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Climatic Constraints and Human Activities

Jesse Ausubel and Asit K. Biswas, Editors

International Institute for Applied Systems Analysis

CLIMATIC CONSTRAINTS AND HUMAN ACTIVITIES

Task Force on the Nature of Climate and Society Research
February 4–6, 1980

JESSE AUSUBEL and ASIT K. BISWAS
Editors

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PREFACE

The Task Force meeting on the *Nature of Climate and Society Research*, 4-6 February 1980, was the third major event in climate studies at the International Institute for Applied Systems Analysis. In February of 1978, a meeting was held on *Carbon Dioxide, Climate and Society* to bring together experts from around the world to assess the state of knowledge on the prospects of climate change taking place as a result of increasing injections of carbon dioxide into the atmosphere, and in particular to review work undertaken on this subject under the IIASA Energy Systems Program. The results of this conference, including both contributed papers and recommendations about prudent energy strategies and further needed research, were edited by Dr. Jill Williams and published in the IIASA Proceedings Series. In April of 1978, IIASA hosted the conjoint sessions of the *International Workshop on Climate Issues* organized by the Climate Research Board of the US National Academy of Sciences and the preparatory meeting for the World Climate Conference organized primarily by the World Meteorological Organization (WMO) of the United Nations. A report on the Workshop entitled *International Perspectives on the Study of Climate and Society* was prepared by the Climate Research Board, while the proceedings of the World Climate Conference, which was held in Geneva in February 1979, are available from the WMO. With this promising start on research on climatic questions and successfully established collaboration with outside groups, climate was included in IIASA's research plan as a subject for a possible future program. Within IIASA interest broadened from the Energy Systems Program to the Resources and Environment (REN) Area where the relationship of climate to a variety of human activities might be explored. To help define promising avenues of research with respect to climate, to explore the potential for climate-related research within IIASA, to coordinate IIASA's climate activities with outside groups, and to examine a possible role for IIASA within the World Climate Program, the REN area organized the Task Force whose meeting provided the basis for this volume.

SUMMARY

Climatic Constraints and Human Activities contains a summary essay and seven invited papers from the Task Force meeting on the *Nature of Climate Society Research*, convened in February 1980 at the International Institute for Applied Systems Analysis in Laxenburg, Austria. The introductory essay examines the differences in research methods on questions of short-term climate variability and longer-term climatic change, and identifies some important avenues for research. The first two papers, by Ausubel and Meyer-Abich, take broad looks at climate and public policy. Ausubel offers arguments from an economic point of view as to why the atmosphere is increasingly associated with developments, like climatic change, that are threatening to human activity. The paper by Meyer-Abich surveys from a political point of view the reasons that regulation of activities which could control or prevent climatic change are unlikely to take place, and why adaptation is the most likely path to be followed, especially given the current weakness of the interdisciplinary analysis of the problem of climatic change. The paper by Biswas narrows the focus and illuminates the uncertainty associated with one specific but very prominent area, the relationships between climate and crops, which one might easily assume otherwise to be a more secure area of knowledge. Three case study approaches follow, two emphasizing a geographical perspective and one a social group. Warrick's historical study of the possible "lessening" of drought impacts in the Great Plains of the United States emphasizes the need for a clear setting out of hypotheses to be tested in research on the relationship of climate and society and the need for improvements of the modeling of the overall system. Spitz develops a model of a food-producing class which is also self-provisioning, i.e., where food has a dual nature as both a basic need and as merchandise to be traded, and explores the significance of drought to such a group, with particular reference to Eastern India. Czelnai's paper on the Great Plain of the Danube Basin offers interesting

insights into the extent to which natural systems have already been transformed by man and proposes ways in which sensitivity and vulnerability to climatic factors may be defined and explored. Finally, Sergin proposes a method of estimating plausible patterns of climatic change based on the similarity between seasonal changes and climatic changes of physical fields on longer time scales.

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INTRODUCTION AND OVERVIEW

Jesse Ausubel and Asit K. Biswas

THE PROBLEM

Climate, defined as either the expected or the observed statistical character of weather over some specified period, varies on all time scales. Indeed, climate is perhaps the most variable aspect of our natural environment. Climatic variability thus introduces an important stochastic element into those human activities, such as agriculture and water resource management, that it influences. The extreme climatic events that are inevitable consequences of this variability pose particularly great risks to the successful functioning of these activities. Moreover, there is reason to believe that human activities themselves may lead to long-term climatic changes, with attendant changes in the statistical characteristics of climate and the return periods for defined risks.

Study of climate and its interactions with society is motivated by two general concerns. First, in complex, increasingly strained, interlinked, and rapidly evolving economic systems, climatic variability poses significant and changing risks. The return periods for extreme climatic events such as droughts are long relative to the current developmental time scale of society. Thus, the disastrous Sahelian drought of 1968-1973 pressed upon a far different society than did the earlier droughts of the century, and old relief plans and measures were largely inappropriate. Analysis is therefore desirable to understand the sensitivities and risks in economic and developmental policies that may lie unnoticed until after some climatic shock or disaster has revealed them in a most undesirable way. Second, it has become evident that human activities may lead to global climatic changes. A particular concern is the injection of carbon dioxide into the atmosphere as a consequence of fossil fuel combustion. While other aspects of the global carbon cycle are also extremely important from the point of view of potential climatic change, it is this link of climate to energy policy that probably accounts for the largest share of interest in climate in industrialized countries.

Climate is a classic multidisciplinary problem. Its study ranges from mathematical and physical sciences, through biological and ecological investigation, to economic and political issues. It is at one extreme a subject for basic geophysical field research and computer modeling and at the other an applied question of immediate importance to policy makers concerned with disaster relief, agricultural policy, and so forth. During recent years, attention from both the scientific and policy-making communities has been given to climate, and recommendations about programs of research and action have been made.

COOPERATION AMONG ORGANIZATIONS

The World Climate Conference (Geneva, February 1979), to which IIASA actively contributed, called for further study of the climate system and of the relationship of climate and human activities. A World Climate Program has been approved by the World Meteorological Organization (WMO) and should serve as the coordinator of the activities of several international organizations, both governmental and nongovernmental. With respect to the study of the dynamics of climate, it is expected that an activity growing out of the Global Atmospheric Research Program (GARP) of WMO and the International Council of Scientific Unions (ICSU) will be most significant. With respect to supporting study of the impacts of climate on human activities, the United Nations Environment Programme (UNEP) is expected to play a leading role. The Scientific Committee on Problems of the Environment (SCOPE) of ICSU has also shown interest in this area and is planning future activities. A number of other international organizations have also expressed interest in climate, as have numerous academic and scientific institutes in countries of IIASA's National Member Organizations (NMOs). In February 1980 IIASA's Resources and Environment Area held a Task Force Meeting on the Nature of Climate and Society Research. The meeting provided an opportunity for IIASA to coordinate its activities with the various interested groups and to identify important research topics in the area of climate and human activities in general and for IIASA in particular.

