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The Long Time Scales of Human-Caused Climate Warming: Further Challenges for the Global Policy Process

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conference

The Timing of Climate Change Policies

The Long Time Scales of Human-Caused Climate Warming:
Further Challenges for the Global Policy Process

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Conference Presentation

October 10-12 2001

The Westin Grand Hotel

Washington, DC



PEW CENTER
Global CLIMATE CHANGE



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Further Challenges for the Global Policy Process**

Jerry D. Mahlman

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**Presented at the Pew Center Workshop on
The Timing of Climate Change Policies**

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Executive Summary

In 2001, the Intergovernmental Panel on Climate Change's (IPCC) Third Assessment Report revealed important increases in the level of consensus concerning the reality of human-caused climate warming. The scientific basis for global warming has thus been sufficiently established to enable meaningful planning of appropriate policy responses to address global warming. As a result, the world's policymakers, governments, industries, energy producers/planners, and individuals from many other walks of life have increased their attention toward finding acceptable solutions to the challenge of global warming. This laudable increase in worldwide attention to this global-scale challenge has not, however, led to a heightened optimism that the required substantial carbon dioxide (CO₂) emissions reductions deemed necessary to stabilize the global climate can be achieved anytime soon. This fact is due in large part to several fundamental aspects of the climate system that interact to ensure that climate change is a phenomenon that will emerge over extensive time scales.

Although most of the warming observed during the 20th century is attributed to increased greenhouse gas concentrations, because of the high heat capacity of the world's oceans, further warming will lag added greenhouse gas concentrations by decades to centuries. Thus, today's enhanced atmospheric CO₂ concentrations have already "wired in" a certain amount of future warming in the climate system, independent of human actions. Furthermore, as atmospheric CO₂ concentrations increase, the world's natural CO₂ "sinks" will begin to saturate, diminishing their ability to remove CO₂ from the atmosphere. Future warming will also eventually cause melting of the Greenland and Antarctic ice sheets, which will contribute substantially to sea-level rise, but only over hundreds to thousands of years. As a result, current generations have, in effect, decided to make future generations pay most of the direct and indirect costs of this major global problem. The longer the delay in reducing CO₂ and other greenhouse gas emissions, the greater the burden of climate change will be for future life on earth.

Collectively, these phenomena comprise a "Global Warming Dilemma." On the one hand, the current level of global warming to date appears to be comparatively benign, about 0.6°C. This seemingly small warming to date has thus hardly been sufficient to spur the world to pursue aggressive CO₂ emissions reductions. On the other hand, the decision to delay global emissions reductions in the absence of a current crisis is essentially a commitment to accept large levels of climate warming and sea-level rise for many centuries. This dilemma is a difficult obstacle for policymakers to overcome, although better education of policymakers regarding the long-term consequences of climate change may assist in policy development.

The policy challenge is further exacerbated by factors that lie outside the realm of science. There are a host of values conflicts that conspire to prevent meaningful preventative actions on the global scale. These values conflicts are deeply rooted in our very globally diverse lifestyles and our national, cultural, religious, political, economic, environmental, and personal belief systems. This vast diversity of values and priorities inevitably leads to equally diverse opinions on who or what should pay for preventing or experiencing climate change, how much they should pay, when, and in what form. Ultimately, the challenge to all is to determine the extent to which we will be able to contribute to limiting the magnitude of this problem so as to preserve the quality of life for many future generations of life on earth.

I. Introduction to Human Caused Climate Warming and the “Global Warming Dilemma”

This essay discusses the global implications of the very long time scales associated with human-caused climate warming (popularly termed “global warming”). This emphasis is chosen because of the major impact that these long time scales will likely have on how policy decisions concerning this problem will be determined over the 21st century.

In 2001, the Intergovernmental Panel on Climate Change's (IPCC) Third Assessment Report, *Climate Change 2001*, revealed important increases in the level of consensus concerning the reality of human-caused climate warming during 21st century and beyond (IPCC, 2001). In addition, at the request of U.S. President George W. Bush, the National Research Council of the U.S. National Academy of Sciences issued a special report, *Climate Change Science: An Analysis of Some Key Questions*, that endorsed the key conclusions of the IPCC assessment (NRC, 2001). The scientific basis for global warming has thus now been sufficiently established to enable meaningful planning of appropriate policy responses to address global warming.

The key IPCC (2001) climate-change conclusions are as follows. Atmospheric carbon dioxide (CO₂) concentrations have increased from about 280 parts per million by volume (ppmv) in the 18th century to nearly 370 ppmv in the year 2002 and are expected to at least double pre-industrial concentrations before the end of the 21st century. The global average surface-air temperature has increased over the 20th century by about 0.6°C. IPCC specifically noted that “There is new and stronger evidence that most of the warming over the last 50 years is attributable to human activities.” These strong conclusions have led to an increasing level of public recognition of the reality of the global warming problem. The IPCC report also stated that the global average surface-air temperature is projected to increase by an additional 1.4°C to 5.8°C over the period 1990 to 2100. This range incorporates both “best-guess” estimates of the present uncertainties in climate model projections and of the uncertainties in policy decisions concerning future CO₂ and other greenhouse gas emissions into the atmosphere over this century.

The IPCC and earlier national climate change assessments have described a number of likely detrimental impacts on humans and other organisms if global warming plays out consistently with the increasingly accepted international scientific consensus (IPCC, 2001; USGCRP, 2001). Listed below are some regional climate changes generally expected with a global warming of the magnitude projected by IPCC (2001).¹ Land areas are very likely to warm more than oceanic areas. Although projected atmospheric CO₂ concentrations are very likely to increase global mean surface-air temperatures, high northern latitudes are very likely to warm more than other areas. Summertime, mid-continental areas are likely to be considerably less able to sustain current levels of soil moisture. In moist subtropical areas such as the southeastern United States, the summertime heat index (a measure of the additional feeling of heat discomfort due to high atmospheric moisture concentrations) is likely to add roughly another 50 percent sense of warming, beyond the increased temperature warming effect (Delworth, et. al, 1999). Hurricanes are likely to become more intense, and contribute considerably more rainfall to land surfaces. Perennial Arctic sea ice is likely to virtually disappear. The overturning circulation of the Atlantic Ocean is likely to

weaken noticeably, although models differ in the magnitude and timing of the weakening. Sea level is virtually certain to rise due to thermal expansion of the warming world ocean and to increasing melting of glaciers and ice sheets.

Other speculated effects of climate change are frequently discussed but are far more scientifically uncertain at this time. Examples include more extra-tropical storms, more frequent and more intense El Niño episodes, planet-saving negative feedbacks (natural processes that might sharply reduce the level of climate warming), a CO₂-enhanced greening of the biosphere, more frequent hurricanes and tornados, and catastrophic weather extremes. At this time, none of these often-cited potential outcomes are consistent with the current state of scientific knowledge about climate change. It is very likely, however, that we will continue to hear such assertions, often to buttress a particular point of view about policy preferences.

