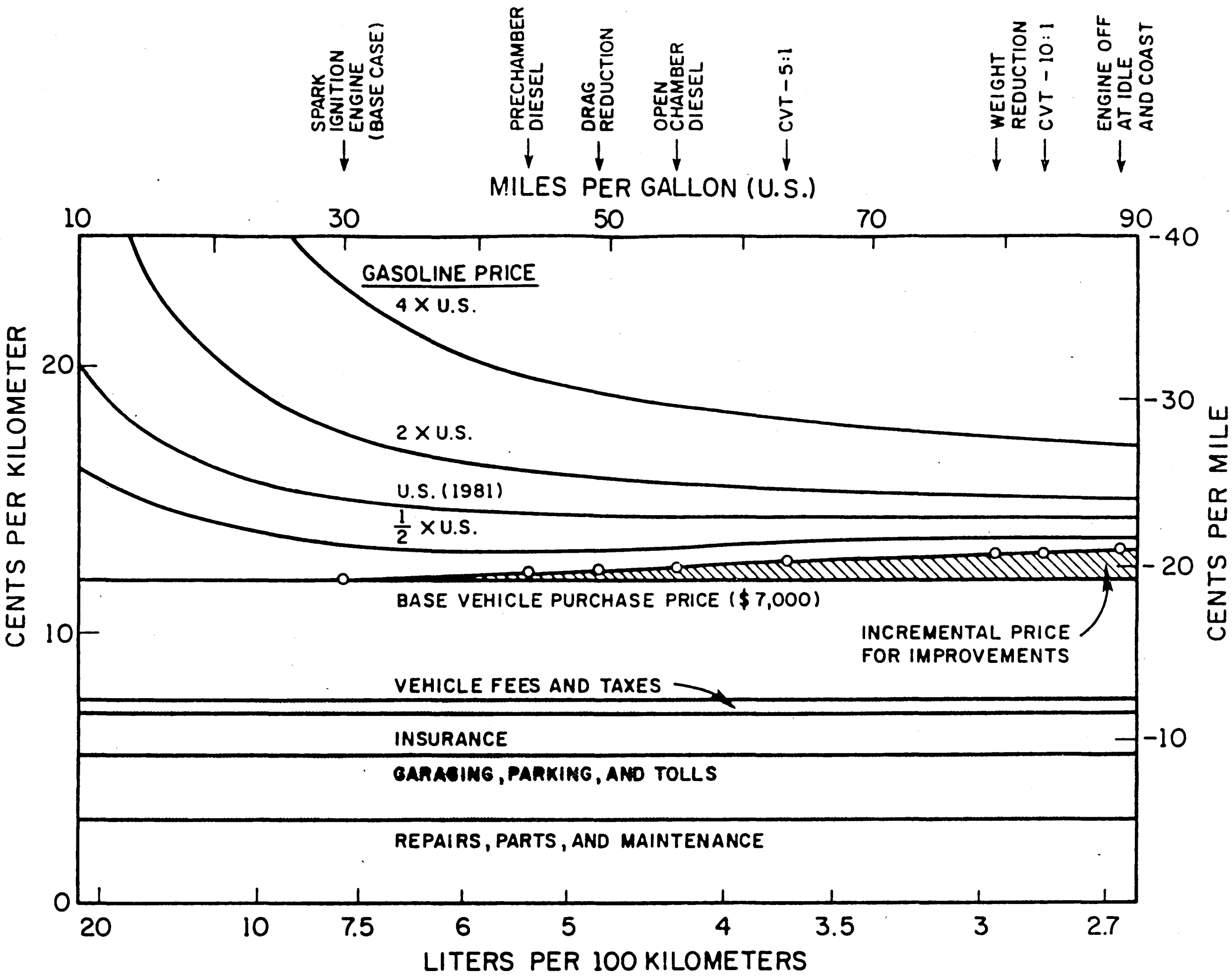
There are also important roles for government in improving the flow of information to consumers about the energy performance and cost effectiveness of alternative energy end-use technologies. For example, laws requiring the labeling of energy performance information may be desirable, for automobiles, for consumer appliances, and even for houses (both new and existing), say, at the time of sale.