In response to comments from individual scientists and the NMOs, emphasis of climate activity at IIASA has moved from the study of global climate models and the establishment of links with major modeling institutions to an emphasis on applied questions relating climate to human activities. These questions include analysis of human activity which may influence the climate and the impact of short-term climatic variation and long-term climatic change on the environment and human activity. The Task Force Meeting and the associated planning process also raised the question of the scale of climate activity within IIASA. At one time climate was being considered as the basis of a possible "Program," a quite large effort. However, internal and external groups concurred that climate is not a suitable subject for a major IIASA program. The more modest idea of developing a core activity dealing with climate within IIASA's Resources and Environment Area and of using climate as a "cross-cutting theme" was preferred. Given its multidisciplinary character, climate might be an intelligent "user" of other IIASA research. But what types of problems and time scales should be emphasized?

VARIABILITY OR CHANGE?

In looking at research on the relationship of climate and human activities, one of the first distinctions which can be made is on the basis of time scale. For purposes of studying the impact of climate on human activity we may think of "climatic variability" as being essentially descriptive of short-term phenomena, that is the internal variability associated with any given reference period of time. The great variability of climate often misleads people into thinking that a real "change" of climate is in progress. However, by change we refer to a lasting impulsive change or consistent trend in the central tendency of climate. Studying the effects of variability about a central tendency is, in important respects, different from studying the effects of a long-term change in central tendency.

To clarify the distinction, research on climatic variability refers primarily to seasonal or annual variation, which manifests itself as periods of drought, unusually cold winters and short summers, or other consequential deviations from estimates of average values of important climatic elements. The structure of work in this field tends to be to model agricultural systems, water resource systems, or regional economies, and study the effects of some climatic impulse or shock. There is considerable possibility for historical or empirical work here. Findings on the role of variability are of interest to those who work on problems of nutrition, price fluctuations, balance of trade, disaster relief, and civil defence and to meteorological and hydrological services engaged in monitoring and forecasting. Some existing geophysical and econometric models might be adapted for policy purposes. While research on the problems associated with variability tends to focus primarily on short-term responses, critical situations, such as those arising with drought, also offer excellent opportunities to learn about underlying long-term structural features of social systems.

If a climatic change should occur on a time scale relevant to applied research, for example, an increase of the global mean temperature of between 2 $^{\circ}$C and 5 $^{\circ}$C over the next 40 to 100 years, it is likely to be the result of human activity. Thus, in looking at climatic change and human activities, we are interested in evaluating both potential sources of the change, and the consequences of the change.

Having identified possible causes of climatic change, such as carbon dioxide, oxides of nitrogen, and chlorofluoromethanes, one can look at three strategies of response: prevention (stopping emissions), compensation (allowing the emission and then trying to reduce climatic change in some other way, for example, planting fast-growing trees to absorb increasing atmospheric CO_2), and adaption to an accepted climatic change, as predicted by numerical models of the climate system or described by historic analogues.

If there is a possibility of controlling the specific cause of possible climatic change, then research is likely to focus on prevention and compensation. For each potential source of climatic change it may be possible to a greater or lesser extent to undertake cost-benefit or risk-benefit studies. For example, one may look at the value of using the stratosphere for waste disposal versus the effects of climatic change, the value of using certain fuels versus the effects of climatic change, and so on. Such studies would desirably be embedded in a larger context of, for example, comparative risks associated with energy strategies or agricultural technologies.

However, it is not necessary to identify a specific cause in order to commence examination of the impacts of climatic change. Indeed, one line of argument is that in the course of the 1970s meteorologists and atmospheric chemists have steadily presented evidence of threats to climate. Some of these have subsequently been reevaluated as probably not dangerous, for example, stratospheric flight, but the likelihood that some pervasive, cumulative human activity will change the climate appears to be growing.

In order to gain a better understanding of the potential dimensions of such environmental change, as well as to improve methods to understand it as it is specified more clearly, one might alternatively simply postulate a drastic change (or "scenario") and explore its meaning. Whatever the cause of a long-term change, the factors and the policies and actions available for consideration will not be the same set as those for variability. Most importantly, as one is faced with thinking generations ahead, technological change becomes a dominating feature in the analysis, as well as the underlying ethical issue of human interest and responsibility in nature. More specifically, for example, questions of human migration, large-scale capital investments, and environmental preservation may change significantly as functions of the time scale being considered.

Of course, whether or not a cause is posited, much greater uncertainty will also characterize the long-range evaluation of the relationship of changing climate to, for example, agriculture or ecology, and ensuing social, economic, and political analysis will be very tentative. Existing economic models are unlikely to be useful, but certain aspects of economic theory may shed light on the problem. For example, issues of common property and intergenerational equity arise, and insights into desirable and feasible policies may be gained through consideration of factors such as these. The policy orientation of studying climatic change will differ from that of variability to the extent that the work on climatic change will be more directed toward those interested in long-term planning in society and questions of choice of energy path, environmental preservation, and so forth.

While there are methodological differences associated with the different time scales of these two categories of research, it does not make sense to investigate them entirely independently of one another. As Czelnai points out in his paper in these proceedings, the impact of a slow and gradual climatic change on society and economy will probably appear in the shape of difficulties caused by the changing recurrence time of extreme values on which important designs are based. Any assessment of long-term impacts must therefore be accompanied by study of the impacts of short-term variability. Moreover, the short-term variability is usually much larger than the rate of long-term changes, and the combined effects of short- and long-term variations may also become a new source of difficulty. Finally, decisions required for short-term problems may be in conflict with those for long-term problems, so some coordination between those dealing with the two general areas is desirable. Clearly, in the end, studies of the two kinds of problems are complementary. Indeed, studying the effects of variability may be one of the better ways of coming to understand the magnitude of the effects of a possible large-scale, longer-term change.

IMPORTANT AVENUES OF RESEARCH

On the basis of the Task Force Meeting and associated activities, a number of directions for future research were identified. These include (1) improving the climatological basis for studies of the effects of climatic variability and change, (2) specifying better from the point of view of economic geography where future injections of CO_2 may originate, (3) exploring issues involved in linking "physical" and "socioeconomic" models in a problem oriented integration, (4) developing knowledge of the relationship of climate to water and food on a sectoral basis, and (5) developing knowledge of the interactions of climate and human activities from a national or regional perspective. A brief description of each of these research areas follows.