It is useful to point out here that the science of global warming indicates that a quadrupling of atmospheric CO₂ over pre-industrial levels would essentially double the climate changes expected from the anticipated CO₂ doubling. This magnitude of global warming, under today's best estimates, is expected to lead to very substantial negative impacts on earth's life systems. Why is this relevant? To date, most assessments of future warming and the subsequent impacts are based upon an assumed doubling of atmospheric CO₂. Although stabilizing CO₂ concentrations at a doubling remains achievable with the implementation of highly focused global CO₂ emissions reduction policies over the 21st century, to a reasonable approximation, quadrupling of CO₂ is where earth is headed under "business as usual" scenarios. Therefore, most assessments of global warming have not yet considered its full implications.

Because of the increasingly strong conclusions concerning the expected effects of human activities on the warming of earth's climate, the world's policymakers, governments, industries, energy producers/planners, and many other walks of human life have increased their attention toward finding acceptable solutions to the challenge of global warming. This laudable increase in the worldwide attention given to this global-scale challenge has not, however, led to a heightened optimism that the required substantial CO₂ emissions reductions can be achieved anytime soon. The global warming problem contains many distinct facets that combine to produce what is called here the "Global Warming Dilemma."

The Global Warming Dilemma can be summarized in the following manner. On the one hand, large increases in atmospheric CO₂ concentrations have occurred, with considerably more "in the pipeline." Yet, the magnitude of documented warming to date is comparatively small, about 0.6°C. This relatively benign increase is hardly enough to warrant major concerns about the viability of earth's life systems. Thus, there has been little motivation today to resort to a major effort to reduce global CO₂ emissions. On the other hand, delaying major CO₂ emissions reductions until substantial climate warming occurs would very likely "wire in" the world to globally troublesome global warming for many centuries. Thus, the science tells us that major efforts will be required to restrain the final global warming to relatively benign levels. Therefore, the

choices are quite daunting: we can make very large policy commitments now with little visible short-term payback, or we can delay policy action indefinitely (the de facto current strategy), with very large coping and adaptation costs decades and centuries from now. This is the Global Warming Dilemma.

The Global Warming Dilemma arises because of a number of separate physical effects operative in the climate system, the sum of which are almost guaranteed to shape future policy deliberations in important new ways. The Global Warming Dilemma is due to a variety of key scientific findings. The science of global warming tells us that the phenomenon is real, its presence in the climate data is very likely consistent with model calculations, and its most serious effects will be delayed for decades to centuries. Reducing the likelihood of serious damage from climate change requires substantial emissions reduction of CO₂ and other greenhouse gases over the first half of this century, but with most of the damage-reducing benefits accruing to future generations of earth's inhabitants. This long delay in such benefits introduces many challenges to the global policy response process. These challenges will continue to produce considerable barriers to achieving meaningful policy actions, nationally and globally. A number of the factors that combine to produce the Global Warming Dilemma are listed below.

- The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) has been thwarted by a major difficulty in achieving timely implementation of the required social, political, technological, and infrastructure commitments on the roughly one-decade time scale outlined in the protocol. In short, the protocol requires the developed nations to achieve reductions of CO₂ emissions into the atmosphere due to burning of carbon-based fossil fuels (coal, oil, and natural gas), but without similar commitments from countries in the developing world whose CO₂ emissions are growing at a rapid rate. Also, it is now clear that even complete implementation of the Kyoto Protocol will not come close to mitigating the projected global warming. On the contrary, full implementation of the Kyoto Protocol would only imply a relatively modest reduction in the rate of increase of global atmospheric greenhouse gas concentrations. Yet, four years after the initial UNFCCC Conference of the Parties in 1997, we still are without globally meaningful new CO₂ emissions reduction policies. Much of the blame for this is properly cast toward the inability of U.S. policy to be guided by the science of climate change that has been mainly led by U.S. scientists over the past three decades. However, even if the United States abandons its ill-advised resistance to implementation of the Kyoto Protocol, there are still major political, technological, and socioeconomic barriers to implementation of a cohesive and significant reduction of global CO₂ emissions.
- A number of policymakers worldwide have adopted the superficially reasonable position that if we can hold global CO₂ emissions constant with time, we can strongly reduce global warming to acceptable levels. This is far from the truth. The generally ignored, but invaluable, IPCC Climate Change Special Report on Radiative Forcing of Climate Change made it dauntingly clear that no such "comfort zone" would exist, even if this admittedly huge achievement of holding global CO₂ emissions constant with time were to be achieved (IPCC, 1994). Indeed, that report showed convincingly

that it would very likely require a 60-80 percent reduction in today's emissions just to keep CO₂ concentrations from rising in the atmosphere. From a sociological, geopolitical, and technological perspective, such a level of global CO₂ emissions cuts over the next several decades is exceptionally unlikely, given the continued strong global growth since in CO₂ emissions. Simply put, the major policy challenge will be how to reduce growth in CO₂ emissions in the face of continued demand for more energy in the developed nations, huge demand growth in the developing nations, and the overall demands of an increasing world population. Regardless, it is unlikely that any combination of achievable mitigation actions will produce a world in which global atmospheric CO₂ levels will always remain below a doubling of the levels at pre-industrial times.

- It is fair to note that the IPCC (2001) did assert that it is technically feasible to mitigate CO₂ emissions at a rate that would eventually stabilize CO₂ concentrations at below a doubling of pre-industrial levels. However, the IPCC authors were very well aware that actually achieving this would be very daunting on the global policy side. These insights lead to the realization that the actual level of climate warming will have to be considerably smaller than currently projected to prevent substantial future impacts on humans and most other life forms on earth. It is fair to note that many individuals remain optimistic that major reductions of greenhouse gas emissions are achievable over the next decade or two. The burden, however, remains on them to propose clear and enforceable mechanisms by which such major global CO₂ emissions reductions would be achievable.
- Scientific studies show that if, by some unforeseen spectacular mitigation breakthrough, all CO₂ and other greenhouse gas concentrations in the atmosphere were to be held constant at current levels, the earth's surface would still warm further by about 0.5-1.5°C above today's record high levels (Wetherald et al., 2001). This time lag in the realized warming is caused by the expected continued absorption of much of the warming signal by the world ocean. Indeed, it may require a thousand years to "catch up" with the warming level that would have already been observed if earth had a very shallow ocean with very small heat storage capacity (see Section 3).
- The above points make it clear that the irreducibly high amount of minimum warming already "wired in" reveals an unplanned global strategy of relying on coping and/or adaptation to a substantial climate warming, no matter what policy-makers do over the next decade or two. Thus, all anticipated benefits of future mitigation policies are much more for future humans, animals, and plants than they are for earth's current inhabitants.
- All carbon cycle models reveal a key insight: the more CO₂ that is added to the atmosphere over the next century or so, the longer newer emissions will remain in the atmosphere. This is because the relatively "fast" uptake CO₂ reservoirs (time scale of decades), such as the upper ocean and the terrestrial biosphere, will become nearly saturated with the CO₂ already added to the atmosphere (IPCC,

1994). What this reservoir saturation effect means is that the burden of the CO₂ uptake over this century increasingly will shift to the next fastest reservoirs, such as the intermediate layers of the ocean and the deeper layers of the terrestrial biosphere, a process that requires centuries. Further removal to the deepest ocean by seafloor carbonates requires very roughly a thousand to ten thousand years. Thus, as more CO₂ is added to the atmosphere, the rate at which it is removed from the atmosphere becomes progressively slower (see Section 4).