Regulation of energy performance can also be an important policy instrument for promoting energy efficiency improvement. Regulation can be especially important in generating social benefits that are not likely to be realized with the price mechanism alone. A case in point involves automotive fuel economy.

A shift to super-mpg cars throughout the industrialized world would lead to large reductions in the dependence of the industrialized market economies on imported oil, resulting not only in direct oil savings but in reduced costs for oil not saved as well, as a result of a lower world oil price.[66] Market forces acting alone would probably not be adequate to bring about such a shift, in part because over a wide range of fuel economy improvements the savings in reduced fuel costs is approximately offset by the extra first costs incurred in making the fuel economy improvements (see Figure 8). In addition, for fuel economies better than about 8 liters per 100 km (30 mpg), the cost of fuel is only a small fraction of the total cost of owning and operating a car. Since the individual consumer would thus be little motivated to seek high fuel economy, although society as a whole would be better off if he or she did, some form of market intervention to promote high fuel economy (e.g., fuel economy standards or "gas-guzzler" taxes) may be desirable.

Figure 8

TOTAL COST OF OWNING AND OPERATING A CAR IN 1981 VERSUS FUEL ECONOMY*



*The energy performance values used to construct these curves are based on computer simulations of modifications of the VW Rabbit (gasoline version) as the base case.

From F. von Hipple and B. Levi, "Automotive Fuel Efficiency: The Opportunity and Weakness of Existing Market Incentives," *Resources and Conservation* 10 (1983): 103.

While the subsidy is a politically attractive instrument for promoting particular technologies, subidies should be used cautiously. One of the most serious shortcomings of subsidies that target particular technologies is that that they can stifle innovation by excluding innovations that are not defined in the qualifying rules--an especially serious problem for the diverse range of technologies associated with energy end-uses. Moreover, institutional obstacles can often be removed with less costly market interventions--by improving the flow of information, by making capital more readily available, etc. Subsidies should be restricted to the pursuit of social goals that cannot readily be met otherwise. Because the market is inherently incapable of looking after the needs of the poor and after the long-term, energy efficiency investments needed by the poor and research and development are prime targets for subsidies.

Public policy should foster the development of an industry that markets energy efficiency the way energy supplies are marketed today--an industry that provides information, financing, and installation services relating to energy efficiency improvements and stands behind its services. Efforts to convert utilities from being simply purveyors of energy supplies into purveyors of energy services would be steps in this direction, as would efforts to develop entirely new energy service industries.

While many policy reforms are needed, the required efforts are certainly not draconian and would probably require much less government intervention than what is usually called for in the way of massive subsidies to facilitate an energy supply oriented path to the post-petroleum era.

CONCLUSION

The discussion in this paper indicates that, because of ongoing structural shifts in their economies and the opportunities for using energy more efficiently, it would be technically and economically feasible to reduce per capita energy demand by about 50 percent in Sweden and the United States while considerably increasing per capita consumption of goods and services.

Much of what we have learned from our analyses of the Swedish and U.S. situations is probably applicable to most other industrialized countries as well, especially to many of the OECD countries. In light of the paucity of data available to us concerning patterns of energy use in industrialized communist countries, the extent to which our findings are relevant to the Council of Mutual Economic Assistance (CMEA) countries is less certain. But since average per capita energy use levels are comparable in OECD and CMEA countries, while the levels of amenities made possible by energy are probably higher, on the average, in the West than in the East, it may be true that what can be achieved in countries like the United States and Sweden is an existence proof of what can be achieved in any industrialized country.

Low energy demand futures offer considerable flexibility in putting together the energy supply mix, obviating the necessity of pushing all energy supply options to the limit. Low energy demand futures make it possible to avoid or reduce dependence on the more troublesome supply options, thereby reducing the scope and intensity of those global problems (carbon dioxide-induced climate change, nuclear weapons proliferation, etc.), the seriousness of which increases with the overall level of dependency on particular energy sources.[67]

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NOTES

1. M. Ross, E. Larson, and R. Williams, "Energy Demand and Materials Flow in the Economy," Center for Energy and Environmental Studies (Princeton, N.J.: Princeton University, 1985).