(1) Studies of the interaction of climate and human activities must be founded on the best possible climatological basis, with respect to both climatic variability and change. A number of useful activities might be undertaken in this field by climatologists and atmospheric modelers working in consultation with agriculturalists, water resource experts, geographers, economists, and others. An initial activity might be development of a data base on plausible

patterns of climatic change through the next century and on models of climatic variability suitable for use in "impact" analyses. Preliminary scenarios of climatic change might be developed based on reviews of worldwide research and on consideration of critical scientific issues such as ocean-atmosphere coupling and role of soil and biomass in the carbon cycle. There is a growing amount of research deriving scenarios for future climate based both on numerical modeling using general circulation models and on the use of past periods as analogues for the future (see, for example, the paper by Sergin in these proceedings). As the available material grows, it will become useful to engage in comparisons of projections of climatic change and to attempt to improve the realism of these projections, particularly with respect to applicable time and space scales. With respect to studies of the role of climatic variability, certain kinds of statistical studies of climate may provide a useful framework. Again, these must be designed in such a way that the "user" disciplines will be able to apply them.

(2) Strategies of response to the CO_2 issue must be concerned with the national or regional origin of CO_2 emissions and the rate at which CO_2 may be expected to be injected by various groups into the atmosphere. The rate at which CO_2 is injected is a critical determinant of the rate of the projected climatic change. Choice of possible prevention or compensation strategies may be largely determined by who is injecting CO_2 into the atmosphere and how fast. It is necessary to review, compare, and further detail projections of future CO_2 injections into the atmosphere, primarily injections from fossil fuel combustion. Most studies have taken a "demand" approach to the problem, hypothesizing global demand for energy and then working back through fuel mix to CO_2 injection. It is also necessary to look at the supply side of the question. Who has the carbon reserves and resources? How quickly can these be extracted and converted to CO_2? To what extent can the information on "carbon wealth" (stocks of carbon convertible to atmospheric CO_2 on a time scale of about 100 years) be integrated with models of energy demand to give a picture of the geopolitical and economic structure of a CO_2 problem? What can we learn about the relative desirability and likelihood of preventive, compensatory, and adaptive strategies to CO_2-induced climatic change by clarifying possible quantities and sources of future injections? Are there issues of liability and distributive justice?

(3) Understanding the relationship of climate and human activities is inherently multidisciplinary. A problem oriented integration of sciences is required, but often the contributions of individual disciplines are such that they remain isolated and untranslatable or untranslated into terms of another discipline, much less into "political facts." (See the paper by Meyer-Abich in these proceedings.) For example, bringing together natural and socioeconomic models involves many problems. Existing models usually cover

subsystems. Present simulation models of the atmosphere at one extreme of the spectrum and econometric models at the other offer quite different approaches to modeling problems, and there is little possibility of interaction among them. Similarly, crop-climate models require more development and comparison of results before they can be reliably utilized in conjunction with either more sophisticated models of climate or of the agricultural sector. (See the paper by Biswas in these proceedings.) Issues involved in joining the various "physical" and "socioeconomic" models should be explored. The purpose of the explorations would be to develop methods for eventually linking socioeconomic models and empirical or dynamic models of climatic variability and change to study sensitivity, risk levels, and policy options in sound integrated assessments. New approaches may be needed. For example, it has been suggested that in studying the differential impact of drought on societies, recent structural theories, such as the theory of dissipative systems, may present a promising avenue to be explored. While some of the work in this area is theoretical, it may also be linked to concrete case studies. Finally, it should be pointed out that trying to grasp the functional circle of science and economy raises fundamental ethical issues in the philosophy of nature. Ultimately, this kind of research is not meant merely to help generate reliable numerical assessments, but also to help us judge what is good or bad with respect to nature.

(4) In certain respects it may be possible to arrive at the most concrete results by limiting the field of study to climate and one important natural or socioeconomic sector. Food and water appear to be the sectors with the highest priority, but interesting work might be undertaken with respect to ecology and other sectors. In this kind of work, for example, agricultural models might be used to test "climatic shocks" to the food system, or climatic variability might be explored as an environmental constraint to agriculture. Similarly, the connection of climatic variability and issues of water supply and quality have not been fully explored.

(5) Rather than a sectoral approach, it is also possible to undertake analysis of the interactions between climate and human activities from a national or regional perspective. Such studies offer a continuing source of ideas about the kind of problems and situations a model might be asked to represent, as well as offering concrete explorations of policy decisions. A number of these studies have been carried out, but no critical reviews, which would emphasize methods, theoretical frameworks, and underlying hypotheses, have been made. Subsequently, it might be useful to try to bring together researchers in this area, for example, by creation of a network of case studies in different geographical areas. An example of a specific topic is uses and limitations of crop-climate models in such studies.

SUMMARY OF CONTRIBUTIONS

In "Economics in the Air: An Introduction to Economic Issues of the Atmosphere and Climate," Ausubel suggests that for most purposes nations continue to treat the atmosphere as if it is endlessly assimilative and resilient. Because many of the consequences of the use of the atmosphere are felt far away in space and time, and because most of the uses of the atmosphere carry no price, the atmosphere remains one of a class of environmental goods that present economic systems encourage heavy use of. So, for example, households and firms normally dispose of their sulfur and carbon residuals not by scrubbing them from emissions but by pouring them freely into the atmosphere.

In the past 10 years, a series of "threats" to the atmosphere has been posed by the findings of natural scientists. Regardless of the seriousness of any particular issue at the present time, the outlook is that over the next 50 to 100 years, the atmosphere, including climate, will join the ranks of drastically altered aspects of the earth's environment. No such thing as a "forever wild" position can realistically be argued for the atmosphere. Societal choices with respect to the atmosphere will almost never be whether or not to have an activity, but to determine at what level an activity should be undertaken and how one activity should be balanced against another.

Conflicts tend to proliferate in a setting where no competing party or interest group is really informed about the scientific status or economic value of the resources in question. In trying to devise satisfactory long-term, international policies for a global common such as the atmosphere, there is an urgent need for better information and analytical criteria and better sharing of these. Indeed, our knowledge needs to be dramatically improved, if we are ever to be able to apply efficiency criteria to the entire set of uses of the atmosphere in order to allow consideration of the welfare implications of trade-offs between alternative uses or groups of uses. In the past, the uses and users of the atmosphere have been independent enough so that they need not be considered in a holistic way. However, the subject of atmospheric policy is now maturing to the point where a comprehensive, long-term, integrated examination of the future relationship of the atmosphere and human activities may be warranted. In this respect, the atmosphere appears to be following the tendency in resource management to organize functionally defined units across spatial or physical regimes.