- The very slow uptake of the climate warming signal by the ocean implies a very slow, but inexorable, sea-level rise due to the slow warming of the ocean. This contribution to sea-level rise is due to the elementary fact that warmer water occupies a larger volume than colder water. All climate models, complex and simple, show global sea level rising for more than a thousand years due to this delayed ocean warming effect.
- The melting of the great Arctic and Antarctic ice sheets could contribute eventually to tens of meters of sea-level rise, arguably most of it occurring on a time scale longer than a thousand years. However, West Antarctic ice sheet melting could possibly add to sea-level rise over the next few centuries (Oppenheimer, 1998).
- Finally, the science of global warming has become increasingly solid over the past 20 years. The essence of the problem is now rather well understood. Some key uncertainties remain, none of which are likely to change the essence of our understanding of global warming. However, much of the detailed regional information that is typically sought by policymakers will likely remain elusive, thus providing still more reasons to evade commitment to globally meaningful CO₂ emissions mitigation.

These contributors to the Global Warming Dilemma make it very clear that addressing this problem meaningfully is likely to be far more daunting than is currently perceived by the policymakers, the press, and the world's educators. The subsequent sections in this essay will describe in more detail why the above-described contributors to the Global Warming Dilemma are true, and why the science behind most of the sources of this dilemma is quite solid and rather widely understood. Perspectives on lessons for policy challenges and policy barriers will be offered in Section 7.

II. Basics of the Atmospheric "Greenhouse Warming" Phenomenon

This section explains the basic science of human-caused climate warming.² It is designed to be accessible to the "educated layperson" who is not an expert in atmospheric or climate sciences, but who has some grounding in the physical sciences. The information contained here can provide an improved understanding of the reasons behind why human-caused climate change is a serious issue, why it is grounded in sound scientific principles, and why this knowledge leads to the Global Warming Dilemma. Readers who are either well versed in the science of climate change or are not particularly interested in pursuing the more difficult parts of the basic science can skip to Section 3 without significant loss of capability to understand the key points in the remaining sections.

Surprisingly, all of the physical drivers of the global warming problem are contained within the atmosphere. Despite being a region of relatively inconsequential mass, water amount, and heat capacity, it is in the atmosphere that the temperature at the earth's surface is ultimately determined. The special properties of the atmosphere define the essence of how climate warming works.

The earth is strongly heated every day by incoming radiation from the sun. This heating is offset by an equally strong infrared radiation leaving the planet. Interestingly, if Earth were without any atmosphere, and if its surface reflectivity did not change, global mean surface temperature would be roughly 33°C colder than it is today. This large difference is due to the strong atmospheric absorption of infrared radiation leaving the earth's surface. The major atmospheric infrared absorbers are clouds, water vapor, and CO₂. This strong infrared absorption (and strong reemission) effect is extremely robust. It is readily measured in the laboratory and is straightforwardly measured from earth-orbiting satellites. Simply put, adding CO₂ to the atmosphere adds another "blanket" to the planet and thus directly changes the heat balance of the earth's atmosphere.

Individuals skeptical about the reliability of global warming have correctly noted that, in terms of direct trapping of outgoing infrared radiation, water vapor is by far the dominant greenhouse gas on earth. Since water vapor dominates the current radiative balance, how can it be that CO₂ is anything other than a minor contributor to earth's absorption of infrared radiation? Part of the answer comes from the well-known modeling result that net planetary radiative forcing changes roughly linearly in response to logarithmic changes in CO₂.³ Thus, a quadrupling of CO₂ gives another roughly 1°C direct warming over the direct 1°C warming for a CO₂ doubling, valid for the extreme assumption that water vapor mixing ratios and clouds do not change.⁴ Interestingly, this approximate relationship also holds for a large extended range as CO₂ is decreased.³

It is thus hard to escape the conclusion that increasing atmospheric CO₂ concentrations provide a measurable direct addition to the atmospheric trapping of the infrared radiation leaving the surface of our planet. However, a simple comparison of the relative greenhouse efficiencies of water vapor and CO₂ quickly becomes problematic because water vapor enters the climate system mostly as a "feedback" gas.

All models and observations currently indicate that as climate warms or cools, the observed and calculated global-mean relative humidity of water vapor remains roughly constant as the climate changes, whereas its mixing ratio does not.⁵ Thus, as climate warms (cools), the holding capacity of atmospheric water vapor increases (decreases) exponentially. This is a powerful water vapor positive feedback mechanism—that is, a process that acts to amplify the original warming caused by increasing CO₂ levels. With this major positive feedback, the modeled "climate sensitivity" increases by about a factor of three to roughly 3°C.⁶ Currently, observational evidence remains generally consistent with the modeling results that project a strong positive water vapor mixing ratio feedback under approximate constancy of relative humidity as the climate changes (Oort and Liu, 1993; Sun and Held, 1996).

An additional, but smaller, positive feedback is the relationship between ice (or its absence) at the earth's surface and its reflectivity of solar radiation. In essence, if ice or snow cover melts, the surface left exposed (ground, vegetation, or water) is generally less reflective of incoming solar radiation. This leads to more absorption of the solar radiation, thus more warming, less ice and so on. This feedback is expected to become important as snow lines retreat poleward and when polar ice sheets begin to melt at their lower-latitude edges.

Inclusion of this "ice-reflectivity" feedback process in mathematical models of the climate amplifies further the calculated warming response of the climate to increased concentrations of CO₂ and infrared absorbing gases. It would also amplify any calculated cooling if ice at the earth's surface were to increase. Other kinds of feedbacks, both positive and negative, result from the interaction of land-surface properties (e.g., changes of vegetation that lead to reflectivity and evaporation changes) with climate warming/cooling mechanisms or from changes in CO₂ uptake by the biosphere. Both the ice-reflectivity and the vegetation feedbacks still remain somewhat uncertain, particularly in their details on the regional scale.