2. E. Larson, R. Williams, and D. Bienkowski, "Material Consumption Patterns and Industrial Energy Demand in Industrialized Countries," Center for Energy and Environmental Studies report 174 (Princeton, N.J.: Princeton University, 1984).

3. See note 1 above.

4. R. Williams, G. Dutt, and H. Geller, "Future Energy Savings in U.S. Housing," *Annual Review of Energy* 8 (1983): 269.

5. G. Dutt et al., "The Modular Retrofit Experiment: Exploring the House Doctor Concept," Center for Energy and Environmental Studies report 130 (Princeton, N.J.: Princeton University, 1982).

6. See note 4 above.

7. F. Sinden, "A Two-Thirds Reduction in the Space Heat Requirements of a Twin Rivers Townhouse," *Energy and Buildings* 1 (1978): 243.

8. See note 4 above.

9. Ibid.

10. T. Johansson et al., *Perspectives on Energy: On Possibilities and Uncertainties in the Energy Transition*, report to the Swedish 1981 Energy Commission, Ministry of Industry, DsI 1983:18 (Stockholm: Liber Forlag, 1985), in Swedish.

11. M. Ross and S. Whalen, "Building Energy Use Compilation and Analysis (BECA) Part C: Conservation Progress in Retrofitted Commercial Buildings," *Proceedings of the August 1982 Summer Study of Energy Efficient Buildings* (New York: Energy Information Center, 1983).

12. Energy Information Administration, U.S. Department of Energy, *Nonresidential Buildings Energy Consumption Survey: 1979 Consumption and Expenditures Part 2: Steam, Fuel Oil, LPG, and All Fuels* (Washington, D.C.: U.S. Government Printing Office, 1983).

13. Solar Energy Research Institute, *A New Prosperity: Building a Sustainable Energy Future*, SERI Solar/Conservation Study (Andover, Mass.: Brickhouse, 1981).

14. International Energy Agency, *Energy Balances of OECD Countries* (Paris: Organization for Economic Cooperation and Development, 1984).

15. F. von Hippel and B. Levi, "Automotive Fuel Efficiency: The Opportunity and the Weakness of Existing Market Incentives," *Resources and Conservation* 10 (1983): 103.

16. S. Fawcett and J. Swain, "Prospectus for a Consumer Demonstration of a 100 MPG Car," Battelle Memorial Institute paper, Columbus, Ohio, 1983.

17. See note 15 above.

18. Volvo, "Volvo LCP 2000--Light Component Project," Volvo Personvagnar AB, S-405 08, Gothenburg, Sweden, 1984.

19. E. Horton and W. Compton, "Technological Trends in Automobiles," *Science* 225 (1984): 587.

20. See note 18 above.

21. See note 16 above.

22. R. Sekar, R. Kamo, and J.C. Wood, "Advanced Adiabatic Diesel Engine for Passenger Cars," SAE Technical Paper Series 840434, International Congress & Exposition, Detroit, Mich., February 27-March 2, 1984.

23. Office of Mobile Source Air Pollution Control, "Perspective on Pure Methanol Fuel for Transportation," Environmental Protection Agency, Ann Arbor, Mich., 1982.

24. A. Neitz and F. Chmela, "Results of MAN-FM Diesel Engines Operating on Straight Alcohol Fuels," in *Proceedings of the International Symposium on Alcohol Fuels Technology* (Sao Paulo, Brazil: Guaruja, 1980).

25. See note 22 above.

26. F. von Hippel, "U.S. Transportation Energy Demand," Center for Energy and Environmental Studies report 111, Princeton University, Princeton, N.J., 1981.

27. Ibid.

28. M. Ross, "Industrial Energy Conservation," *Natural Resources Journal* 24 (1984): 369.

29. R. Solow, "Technical Change and the Aggregate Production Function," *The Review of Economics and Statistics* XXXIX (1957): 312; and C. Berg, "Energy Conservation in Industry: The Present Approach, the Future Opportunities," report prepared for the President's Council on Environmental Quality, Washington, D.C., 1979.