While it is true that the trade-offs which may eventually need to be made may be primarily functions of societal purpose (energy, food, and so forth) rather than competing uses of a natural system, the natural system probably still offers an excellent opportunity for applied research and policy analysis. Given the scientific and economic uncertainties about many of the uses of the atmosphere, and the structure of control and management of the atmosphere, or lack of it, both nationally and internationally, it is hard to believe that society will be able to come to grips in a decisive way with major atmospheric issues, such as climatic change, in the next decade. But, rather than accept this situation one may begin efforts to avoid an ever more irrationally exploited and degraded atmosphere.

In "Chalk on the White Wall? — On the Transformation of Climatological Facts into Political Facts," Meyer-Abich asks what kinds of political actions can be conceived in response to climatological developments so that facts about climate expressed in the language and terms of the sciences may change the political situation, and thereby become political facts. In principle, there are three options: prevention, compensation, and adaptation. While ultimately these options may be basically equivalent, Meyer-Abich shows that from a political point of view prevention and compensation (or abatement) are much less practical than adaptation. In particular, adaptation allows one to confine oneself to the least marginal action in the present and to defer expenses most distantly into the future. Adaptation also does not require long-term international cooperation or agreement on long-range goals. Adaptation, thus, for the time being is the most rational political option. Given this assessment of the issue of climatic change and the specific characteristics of an adaptive strategy, the climate problem, paradoxically, tends to fade out compared to the already existing extremely serious problems of the politics of development and industrial change.

Biswas, in "Crop-Climate Models: A Review of the State of the Art," looks at an area that is at the center of the issue of climate and human activities, since it is widely agreed that, barring a catastrophic occurrence like the collapse of the West Antarctic Ice Sheet, the most important and vulnerable human activity with respect to both climatic variability and change is agriculture. Biswas points out that there are two basic approaches to the question of the effects of climatic fluctuations on agricultural production. One is detailed ecological study which tries to understand the different determining physical processes involved and to assess the behavior of crops under different specific conditions. In contrast, "crop-climate models" attempt to relate climatic variables to production data through statistical techniques. Most crop-climate models developed so far are based on multiple regression and use empirical relationships derived from historical crop yield and climate data to predict potential future yields from different climate scenarios.

Following a review of the major models for different crops and geographical locations (Thompson, Haigh, Williams), Biswas points out some of the major problems. Among these problems are the black-box structure of the models, the fact that the coefficients derived are statistical estimates and not universal constants, the nonlinearity of the relations between crop yields and different climatic variables, the assumption that the independent meteorological variables are not closely related to one another, and the difficulty of separating factors of management, technology, and climate. While crop-climate models provide some interesting insights, Biswas concludes that further developments, both in terms of modeling sophistication and in our understanding of the interrelationships among the different processes involved (especially with respect to more specific time periods), are essential before the potential of the models can be fully realized and the models used in decision-making and planning processes.

Warrick's report, "Drought in the Great Plains: A Case Study of Research on Climate and Society in the U.S.," sets out an important hypothesis about the role of climate in relation to human activities and tests it with specific historical research offered in the framework of two models of climate-society interactions. The hypothesis states that persistent and adaptive societies, through their technology and social organization, *lessen* the impacts of recurrent climate fluctuations of similar magnitude on the resident population and indirectly on the entire society. This "lessening" hypothesis is investigated in relation to both a simple static model of climatic impacts in which a climatic event (drought) affects some sector of society (agricultural production) and "causes" societal impacts. A more sophisticated dynamic model is also discussed. In this model patterns of response alter either physical systems, social systems, or both, and in so doing transform the interaction of climate and society over time. Thus the social basis of vulnerability and the dynamics of adjustment may be explored.

The preliminary results of the Great Plains case study offer substantial evidence of support for the hypothesis of lessening impacts. Although there are difficulties in accounting for differences in the severity of drought and in separating its effects from more external economic effects, the overall picture which is emerging is one of progressively lessened impact upon local agricultural residents. Meanwhile, the pattern of impact has shifted to encompass a broader social network, as reduction of local stress has been accompanied by willingness to spread costs throughout society. However, while the societal impacts diminish, it is not clear that this reduction results from a lessening in the drought-yield linkage. The data are ambiguous, and this point invites connection with material in the papers by Biswas and Czelnai. Warrick suggests tentatively that the bulk of lessening has not occurred because of the technological mechanisms and changed farm operations that intervene between drought and yields, but rather it is more likely that lessening has occurred from intervention between yield declines and societal well-being, that is, through programs of reserves, insurance, and so forth.

While Warrick explores primarily effects changing through time, Spitz, in his paper "Drought and Self-Provisioning," looks at distributive effects of climatic variability on specific social groups. Spitz, drawing examples from Indian data, takes as his subject a social system of cereal production in which consumption by the producer, or self-provisioning, plays a major role. He examines the impact of shortfalls in production depending on the size of domestic stocks and relative strength of the forces of extraction of food from the household (food as a commodity) and the forces of retention of food in the household (food as a basic need). It is this dual nature of food, often ignored in microeconomic analysis, that in many poor areas accounts for the extreme sensitivity to variations in production and makes linear analysis of agricultural crises of little value. Moreover, those already relatively poor within the self-provisioning economy, namely those with small carry-over stocks, are affected most severely. The lower the nutritional level of a given group at the outset of a drought, the more it is likely to be reduced by the drought. In the case of a fall in production intended for self-provisioning and in the absence of any means of exchange for procuring a living, those without reserves are forced to emigrate, while those with greater and more diversified resources may find that drought enables changes to be made even more to their advantage through favorable prices for factors of production. The potential for conflict in a drought situation in a self-provisioning society is thus clear, as the vulnerability and resilience of different elements of the social and economic system are tested in the struggle for social control of reserves.

In "Climate and Society: The Great Plain of the Danube Basin," Czelnai explores this area as a possible candidate within eastern-central Europe for closer study of the interface between climate and human activities in developed countries. It appears to be an interesting choice for study because it is a food-surplus area with good availability of data and distinctive climatic features. Czelnai offers some general remarks about the stratification of climatic impacts, and reviews societal adjustment strategies in the light of a possible range of responses to a "single pulse" short-term climatic forcing. The environmental history of the Great Plain is briefly outlined with special regard to the factors that have shaped the hydroclimatic regime of the area. Czelnai then discusses some of the relationships of climate and economy in connection with agriculture, which he estimates contributes by itself 60% of the overall climatic sensitivity of the socioeconomic systems within the geographical area. It is shown that the prevailing negative water balance reduces the natural agro-climatic potential by some 50%. This means that an intensive agricultural system, with irrigation, could double the productivity. However, it appears that with present prices such a system would not be cost-effective and, moreover, would probably increase the climatic sensitivity of the area. Finally, it is suggested that a pervasive cooling, or an increasing of the recurrence of low temperatures, could be particularly detrimental to a broad range of plant culture.