The major source of uncertainty in determining climate feedback concerns the impact of clouds on the radiative balance of the climate system.⁷ A CO₂-induced increase in low clouds would mainly act to reflect more solar radiation and would thus act to produce a negative feedback to global warming. An increase in high clouds mainly adds to the absorption of infrared radiation trying to escape the planet and would thus provide a positive feedback. A change in cloud microphysical and optical properties could go either way. Which of these would dominate in an increasing CO₂ world? We are not sure. Our inability to answer this question with confidence is the major source of uncertainty in today's projections of how the climate would respond to increasing greenhouse gases. Furthermore, it is not likely that this cloud-radiation uncertainty will be sharply reduced within the next 5 years. This is because there still remain formidable barriers in obtaining the needed cloud measurements, in preparing sufficiently comprehensive cloud models, and in formulating accurate theories of cloud behavior and cloud properties.

Although clouds dominate the climate modeling uncertainty, other key processes are also in need of improved understanding and modeling capability. An example is the effect of human-produced airborne particulates (aerosols) composed mostly of sulfate (from oxidation of the sulfur in fossil fuels) or carbon (from open fires). Sulfate aerosols are mostly reflective of solar radiation, producing a cooling effect, whereas carbonaceous aerosols in the lower troposphere mostly absorb solar radiation, producing a net heating effect. Efforts to reduce the current uncertainty are limited by inadequate measurements of aerosol concentrations and the sensitivity of climate to their radiative effects. Even more uncertain are the so-called indirect effects that atmospheric aerosols play in the determination of cloud amounts and their radiative properties.

Another key uncertainty lies in modeling the response of the ocean to changed greenhouse gases. This affects the calculated rate of response of the climate over the next several centuries. For details, see Section 3.

III. The Climate-Regulating Role of the Global Ocean

The description of the physics of global warming in Section 2 focused almost solely on the physical processes acting in the atmosphere to explain the essence of this phenomenon. Yet, as we shall see, the ocean plays a very important role in determining how the expected climate warming will evolve over this and future centuries.

Most people have experienced the mild shock of jumping into a body of water in mid-to-late spring when the air temperature is warm, only to find out that the water temperature is much colder, while the opposite can be experienced in the cooler days of early fall. This effect is mostly due to the much higher heat capacity of the ocean or a lake relative to that of the overlying atmosphere. Even in moderately sized water bodies, this produces a clear "seasonal lag" of the water temperature changes relative to the march of the seasons.

Interestingly, a perceptive observer may have also noted that lakes and swimming pools tend to cool off more efficiently than they warm up. In the fall, as the weather cools, the upper water surface cools rather quickly. However, the cooling upper water becomes denser and thus sinks efficiently to lower levels, thereby transferring the cooling effect through the entire depth. As waters warm in the spring, the highest levels of a lake can feel comfortably warm, but the unwary swimmer often experiences much colder water a short distance below the surface. In this case the spring warming heats the upper layer of the water, makes it less dense, and therefore the warmed water tends to just remain at the top without appreciable downward mixing.

A similar set of processes act over long time scales when the climate is changing. A cooling climate can rather efficiently propagate the cooling signal to the interior of the ocean. A warming climate tends to concentrate the heat in the upper levels of the ocean and actually can produce an oceanic resistance to mixing the warming signal downward. This effect can produce an early atmosphere/upper-ocean response to an atmospheric warming forced by increased greenhouse gases. The ultimately realized warming can become delayed for long time intervals because of the slow mixing of the warming into the deeper ocean.

This effect is amplified greatly in the world ocean because it has a far greater heat capacity than that of the atmosphere. Indeed, the heat-carrying capacity of the global ocean is over 1000 times greater than that of the global atmosphere. This key observation carries many implications for how the atmosphere and earth's surface can respond over time to increasing atmospheric greenhouse gases.

Suppose, for example, that only, say, the top one meter of the ocean could "feel" the atmosphere's heating and cooling effects, while the rest of the world ocean remained totally disconnected (no circulation, no mixing, no exchange with the top meter). In this case, the atmosphere/one-meter ocean system would respond within a year of a CO₂-added greenhouse warming of the climate. The upper meter of the ocean would soon be in equilibrium with the current atmospheric CO₂ amount and the time lag to equilibrium would be very short. (We used to use models like this to save computer time in global warming calculations!)

Now, suppose that our "one-meter lid" ocean is replaced with the real ocean, but with nearly infinitely fast mixing all the way to the bottom. In this case, the rate of atmospheric warming due to added CO₂ would be sharply suppressed because the modest heat capacity atmosphere would be losing its added heat to the cooler ocean with its more than 1000 times greater heat capacity. In this case, one would have to wait for some time to even be able to measure the amount of atmospheric warming. Indeed, the atmospheric warming trend would be small relative to the natural variability of global-mean surface temperature for a long time.

The real world lies between these hypothetical extremes. In reality, what we see from earth's climate measuring systems is a lower atmosphere that is warming considerably slower than an almost "atmosphere-only" planet would, but noticeably faster than it would in the "infinitely fast mixing" ocean case.

A bottom line constraint is still applicable, however. The new climate cannot be in equilibrium until the ocean is no longer warming up, all the way to the bottom. Indeed, the last degree or two of warming could take well over a hundred years beyond the time that greenhouse gas atmospheric concentrations have been stabilized, while the last few tenths of a degree warming could require over a thousand years.

Most state-of-the-art climate models of global warming suggest a slowing down of the ocean's overturning circulation, and thus less mixing of excess CO₂ into the ocean. That same slowing down phenomenon would also act to slow down the mixing of heat into the deeper layers of the ocean. This effect acts to produce an earlier warming, but a delay of the "end game" warming due to this suppression of mixing of the added heat into the interior of the ocean.

Levitus et al. (2001) demonstrated that most of the heat storage due to the warming of the twentieth century is in the ocean, and not in the atmosphere, soil, or land glaciers. This observational result is fully consistent with theoretical and modeling expectations. It is fair to note, however, the rate of the oceanic mixing that eventually fills up the huge ocean heat reservoir is a source of significant uncertainty in itself.

Oceanic mixing is also a factor in evaluating the observed 20th century warming in the context of climate-change science. The amount of global warming that has accumulated to date is primarily determined by the amount of greenhouse gases added to the atmosphere, minus "offset" negative forcing caused by factors such as sulfate particles. However, the rate at which such warming occurs is strongly dependent upon the rate at which the warmer atmosphere loses some of its added heat through mixing it into the ocean. Also, the apparent warming or cooling effects due to decade-to-century-scale natural variability and to data imperfections must be considered. Obviously, the climate model calculations are also imperfect. However, the very point of these types of studies is to evaluate the credibility of the theory-based climate models.