30. E. Gyftopoulos, L. Lazaridis, and T. Widmer, *Potential Fuel Effectiveness in Industry*, report to the Energy Policy Project of the Ford Foundation (Cambridge, Mass.: Ballinger, 1974).

31. Annual Bulletin Steel Statistics for Europe, 1980.

32. G. Hane et al., "A Preliminary Overview of Innovative Industrial Materials Processes," report prepared for the U.S. Department of Energy by the Pacific Northwest Laboratory, PNL-4505, UC-95f, Richland, Wash., 1983.

33. L. Riechert, "The Efficiency of Energy Utilization in Chemical Processes," CES 29 (1974): 1613.

34. A. Ronn, "Laser Chemistry," *Scientific American* 238 (1979): 114.

35. See note 32 above.

36. H. Lonsdale, "Membrane Separation in the 1980s," Bend Research, Inc., Bend, Oreg., 1982.

37. See note 32 above.

38. W. Carnahan et al., *Efficient Use of Energy: A Physics Perspective* vol. 25, American Institute of Physics Conference Proceedings for the American Physical Society's Summer Study on Technical Aspects of Efficient Energy Utilization, 1974.

39. See note 18 above.

40. J. Birchall and A. Kelly, "New Inorganic Materials," *Scientific American* 248 (1983): 88.

41. A.D. Little, Inc., "Energy Efficiency and Electric Motors," prepared for the Office of Industrial Programs, U.S. Federal Energy Administration, Washington, D.C., 1976.

42. N. Mohan, "Techniques for Energy Conservation in AC Motor-Driven Systems," report prepared for the Electric Power Research Institute, EPRI EM-2037, Palo Alto, Calif., 1981.

43. D. Ben-Daniel and E. David, "Semiconductor Alternating Current Motor Drives and Energy Conservation," *Science* 206 (1979): 773.

44. D. Zegart, "AC Drive Costs Plummet, Spur HVAC Applications," *Energy User News*, March 26, 1981; and J. Barber, "Drive Prices Continue to Drop; Manufacturers Reducing Failure Rate," *Energy User News*, October 3, 1983.

45. R. Williams, "Industrial Cogeneration," *Annual Review of Energy* 3 (1978): 313.

46. M. Ross, "Energy Consumption by Industry," *Annual Review of Energy* 6 (1981): 379.

47. E. Larson and R. Williams, "Steam-Injected Gas Turbines," Center for Energy and Environment Studies report 200, Princeton University, Princeton, N.J., 1985.

48. See P. Steen et al., *Energy: For What and How Much?* (Stockholm: Liber Forlag, 1981), in Swedish. Summarized in T. Johansson et al., "Sweden Beyond Oil: The Efficient Use of Energy," *Science* 219 (1983): 355.

49. Ibid.

50. Ibid.

51. See J. Goldemberg et al., *Energy for a Sustainable World* (New Delhi, India: Wiley-Eastern, 1987).

52. See note 5 above.

53. See note 4 above.

54. See American Council for an Energy Efficient Economy, "The Most Energy Efficient Appliances: Fall-Winter 1984-1985," Washington, D.C., 1984.

55. Energy Information Administration, "Residential Energy Consumption Survey, Consumption and Expenditures, April 1982 through March 1983," DOE/EIA-0321/1(82), Department of Energy, Washington, D.C., 1984.

56. See note 13 above.

57. See note 15 above.

58. See note 26 above.

59. See note 2 above.

60. See note 51 above.

61. Energy Information Administration, "Price and Expenditure Report 1970-1982," DOE/EIA-0376(82), Department of Energy, Washington, D.C., 1985.

62. See note 29 above.

63. L. Norford et al., "Monitoring the Energy Performance of the Enerplex Office Building: Results of the First Year of Occupancy," Center for Energy and Environmental Studies report 203, Princeton University, Princeton, N.J., 1985.

64. See note 1 above.

65. See note 51 above.

66. R. Williams, "A Global End-Use Energy Strategy," this volume, figure 1.

67. Ibid.

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