As mentioned earlier, one of the needs in the area of research on climate and human activities is for improved information on plausible patterns of climatic change. Sergin's research on estimating climatic fields based on the similarity of seasonal and longer-term climatic variations offers a promising method for doing this, as well as some tentative results. The present state of development restricts the applicability of general circulation models for determining regional changes in the geographical pattern of temperature, precipitation, and winds. The use of past periods as analogues of the future, or a "similarity method" as Sergin describes his related approach, allows the possibility of using past instrumental records of climate to gain insight into possible futures. The similarity method does not offer a way of forecasting. However, the theory of similarity does provide a method for estimating fields of meteorological elements for new, given climatic states.

In his paper, Sergin outlines the theory of the similarity of states of global atmospheric circulation in the course of seasonal and longer-term climatic changes and shows that seasonal variations in the fields of meteorological elements can be taken as a physical model of climatic variations in the average annual field. If an atmosphere with a given seasonal course of boundary conditions is regarded as an experimental unit, then by applying the rules of the theory of similarity one can obtain basic quantitative estimates characterizing the average annual fields of various climatic states. A new state may be characterized by the specification of one pair of numbers, namely the average atmospheric temperature in the hemisphere and the temperature difference between the equator and the pole. Sergin makes experimental estimates for a warming and a cooling of the average annual surface temperature by 2 ^{o}C. While the average climate of the warmer epoch is characterized by greater humidity, cloudiness, and precipitation, the distribution of changes is uneven, and many arid areas become drier. In contrast, in the cooler epoch the amount of precipitation increases in most of the arid regions. Estimates such as these may prove useful in evaluating the significance of the effects of human activities upon the climate. However, we must keep in mind that in making use of natural fluctuations we are assuming that, given similar boundary conditions, there are broad similarities in the way the atmosphere responds to different types of forcing.

ECONOMICS IN THE AIR --
An Introduction to Economic Issues of the Atmosphere and Climate

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> *Is it conceivable...that a scientific calculus exists for deciding what increases of environmental disruptions and frequencies of disease are acceptable in exchange for such-and-such advantages of industrialization, and what are not?*
>
> *We will never be able to judge what is good or bad with respect to nature if we do not from the outset start with a normative concept of nature, including the recognition of nature as our own nature.*
> *(Meyer-Abich, 1979)*

INTRODUCTION

The atmosphere is obviously recognized as an asset to society. Yet, long after this asset has begun in certain respects to become scarce and valuable, societies continue to treat the atmosphere as if it were limitless and endlessly assimilative. Because for most purposes the atmosphere carries no price, and because many of the consequences of use of the atmosphere are felt far away in space and time, individuals and industries use it with freedom, rarely economizing on it as one normally would with a conventional factor of production. Of course, the atmosphere is one of a class of environmental goods which has been treated this way. As Kneese and Schultze (1975:1) have commented:

> To an important extent the nation's economic and social structure has been conditioned by the fact that, historically, we have paid little attention to the problems of the environment. Goods and services have not commanded a price to cover the real environmental costs that their production and use imposed on society. As a consequence, we have enjoyed cheap automobiles, paper, chemicals, food, energy, and a host of other products while suffering a deteriorated environment.

And now, for example, climatic change may take place because the institutional arrangements of societies encourage heavy use of environmental assets.

But, just as the costs of a deteriorated environment are real, so are the costs of the alternative. In most circumstances, the value of resources that might be directed toward controlling emissions into the atmosphere will not be available for meeting the other wants of societies. It is not merely a question of capturing profits from oil and coal companies, but of altered and probably higher prices and taxes which everyone will be paying for a modified or different set of commodities, some of which are environmental. Thus, making policy with respect to climate or other aspects of the atmospheric environment confronts us, especially as higher levels of control are proposed, with choices between environmental quality and other aspects of the standard of living. There is obviously no such thing as a "forever wild" position with respect to the atmosphere. The societal choice with respect to the atmosphere is almost never whether or not to have an activity, but to determine up to what level a particular activity should be undertaken, and how one activity should be balanced against another.

While struggles over well-identified wealth are all too evident, it is also true, as Wilkinson (1979:254) has commented, that from an economic point of view conflicts tend to proliferate in a setting where no competing party or interest group is accurately informed about the value of resources in question. In trying to decide how much, if any, of an atmospheric activity should be undertaken, this problem of a lack of information is severe. At a basic level there is a need to improve analytical criteria for use of atmospheric resources. There is a need, with respect to certain crucial uses, to develop these one by one, on a partial basis. There may also be a need for a broader analytical approach, which permits the simultaneous determination of the value of many activities related to the atmosphere, if economic criteria are to be applied to the entire set of uses of the atmosphere in order to allow us to consider the welfare implications of tradeoffs between alternative uses or groups of uses.

This paper is an introduction to issues and concepts in economics which are relevant to explaining the current condition of the atmosphere and to some perspectives which may be useful in advancing management of atmospheric resources. It is an attempt at breadth and inclusiveness, and as such may be informative primarily for researchers from disciplines other than economics, or as preliminary material to the more sophisticated and detailed analysis related to atmospheric problems which is currently being conducted by Kneese, Lave, Ayres, and others. The paper begins with a discussion of the concept of common property, and a survey in the framework of national income accounting of what the uses of the atmosphere are. Then, it examines some of the problems economic analysis has with evaluating the atmosphere, largely because of problems of externalities and technical difficulties in arriving at consistent and reliable cost and benefit estimates. Implications for allocative efficiency and equity are discussed. Finally, the paper looks briefly at the potential application of decision analysis for the major conflicting uses of the atmosphere and concludes by examining various obstacles to the improvement of atmospheric management.

THE ATMOSPHERIC COMMON

In recent years discussions in international law and economics have frequently referred to problems of "common property resources" and "the global commons." What are these concepts? Do they shed light on the condition and problems of the atmosphere?

First, let us look briefly at the history of the term "commons." Commons originally referred to a form of land tenure widespread during the Middle Ages in England and in continental Europe. This form of land tenure probably reflected elements of ancient practices or customs which had survived the Roman conquest of northern Europe and were maintained, in partial form, on feudal estates. As Schauer (1977:69) describes it:

> Areas of the feudal estate (were) more or less permanently set aside for continuing common use. These included forests, pastures, ponds, streams, and wastelands. Although these areas remained under the political and legal authority of the feudal lord and/or other civil authority, custom reserved them for specified uses by all the inhabitants of the estate. Customary uses included the gathering of wild vegetables and fruits, lumber, fuel, water, dirt, stones as well as pasturage, fishing, and fowling. Commons also provided housing sites for the landless poor, and offered locations for social and recreational activity of the community.