These difficulties explain why the level of the scientific confidence about the match between the observed 20th century warming and retrospective model calculations still has to be expressed in probabilistic terms. The author has stated that there is a greater than

90 percent chance that the observed warming to date is directly attributable to the added greenhouse gases over the 20th century (Mahlman, 1997; IPCC, 2001). The remaining “messiness” in this key calculation would be lowered by more precise climate warming measurements and more accurate modeling of cloud-feedback processes and of the mixing of the warming signal into the ocean. The confidence in this still-imperfect model-data “match” has been elevated to this 90 percent level partly because of the still-remaining lack of any alternative hypothesis that is either consistent with observations, a self-consistent theoretical framework, or a quantitative model simulation.

The multiple layers of the ocean thus will play a key role in how global warming will unfold over the next century or two. If ocean mixing does become strongly suppressed, then the atmospheric warming rate will be temporally enhanced, but the long-term delay in the final magnitude of warming will be extended even further in time.

IV. Natural Reservoirs for Atmospheric CO₂

The perceptive reader might question why scientists and policymakers are so focused on CO₂ when it is well known that other powerful greenhouse gases such as methane, nitrous oxide, lower atmospheric ozone, chlorofluorocarbons, and other manufactured molecules, in combination, are currently adding nearly as much a greenhouse warming forcing contribution as does CO₂. Indeed, this understanding is already being used as a policy tool for near-term priority setting: keep the powerful, long-lived greenhouse gases out of the atmosphere now, because it is effective and comparatively inexpensive to do so. This is a very appropriate mitigation strategy for the next decade or so. On times scales of decades and longer, however, atmospheric CO₂ concentrations will have grown further and the “easy-mitigation” gases will be gradually exiting the atmosphere. In the long run, however, CO₂ dominates everything, including the effects of the cooling sulfate particles, the substance that makes acid rain. The reason CO₂ warming overwhelms sulfate cooling is that sulfate lasts about a week in the atmosphere, while added CO₂ remains for roughly a century. Because of this difference, at today's emission rates of sulfur and CO₂, sulfur concentrations will not grow further, while CO₂ concentrations will continue to grow for centuries. The reason CO₂ levels would continue to grow for centuries at today's emission levels is that, for every unit of CO₂ emitted, about half of it is removed from the atmosphere and half stays, thus adding systematically to the atmosphere's CO₂ concentrations. As a result, the current rate of atmospheric CO₂ increase is about 0.5 percent per year, roughly 50 percent of annual global CO₂ emissions.

Superficially, a CO₂ “piling-on” rate of 0.5 percent per year seems pretty small. However, this current rate compounded gives a doubling of CO₂ levels over pre-industrial levels by the year 2100. This is actually quite significant, because all model calculations indicate that a doubling of CO₂ would produce a substantial climate change with likely significant impacts on human lives as well as most other life on earth (IPCC,

2001). This observation seriously understates the challenge for two reasons. First, the current "business as usual" growth rate of CO₂ emissions projects a tripling over today's emissions by 2100 (IPCC, 2001). Second, as subsequent paragraphs will demonstrate, the percentage of CO₂ emissions remaining in the atmosphere is expected to increase steadily with time as CO₂ concentrations continue to grow. Thus, we expect that a progressively higher fraction of CO₂ will stay in the atmosphere as time progresses. Disconcertingly, even constant CO₂ emissions would progressively result in much more CO₂ in the atmosphere. Surprisingly, to get the same 0.5 percent per year net CO₂ increase we see today, we would eventually have to emit progressively less CO₂ than we do today.

Why is this the case? As known for over a decade (IPCC, 1994; IPCC 2001), the key so-called "CO₂ sinks" become progressively less efficient as more CO₂ is added to the atmosphere. The scientific argument for this assertion is actually quite straightforward. When extra CO₂ first began to be added to the atmosphere through biomass and fossil-fuel burning, the "unburdened reservoirs" of the upper levels of the oceans and the terrestrial biosphere were able to absorb a relatively large fraction of the "new" CO₂. However, over the 20th century, more and more CO₂ has been deposited in these two "fast" reservoirs. As these fast reservoirs eventually become nearly saturated, their ability to absorb newly added CO₂ will become progressively less efficient.

Added atmospheric CO₂ acts to increase the concentration gradient of CO₂ between the atmosphere and the upper ocean, thus producing a relatively efficient exchange, at least until the upper ocean becomes nearly saturated with the added CO₂. Then the exchange of CO₂ between the atmosphere and the ocean becomes less efficient. This decreased efficiency becomes important on time scales of decades to a century. Once this occurs, the transfer of CO₂ from atmosphere to ocean becomes limited by the exchange rate of the upper ocean to the intermediate layers of the ocean, a process that is measured in centuries. With further CO₂ intrusions into the ocean on these century time scales, the intermediate layers also would become saturated, thus limiting the oceanic "escape" of CO₂ from the atmosphere to even longer times, nearly 1000 years. Finally, the excess CO₂ can only be slowly removed by dissolving seafloor carbonates (roughly 10,000 years). This very slow process governs how atmospheric and oceanic CO₂ are changed on geologic time scales, probably not applicable to the global warming problem.

There are a number of other calculated climate feedback processes that may be applicable to the oceanic uptake efficiency of excess atmospheric CO₂. It is well known, for example, that CO₂ is considerably more soluble in cold water than it is in warm water. Consider, for example, the difference in your experience of opening a slightly agitated cold carbonated beverage versus that of opening a similarly agitated warm one. Thus, warmer oceans are more resistant to dissolving atmospheric CO₂ than are colder ones. Surprisingly, this effect is not thought to be a very important one in the CO₂ ocean uptake context, due to the comparatively weak dependence of CO₂ solubility on temperature.

Another feedback process now calculated in most of today's climate models is that as cli-

mate warming occurs, the large-scale overturning of the global ocean is likely to be inhibited, thus reducing the efficiency of the overturning/mixing process that transports the excess atmospheric CO₂ into the interior of the ocean (Stouffer et al, 1989). This process may inhibit the downward oceanic mixing of CO₂ by roughly 10-40 percent. The uncertainty in this effect remains substantial, due to a number of complicating factors that limit our understanding of oceanic overturning.

There are a number of other speculated biological mechanisms that possibly could either accelerate or decelerate the process of oceanic drawing down of the excess atmospheric CO₂. Most of these are not considered likely to change our thinking substantially on this problem. The role of the terrestrial biosphere in the uptake of atmospheric CO₂ remains somewhat problematic. It is clear that added CO₂ is a "fertilizer" for many plant species, increasing their growth rates (and thus their CO₂ uptake rates), assuming requisite water and nutrients are readily available. In unmanaged ecosystems, this is often not true because the availability of water and nutrients is frequently limited. Nevertheless, CO₂ fertilization is still likely to be an important mechanism for accelerated uptake of CO₂. It has been argued, however, that net carbon storage in soils and plants can be inhibited by accelerated biomass decomposition rates in the future warmer, wetter climate, particularly so in biologically productive regions that are already warm and moist.

One place where the terrestrial biosphere is projected to be a strong candidate for acting to draw down higher levels of atmospheric CO₂ is in formerly productive regions that have been heavily deforested or cleared. In those regions, one would expect the tendency to "rebuild" lost carbon would dominate over other processes. Finally, the ultimate sink for excess CO₂ is in the weathering of terrestrial silicate rocks, a process requiring on the order of 100,000 years.

This section can be summarized by simply noting that the earth's scientific "deck" is stacked to make atmospheric CO₂ last in the future atmosphere considerably longer than it does today. Thus, the higher the levels of CO₂ in the atmosphere, the more difficult it will be to remove it if we begin to experience a climate that we no longer wish to "live" with.

V. The Inertia of the Ice Sheets of Greenland and Antarctica

One of the anticipated outcomes of global warming is a tendency to produce melting of the great ice sheets of Greenland and Antarctica. An attention-grabbing, but misleading, statistic is that these ice sheets, if completely melted, would raise sea level by roughly 70 meters.

It is clear from the geological record that ice sheets have melted and have grown. It is also clear that these ice sheet advances and declines can require tens of thousands of years to be completed. In fact, the ice sheet melting from the most recent ice age has led to a roughly 100-120 meter sea level rise from 15,000 years to 6,000 years ago

(roughly, a meter per century). Interestingly, this "recent" sea level rise occurred as a rebound effect of the recovery from the last ice age. The effect of the ice sheet growth, sea level decline, and CO₂ draw down (to 190 ppmv) at the last glacial maximum has been calculated to have produced a negative (cooling) global climate forcing of about 4 to 6 Watts/m². Interestingly, a positive (warming) 4 to 6 Watts/m² forcing of the climate is roughly what we expect for a doubling to a tripling of atmospheric CO₂. This suggests that future sea level rise due to ice sheet melting is likely to be a very lengthy, but substantial and an inexorable process.

This slow melting of the ice sheets could be sped up substantially if the long-specified "collapse" of the West Antarctic Ice Sheet (WAIS) were actually to occur (Oppenheimer, 1998). The basis for the concern is that part of the WAIS is grounded on land that is below sea level and part is in the form of floating ice shelves. If the grounded part were to become detached for any reason, this could carry the potential for up to a 7 meter addition to sea level. IPCC (2001) argues that it is very unlikely that a large sea level rise due to collapse of the WAIS could occur in the 21st century. It is useful to note, however, that collapse of the WAIS, if it were to occur, would require roughly a thousand years to carry itself to completion. From this perspective, the word "collapse" is quite misleading when heard by the non-specialist. "Slow detachment" might be a more appropriate phrase.

The Greenland Ice Sheet is expected to melt at a much faster relative rate than would the West Antarctic Ice Sheet. This is because essentially all of the highlands of Greenland would be exposed to summertime melting if, say, a 5°C high northern latitude warming were to occur within the next century or so. However, because of the greater than 3-kilometer elevation of much of Antarctica, it is expected that the warmer climate would produce greater continental snowfall, thus producing a regional net ice accumulation over the Antarctic Continent. Again, all of these processes act to produce large changes only on time scales considerably longer than a century. Thus, analogous to the warming of the world ocean, the inertia of the great ice sheets of Greenland and Antarctica slows down, and greatly extends, the sea level response to increasing concentrations of greenhouse gases.

It is important to point out, however, that the IPCC (2001) report only considered detailed sea-level rise projections out to the year 2100, thus inadvertently deflecting attention away from the real concerns about this problem. Yet, the body of the 2001 report did make a special effort to point out that sea level-rise has the potential to continue for hundreds to thousands of years in response to increased greenhouse gases in the atmosphere.

VI. Implications for Millennial-Scale Trends in Sea Level

In Section 4, we learned that emissions of CO₂ into the atmosphere, if sustained at today's high levels for much of the 21st century, have the potential to remain in the atmosphere for multiple centuries. Thus, at these high CO₂ levels, even a rapid draw down in CO₂ emissions is not accompanied by a rapid draw down of atmospheric CO₂ concentrations. Elevated atmospheric CO₂ concentrations are thus very likely to lead to elevated global temperatures for at least the centuries required to draw-down the excessive CO₂ concen-

trations back to pre-industrial levels, plus the added centuries required for the oceans to give most of their accumulated heat back to space, roughly another 500 years (as noted in Section 3).

Also, it was noted in Section 5 that the great ice sheets of Greenland and Antarctica can only melt substantially on time scales ranging from centuries to millennia. However, it is thought that the Greenland ice sheet is likely to respond within centuries, at least at its lower-elevation edges. On the shorter time scale of the 21st century, Greenland is expected to add to sea-level rise, while Antarctica is expected to produce a small net negative contribution. This is because negligible ice melting is expected at Antarctica's ice edges, while the warmer, wetter atmosphere is expected to cause a small net accumulation of snow in the continental interior.

So, what do these various facts and circumstances tell us about expected sea-level rise in response to global warming? First, it is important to note that IPCC (2001) chose to emphasize only climate change up to the year 2100. If there actually is a large reduction of global CO₂ emissions throughout the 21st Century, it is reasonable to assume that large future changes in global mean surface-air temperature would be increasingly unlikely after 2100 (even though the oceans would continue to warm for further centuries).

Note also that IPCC (2001) chose not to project sea-level rise amounts beyond the year 2100, even though its Chapter 11, Changes in Sea Level, does discuss the inevitability of sea-level rise for many centuries beyond 2100. They mention that, after 500 years, sea-level rise could range between 0.5 and 2 meters for a doubling of CO₂ and twice that if we were to reach a quadrupling of CO₂, just due to the effects of thermal expansion of the warmed seawater.

IPCC (2001) also recognized that "ice sheets will continue to react to climate change, even if the climate is stabilized." They note that a sustained 5.5°C climate warming over Greenland would melt enough of its ice sheet in a thousand years to lead, by itself, to a 3 meter sea-level rise. Note that a 5.5°C warming over Greenland is about what mid-range climate models project for a stabilization at a doubling of atmospheric CO₂, a level generally acknowledged to be difficult to stay below.

These sea-level rise projections suggest very strongly that the sea-level issue has been substantially overlooked in greenhouse gas emission mitigation negotiations to date. The policy goal of eventual stabilization of CO₂ concentrations is important, but still shortsighted, simply because it incorrectly assumes that climate would then be stabilized. This is not true. Such a major and laudable global policy achievement would still commit earth to a continually rising sea level for the next millennium, a huge and continuing challenge for humankind and the biosphere in coastal zones everywhere. This inexorable sea-level rise would be driven by the millennium-scale increases in global ocean temperature and the resultant inescapable thermal expansion of the oceans. It would also be driven by the likely tendency of the Greenland ice sheet to melt in the presence of the sustained higher temperatures, as explained above.