As these lands and their associated resources became more valuable, or in economic terms, scarcities arose relative to the demands being made, the customary forms of jurisdiction and land use began to break down. In the case of land, the usual response was to carve up the area in question and transfer ownership to individuals. This was the main characteristic of the so-called "enclosure movement" in England. The feudal commons basically succumbed to pressures of population and income encouraged by technologies which made profitable cultivation possible in previously undesirable areas.

While the historical land commons have all but disappeared, the concept of commons has been used increasingly to refer to various other shared resources, for example, river systems and lakes. A number of such common property resources—major river systems, some inland lakes and seas, Antarctica—are shared by several nations. Some are, or are potentially, shared by all nations. These are the great "global" commons—the oceans, the atmosphere, the electromagnetic spectrum, and outer space. But these global commons are not quite the same as the traditional commons, as well as being diverse among themselves. The dominating sense of them is not that they are the property of some identifiable individual entity and subject to use by a traditional community, but that they are part of the "common heritage" of all nations and people, either in terms of established or anticipated access. The global commons may be used by all nations but are the property of none.

Clearly, each common area has distinctive characteristics. For example, the fluid realms, the oceans and atmosphere, have been regarded in a way somewhat different from common agricultural lands.

> Ubiquity has created feelings which are deeply ingrained in the human experience against exclusive ownership of large parts of these realms. International law has reflected this sentiment in the durable doctrine that these realms are *res nullius*, the property of no-one (Brown, *et al.* 1977:5).

Thus the regime which prevailed on the high seas was one in which property *per se* did not exist. But, while the seas themselves were the property of no-one, the capacities of the seas, which were assumed to be unlimited, were a thing held in common, a *res communis*, available for anyone's exploitation. Freedom of access for transportation, fisheries, waste disposal, and so forth, could be maintained almost without any group restricting access to others for these or for other purposes. While the resources were little managed, and said to be the property of no-one (or anyone), it is not correct to say that the oceans were ungoverned. As Wilkinson (1979:251) has noted, one of the conditions for the maintenance of this system was the military and economic domination of the world by those powers best served by open access. In the case of the oceans, this role was played largely by the British. There has been no parallel in the atmosphere to the British role on the oceans.

While the atmosphere has been less politically salient and organized than the oceans, until the 20th century atmospheric politics and law reserved the atmosphere as an open space similar in important respects to the ocean. One may say that the atmospheric regime met the conditions proposed by Wilkinson in that the heavy users of the atmosphere, for example, those involved in the coal economy, were nations or firms well served by open access, and they were militarily and economically dominant. A second condition offered by Wilkinson for the maintenance of a system of open access to the seas was the slow evolution of technology for industrial, transportation, and military purposes, and, indeed, many of the techniques which underlie present use and exploitation of the atmosphere were similarly little used or unknown until this century.

As use has intensified and the need has grown to enforce, for example, pollution control and traffic separation, there has been a movement of "enclosure" with respect to the oceans and atmosphere comparable to what took place with common agricultural lands. Coastal states have increasingly asserted legal, political, and economic control of nearby marine areas in the case of the oceans, and in the case of the atmosphere, nations have increased their claims to overlying airspace in various respects. If parts, or characteristics, of the atmosphere are being "enclosed," can the atmosphere still meaningfully be considered a common either at a global or national level?

In his effort to define a common for outer space, Schauer (1977:69) postulates four requirements:

(1) a common must exist within and as a part of a wider rule or custom;

(2) a common must be identified by practical laws or rules which distinguish it from what is not a common;

(3) a common must be open to community or public use and closed to exclusive appropriation;

(4) a common must be, by nature or as a result of laws or rules applied thereto, in such a condition that use by some does not preclude or significantly interfere with use by others.

While reservations may be expressed with respect to the atmosphere for all four of these postulates, one may argue that the atmosphere still maintains much of the character of a common. Of course, both the jurisdictional scale and the degree to which the atmosphere is a commons vary with respect to the uses of the atmosphere under consideration. That is, with respect to carbon dioxide emissions and climate change, we may need to think of the atmosphere as a global common, but with respect to another case of waste disposal, or a different use, the atmosphere may be considered as the property, or shared resource, of a smaller community.

In considering the first of Schauer's requirements, one may point to the growing body, both nationally and internationally, of what may be called "air law." At the national level this is often in the form of ambient air quality standards and emissions standards. The implication of much of this body of material is clearly that the atmosphere is to be treated as a commons. In a similar fashion (and perhaps equally problematic) we find a growing body of case law, treaties, and declarations among nations about the atmosphere. The earliest important event in the international context was the "Trail Smelter Case," a case of transboundary air pollution involving the US and Canada. A number of relevant doctrines emerged from the United Nations Conference on Human Environment, held in Stockholm in 1972:

Principle 21—calls on states to ensure that activities within their jurisdiction or control do not cause damage to the environment of other states or areas beyond the limits of their national jurisdiction.

Principle 22—calls on states to cooperate to develop international law regarding liability and compensation for victims of pollution and other environmental damage.

Recommendation 70 calls for states to:

> evaluate carefully the likelihood and magnitude of climatic effects from a contemplated action, and to disseminate these findings to the maximum extent feasible before embarking on such activities;
>
> consult fully with other interested states when activities carrying a risk of such effects are being contemplated or implemented. (Quoted in Kellogg and Mead, eds., 1977:82).

More recently one may cite the Nordic Air Pollution Convention, various agreements on weather modification, and efforts to prepare "Draft Principles of Conduct in the Field of the Environment for the Guidance of States in the Conservation and Harmonious Utilization of Natural Resources Shared by Two or More States." (Adede 1979 and UNEP 1978.)

The second requirement of a practical delimitation of space is not neatly fulfilled by the atmosphere. There are difficulties in specifying where the atmospheric common begins and ends. One might roughly suggest that the atmospheric commons begins beyond highly defined local environments, is questionable above an altitude of 50 miles, and may, in some sense, be "stronger" where associated with other common resources, for example, over a national park or over the high seas. For the lower portion of the atmosphere (the troposphere) and the local atmospheric environment, to such an extent as the distinction may be drawn, legal control and rights of use have been established on a municipal, provincial, or national scale. In the upper atmosphere (stratosphere) control and rights have not been clearly established. Again, the nature of the use of the atmosphere is crucial. For example, with regard to certain spatial uses of the atmosphere, like air transport, access to the atmospheric environment is under the control of the sovereignty directly underneath it by provisions of common law and international treaty. Indeed, for certain purposes, according to Schachter (1977:75) "...we are accustomed to the legal principle that the airspace over a country is part of its national territory and entirely under its control." But this still leaves definition of ownership far from complete. Specifically, how does one allot the atmosphere over the oceans or the upper atmosphere? In conclusion, one can only say that for certain purposes and problems, the atmosphere is a global common, for other probably a national common, for others perhaps a local common, and for others it still remains undefined. And with the introduction of novel regulatory devices, like marketable emission permits, new categories may yet need to be created.