The bottom line is that sea-level rise is very likely to begin innocently enough at a very slow rate, pick up its rate of increase as the earth's climate system warms, and then sustain it indefinitely, due to the intrinsically long time scales of atmospheric CO₂, of the global ocean warming rate, and of the ice sheet response of Greenland and Antarctica. Thus, even a very successful greenhouse gas emissions policy may be setting up a sea-level rise "end game" that is well over 10 times longer than the roughly 150 year "setup time" we will have spent getting into this situation.

VII. Implications of the "Global Warming Dilemma" for Climate Change Policy

In Section 1, it was noted that the current scientific knowledge base creates multiple challenges for global warming policymakers to overcome before truly meaningful mitigation policies can be accomplished. In Section 1, it is called the Global Warming Dilemma. The factors leading to the Global Warming Dilemma are briefly restated here to provide a setting for examining new policy possibilities and potential policy dead ends.

- Implementation of the 1997 Kyoto Protocol agreement has been thwarted on all sides by major political and national self-interest barriers to achieving even modest levels of net global CO₂ emissions mitigation.
- Even perfect implementation of the important Kyoto Protocol will still only be a small step toward the solution of the global warming problem.
- Even if the near-term daunting policy goal of holding global CO₂ emissions constant through time were achieved, it would not come close to stopping further global warming.
- It is now widely recognized that it will be very difficult to prevent an eventual doubling of atmospheric CO₂ concentrations over the pre-industrial amounts.
- The above point shows that an "already-committed" irreducibly high warming amount has exposed an unplanned "strategy" of substantial coping/adaptation to significant climate change, almost independent of what politically and technologically acceptable mitigation strategies are established.
- Modeling studies have shown that, even with a spectacular mitigation breakthrough of holding atmospheric CO₂ concentrations at their current levels, another 0.5-1.5°C of climate warming is expected.
- Carbon cycle models reveal that the more CO₂ that we add to the atmosphere, the longer it takes for natural processes to get it back out of the atmosphere over the next several hundred years.
- The very slow oceanic uptake of the added heat due to global warming will produce a sea level rise that is "wired in" for the next thousand years and beyond.

- Polar ice-sheet melting is likely to produce substantial sea-level rise that would likely take considerably longer than would the contribution due to ocean warming.
- The science of global warming has become increasingly solid over the past 20 years. A small, but effective, minority disputes these facts, mainly by pointing out that significant details remain uncertain. Indeed, significant uncertainties do remain. The harsh reality, however, is that no viable alternative hypotheses to current global warming knowledge yet exist, in spite of major efforts to construct them. The likelihood of finding a planet-saving, substantially overestimating flaw in the climate-change science now appears to be exceptionally low, less than a 1 percent chance.

It is not difficult to see why the sum of these well understood truths inevitably lead to the harsh reality of the Global Warming Dilemma. Consider the policymakers' sincere question: "What can we do in a mitigation context to keep global warming from happening?" The blunt answer is almost nothing; climate change is well underway and it carries huge momentum. Clearly, the question needs to be restated: "What are the options available for us to manage this dauntingly difficult problem in the most globally responsible way?" In this form, the question is quite reasonable because it allows avenues for finding rational approaches for dealing with the real problem.

VIII. Personal Comments

It has been clearly beyond the province of climate scientists to offer policy "solutions" to this problem. After all, our expertise is in climate science, not technology, sociology, economics, policy, or ethics. Yet, a number of climate scientists over the past 20 years have assisted in framing out the questions, answers, and insights that science and scientists can offer to assist the difficult policymaking process. For example, widespread recognition of the hard science that has led to the daunting Global Warming Dilemma should eventually lead to a maturation of global policy deliberations, well beyond the almost Lilliputian political stances and frequently incorrect characterizations of the problem that still remain typical. In that spirit, a number of observations are offered below that may contribute to the maturation of these very difficult policy challenges.

Consider, for example, the kinds of arguments today that still dominate policymakers' exchanges and press coverage of the problem. "If we do anything meaningful now on CO₂ emissions, we will damage our economy!" "If the problem is this daunting, the science must be flawed!" "We must act now to keep global warming from advancing any further!" "Science has surely underestimated the magnitude of the terrible effects that will occur." "Science has surely underestimated the magnitude of the benign effects that will occur!" "Let's focus on scientific and political controversies; it sells newspapers and raises ratings!" Most people reading this will almost surely have heard, and maybe even agreed with, some of these perspectives. In my view all of these arguments will be eventually exposed as being wrong, flawed, or emotional, simply because they contain only partial and self-serving "truths".

So, how much do the scientific facts comprising the Global Warming Dilemma provide guidance to the world on how to respond? Quite a lot, in my opinion. Consider the following science-based, policy-relevant observations:

- There are no quick policy fixes, nationally or globally.
- If we don't begin to chip away at the problem soon, it is very likely that serious consequences will be wired in for the world of our great-grandchildren and for their great-grandchildren, etc.
- The previous item is only invalidated if essentially all of the current scientific knowledge about climate change is completely wrong.
- The odds against all of the science being so wrong as to make the problem nearly go away are now very small, less than a 1 percent chance.
- The long time scales of the problem highlighted above will inevitably change the policy debates in ways that we probably cannot yet foresee.
- The long time scales and robustness of the problem almost guarantees that our descendants in the 22nd century will, with historical perspective, see that we were actually confronted with a major planet-scale stewardship/management problem.
- They will most assuredly note how we responded, or how we did not respond to the problem.
- They will also be aware of how our decisions or non-decisions today are still affecting most aspects of their lives and their own continuing responses to the evolving challenge of human-caused climate warming.

With this clearer framing of the policy challenges, is the path to rational and sensible policy choices on CO₂ mitigation sufficiently clarified? Are we now ready to make real and binding commitments that all can agree to and all can adhere to? Probably not. Not yet, anyway. It does seem clear, however, that policymakers could make far more substantive progress if they were to be more thoroughly informed on how and why this problem is both seriously important and seriously daunting, as outlined in the previous sections. However, if policymakers were to be well grounded in these issues, would they then be able to respond much more effectively? Still, probably not. Numerous barriers to legitimate action still lurk in arenas far broader than thorough grounding in climate science, far broader than economic science, and far broader than innovative technological approaches. This next set of challenges appears to be within the realm of, for lack of a better all-encompassing term, global “values conflicts.” It is within this realm that we can see more clearly why it is that intelligent humans can perceive very different realities in the face of what physical scientists might label as clear and objective facts. We do not need to focus on distant or alien cultures to observe this phenomenon. We can see it in high-minded disagreements between Republicans and Democrats, in 5/4 Supreme Court decisions, and in international negotiations on any number of international non-climate issues, say biological

warfare or international fishing rights. We can see it in sharply divergent assertions from highly respected religious leaders. We can see it almost everywhere we look in the sacrifice of long-term goals for short-term interests and needs.