Schauer's third postulate, that a common is necessarily open to community use and closed to exclusive appropriation, well suits the essential physical character of the atmosphere. The atmosphere is mobile, nondivisible, and has little natural basis for being apportioned. It is impossible to separate the atmosphere into physically or biologically unique contents over each sovereignty. From the point of view of waste disposal, it is clear that mixing takes place on geographical scales which have little or nothing to do with political or legal boundaries. Similarly, local supplies of climate are indissociable functions of the global climate system. Even local weather conditions, which may appear to "belong" to a particular area, especially where natural barriers are important features, are self-contained only in a very limited sense, as no local patterns are decoupled from larger circulations.

While the physical character of the atmosphere undermines any attempt at appropriation, firms might be said to be evolving in effect a certain sort of proprietary right by obtaining leases and permits, or even by conforming to certain standards. However, ownership in the more powerful sense of "exclusive authority to dispose of, confer rights to, or otherwise affect the conditions of some thing or place" (Brown *et al.* 1977:10) is remaining either in the hands of the community or in the hands of no-one. Another way of expressing Schauer's third requirement is that the atmosphere may be said to conform, to a considerable extent, to the economist's criteria for a collective or public good: joint availability, non-exclusion, and non-divisibility. There is open access and free use for most purposes: no individual or firm owns the atmosphere, very few can be denied entry, and there is little collection of economic rent for its use.

Schauer's final requirement is not only a part of the definition of a common, but also a condition for its maintenance. In effect, it says that a common must either be so rich as to accommodate all its users without conflict or that it must be successfully regulated. Why is this final qualification needed? The answer is that the dynamic of the previous postulate of open access is what Hardin (1968) aptly called "The Tradegy of the Commons." What is this tragedy and does it have any applicability to the atmosphere?

In general, one sees that, historically, norms of open access and free use which traditionally characterize the use of commons are incompatible with resource scarcities, and that these norms give way to various forms of allocative regimes. Problems have arisen primarily because already accessible regions and resources of commons are being exploited more intensively. Conditions of abundance change to conditions of scarcity, and resources are severely despoiled or depleted. Problems have also arisen sometimes because scientific and technical developments have made it possible to exploit previously inaccessible portions of the earth's common resources. As Brown *et al.* (1977:22) have commented, if the supply were inexhaustible or infinitely elastic, increase in demand would simply cause greater extraction or utilization of a particular resource, often through the development of technologies to reach previously inaccessible supplies. However, in some categories, like fishing, demand for the resource has been rising at a rate which is substantially greater than the supply, and, thus, the applications of new technology may have served only to accelerate the depletion of the supply.

The recognition of scarcity of common resources and the increasing possibilities for the abuse of land and non-land environments have "increased the impetus for extended national ownership to assure supplies and control of at least adjacent areas, and, on the other hand, have stimulated discussions of forms of international ownership as a means of assuring responsible national and private use." (Brown *et al.* 1977:10.)

In general, as Morse (1977) argues, technological change, crowding, environmental degradation, and the growth of complex interdependencies have created new problems of managing common property in society, both nationally and internationally.

In the case of atmospheric resources, the supply is becoming increasingly scarce not only because of the characteristics of each resource use, but also because the uses are not independent—nor are their supply conditions. For example, consider the use of the atmosphere as a medium of transport. Use of the spatial characteristics of the atmosphere for transportation is not one that consumes, or destroys, the spatial characteristics with use. However, congestion problems do arise, and users have to be coordinated. Moreover, use of the atmosphere for transportation may interfere with other uses. For example, at one time it was believed that the residuals associated with stratospheric transport would diminish the capacity of the atmosphere to shield the biosphere from damaging ultraviolet radiation. Another conflict and potential scarcity arises from the use of the atmosphere as a receptacle for waste and as a modulator of the supply of climate. Climate is depletable from an economic point of view: the supply available and suitable for productive activity may augment or diminish. One does not ordinarily think of weather and climate as scarce commodities, but it can be argued that in many parts of the globe the demand for certain kinds of weather and climate regularly exceeds the supply. While there are natural variations of the supply of climate on all time scales, in the last decade a series of human activities involving the atmosphere as a receptacle for waste (for NO_x, CFMs, CO_2, dust, and so forth) has raised the specter of a long-term climatic change. Here then is a fascinating tradeoff between functions of the atmosphere as a receptacle for waste and as a "supplier" of climate. There are other important tradeoffs involving use of the atmosphere for waste disposal, for example, with clean (healthy) air and with clear (aesthetically pleasing) air.

So again, we find that according to which use is under consideration, the atmosphere is to varying degrees a common. For certain purposes, like the supply of oxygen, it remains "by nature" in a condition that use by some does not preclude or significantly interfere with use by others. For some purposes, like air transport, this is true as a result of rules and laws applied to it. For other purposes, principally those relating to waste disposal, the atmosphere may manifest growing characteristics of the tragedy of the commons, where there is a deterioration of quality or decrease in supply. The commons characteristics of the atmosphere may then explain a good deal about its current state and have important implications for attempts at management.

Meanwhile, policies for the most part continue to treat the atmospheric common as if its supply were infinitely elastic, that is, as if there were no expectations of future prices changes. "Allocations" take place most often on the basis of unilateral appropriation, or, in some cases, by more widely agreed methods of determining rights and use. Priority tends to go to first and current users, and important attributes, including "nonexcludability, absence of congestion, and something that might be called renewability (i.e., the asset recovers so that use by one individual does not impair the asset for use by others)," (Krutilla and Fisher 1977:23) are diminishing. What economists usually suggest in such cases is a mechanism for rationing the resource, ending free and unrestricted access for all. What is happening, particularly at the international level? While the "Law of the Seas" has been the subject of much debate, the atmosphere has received much softer and vaguer treatment to date.

Clearly, the principles and recommendations for utilization of the atmospheric common offered internationally so far are very noncommittal. But then, as Daly (1975) points out, to say that anyone whose use of a common property resource damages others should actually be liable for that damage is, implicitly, a statement of who should own that resource. And that the issue, as we have seen here, is often unresolved.