In the context of this essay, it might be helpful to frame this new set of challenges in terms of these deeply held values conflicts. Ultimately, it will be these values conflicts that must be reconciled at levels that objective science can partially guide, but certainly cannot and should not control. Simply put, scientific knowledge ordinarily does not change deeply held belief systems.

These values conflicts are an all encompassing label for the ubiquitous looming presence of sharply differing perspectives on what is important, what is treasured, and what we believe, based upon our national, cultural, religious, political, economic, environmental, and personal value systems. In short, our perceptions of "right," "appropriate," or "good" are very much influenced by our personal and group value systems. Many of us, personally and collectively, have often experienced having our most deeply held values being perceived by others as odd, wrong, or hostile, often to our bafflement.

Why are values conflicts being raised here as major challenges in dealing with the consequences of the objective science of global warming? It is because values conflicts lurk as impediments in a surprising number of the possible approaches to address the challenges of global warming. For example, economic costs of CO₂ mitigation policies are now more frequently being weighed against future economic costs of coping and adaptation to climate change. Yet, mitigation costs will likely be paid mostly by the technologically advanced wealthy nations, while coping and adaptation costs will likely be paid mostly non-financially by the poorest and most vulnerable nations. How will the world decide on a fair division of these very different costs? This is a very challenging task made even more so by these two different costs being levied against two separate human generations. It is even more challenging when one considers that these two contrasting costs deal with very different currencies: economic costs for wealthy nations and viability-of-life costs for the climate-impacted poorer nations. Clearly, such radically different measures of cost must be evaluated in very different ways than those to which we are currently accustomed.

Already values conflicts are evident between those who view human life as inherently special relative to all other life forms (anthropocentric values) and those who view humans as having a major ethical obligation as stewards of earth's environmental health (environmental values). It is clear that adherents of both of these viewpoints often regard their thinking and perspectives as being "morally sound" or "religiously correct", or even "self evident". These differing values positions also have led to very different viewpoints on who "pays" for preservation of species and ecosystems-- the humans that created the threat, or the species and ecosystems that may become non-viable in the future? Clearly, these kinds of values conflicts cannot be easily reconciled on economic grounds alone.

The above conflicts are expanded in scope when global population growth is considered. The anthropocentric viewpoint sees human population growth as either being

benign or in terms of its possible impacts on the quality of human life. The environmental viewpoint sees it as a major and growing threat to all non-human life forms. The economic viewpoint uses very different definitions of cost in the context of this problem. Again, these differing “logically correct” and “morally correct” viewpoints are not readily reconciled.

As the global warming policy debates continue to mature, with an increasing recognition of the multiple ways that values conflicts can inhibit real progress toward reducing the impact of climate change, it will become increasingly clear that global policy negotiations must mature to levels well beyond today's largely ineffective efforts. Will this happen? Who knows? It does seem, however, that it is almost inevitable that the global warming mitigation deliberations will eventually be far more oriented toward recognizing and reconciling national-scale and global-scale values conflicts than is evident today. The key question, given the momentum of the global warming problem is “when”?

I assert that progress can be greatly advanced through widespread recognition of the harsh, but true, science-based message of the Global Warming Dilemma. This, by itself, can force the policy making process to be far more reality grounded than what is evident from today's halting efforts, both in the U.S and globally. Progress can be advanced considerably further when the global-scale “values conflicts” are recognized and respected, and are also seen as a basis for beginning the very difficult process of finding values compromises that are productive and meaningful in the long run. This is likely to prove to be dauntingly difficult. However, given the importance of this century-scale global challenge, future historians will be evaluating our level of success, or lack thereof, in resolving our global values conflicts and in achieving meaningful progress on the global warming problem.

Footnotes

¹ The following phrases are used to describe judgmental estimates of confidence: virtually certain (greater than a 99 percent chance that a result is true); very likely (90-99 percent chance); likely (66-90 percent chance) (from (Mahlman, 1997; IPCC, 2001).

² Parts of this section were taken from a previous essay by the author (Mahlman, 1998).

³ It is straightforward to perform simple one-dimensional radiative/convective model calculations of the climate effects of reducing CO₂. The log-linear relationship has been found to hold down to CO₂ concentrations to as low as one sixty-fourth of pre-industrial levels. As CO₂ is decreased, the atmosphere's ability to hold water vapor collapses and the global temperatures drop sharply, leaving CO₂ as the clearly dominant greenhouse gas.

⁴ Relative humidity is the ratio (in percentage) of the vapor pressure of air to its saturation vapor pressure. The saturation vapor pressure of air, determined from the Clausius-Claperon equation of classical thermodynamics, is a strong exponential function of temperature, roughly doubling for each 10°C. Water vapor mixing ratio is the mass of water vapor of air divided by the mass of dry air; it is generally conserved for a few days following an air parcel when no condensation is present.

⁵ Relative humidity (see Footnote 4) is determined in the troposphere by the interplay among: evaporation at the earth's surface; upward transfer of water vapor (by small-scale turbulence; thunderstorm-scale moist convection; large-scale rising motion); and net removal by precipitation. Equally important is the local lowering of relative humidity in the troposphere due to adiabatic warming in regions of descending air under approximate conservation of water vapor mixing ratio. Any appeal to a sharp change in mean relative humidity in a warming climate thus implicitly hypothesizes a substantial change in the dynamical behavior of the troposphere, in this case a large change in the motions of the troposphere in response to a comparatively small perturbation to the thermodynamics of the climate system.

⁶ The term "climate sensitivity" typically refers to the level of equilibrium global-mean surface air temperature increase that the climate system would experience in response to a doubling of atmospheric CO₂ concentrations. Each model has its own climate sensitivity, almost guaranteed to be somewhat different from the unknown value for the real climate.

⁷ Clouds are effective absorbers and reflectors of solar (visible plus ultraviolet) and absorbers/re-emitters of infrared radiation. Their net effect is to cool the planet, but the effect is very small relative to the 33°C "atmosphere/no atmosphere" difference noted above. However, for projecting the smaller human-caused climate changes examined here, the effect of clouds becomes crucially important.

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Notes



On October 11 - 12, 2001, The Pew Center on Global Climate Change held a Workshop on the Timing of Climate Change Policies in Washington, D.C. This workshop brought together leading economists, scientists, policy-makers, business leaders, and others interested in climate change science and policy.

The purpose of the workshop was to investigate the appropriate timing of the world's policy response to the challenge of global climate change. The workshop produced a consensus that action on climate change needs to begin now to satisfy a variety of concerns.

A summary of the workshop proceedings, final texts of peer-reviewed papers commissioned for the workshop, and other presentation materials are available at www.pewclimate.org

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