Is the appropriate social response to the need to manage or allocate the resource to convert common property into private property or into more definitive public property? And, if public, at what scale? The more people who are included in Schauer's phrase "use by others," the more the tensions that arise between postulates about open access and nondestructive use. "Who is included in *res communis*—all those now living, or all those now living plus all those still to come? Does the present generation own the resources outright or only in trust for future generations?" (Brown *et al.* 1979:8.)

AN ATMOSPHERIC SECTOR?

Is it possible to conceive of an "atmospheric sector" in the economy? Pontecorvo and Wilkinson (1977) have been developing a sectoral approach to the oceans within a national income accounting framework with interesting results (see also Nathan *et al.* 1974). Could a similar analysis succeed for the atmosphere? It is not difficult to see that in some senses the atmosphere may be regarded as a commodity or a bundle of economic goods, but it remains to be seen whether some sort of "atmospheric sector" may be useful in examining either the relationship between an atmospheric sector and the rest of the economy, or the relationship between subsectors within an atmospheric sector. In order to build a useful analytical tool, it would be necessary first to identify the economic uses or resources of the atmosphere. In other words, what stocks or flows of wealth are associated with the atmosphere? One must have some classification scheme. Let us explore the possibility of an atmospheric sector using two general categories of economic activity: those which extract or capture resources (living, energy, mineral, water, etc.) from the atmosphere or relate primarily to its chemical constituents, and those which require the physical use of atmospheric space (transportation, waste disposal, etc.).

How does the notion of extracting or capturing resources apply to the atmosphere? Certain mineral resources, for example, nitrogen and oxygen, might be regarded as part of an extractable atmospheric stock of wealth. In addition, it might be argued that climatic variables ought to be included. Climatic variables are ordinarily not viewed as direct factors of production, subject to manipulation by the user. "Instead, these variables operate through changes in the production function, and thus, affect the level of output by changing the productivities of the direct factors of production or by affecting the choice of the production process employed." (Crocker (d'Arge) 1975, section 3: 84.) Nonetheless, it may be possible to conceive of climate as resources of matter and energy captured from the atmosphere.

Meteorologists usually talk as if climate is simply a set of statistics, rather than anything tangible which can be regarded as a resource. Yet, if an economist were to describe weather modification to a meteorologist as an attempt to bring about an enhancement or redistribution of climatic resources, I think it would be an acceptable statement. From an economic point of view, climate is matter and energy organized in a certain way. If a climatologist were to say to a farmer that the climate is going to change, the farmer could interpret this to mean that deliveries of matter and energy may be going to change in quantity, time, and place, in ways similar to how supplies of fertilizer or gasoline might change.

Of course, the climatic variables are not exclusive to the atmosphere. Various constituents come into and out of the atmosphere; for example, in the hydrologic cycle, water goes into and out of the ocean, land surface, and so forth. Indeed, climate variability and change are functions of the overall "climatic system," of which the atmosphere is only one component. However, on time scales of interest from an economic point of view, say, months to several generations, climatic variables may be treated primarily as attributes of an atmosphere-centered system. From a scientific point of view, this is not entirely correct, as short-term climatic variability and longer-term change may on these time scales be a function of, for example, behavior of the oceans or the sun, but for purposes of economic analysis the variations in the supply of climate and potential changes can still conveniently be regarded as functions of natural atmospheric turbulence and as consequences of other human uses of the atmosphere. Exceptions to this, as they are more definitively explained, could be treated separately. Clearly, a satisfactory definition of climate for purposes of economic analysis has not yet been arrived at, and it is a question which warrants further examination. One interesting approach may be to explore the economic meaning of climate through von Weizsaecker's (1971) resource triad of matter, energy, and information, through which climate cuts in an unusual way. However, for the time being let us use the idea sketched above.

In identifying uses of the atmosphere for potential evaluation, one must also inevitably caution that if one were to evaluate completely the uses, their value would be incalculable or infinite, because the atmosphere is a necessary component for life. The entire supply of 6×10^{15} tons of air may not be indispensable, but every adult human must breath about 30 to 35 lbs of it each day to extract the oxygen necessary for life. So, we must look for uses for which in some sense economics is relevant.

Is there a non-trivial sense in which the atmosphere can be regarded either as a source of minerals or from the point of view of its chemical constituents? While "clean" air may be a complex and difficult term to define, if the atmosphere does not provide a certain level or amount of this, there can be serious health effects, and, thus, supplies may be discussed in economic terms. Another mineral the atmosphere provides, although perhaps in a trivial sense, is nitrogen. Fixed nitrogen, mostly in the form of synthetic ammonia, is compacted by industrial processes from the atmosphere's gaseous supply in enormous quantities for agricultural fertilizers. However, this nitrogen, which composes about 78% of the atmosphere, is in such plentiful supply (price essentially zero), that analysis may be superfluous. Another set of functions of the atmosphere relates to its role as a protective shield. The ozone layer, for example, acts as an important shield against incoming ultraviolet rays. This is not an extractive role, narrowly defined, but as a function of the chemical composition of the atmosphere, it may be left in our first category. The weather and climate variables, principally rain, insolation, and wind, may be regarded as either mineral or energy resources. Finally, one could attribute birds to a category of the living resources of the atmosphere.

Uses of the atmosphere emphasizing physical space include the various functions of the atmosphere as a medium, as, for example, for transporting people and goods, or signals. The uses for transport would also include military uses, for example, for reconnaisance, and for testing and delivery of weapons. A similar use is as the medium of departure to and entry from outer space.

Certainly the most important and difficult spatial use of the atmosphere, from an economic point of view, is as a receptacle for waste. The role of the atmosphere as a receptacle for waste was taken for granted for many years. The quantities involved were relatively modest and geographically distributed, and the substances themselves were usually not inherently very dangerous. Under such conditions, taking advantage of the atmosphere's capacity to transport, dilute, and absorb wastes was generally a health way of disposing of them, for both humans and the environment. However, in a modern economy, waste disposal becomes a serious and pervasive phenomena, rather than a trivial and exceptional one. The contributors are various: transportation, stationary fuel combustion, industrial processes, and agricultural burning. Some products are intentionally disposed, and some are residuals, from both intermediate production processes and final consumption. There are primary pollutants: dust, soot, ash, and smoke. There are secondary pollutants: hydrocarbons, and oxides of nitrogen, sulfur, and carbon.

With respect to the atmosphere, the immensity of the problem of waste disposal can be impressively illustrated with carbon. The earth harbors enormous reservoirs of carbon in the form of gas, oil, coal, and biomass. These undergo combustion, primarily to produce energy for human uses, and as the carbon from these reservoirs is "consumed" by the economy, it must be "disposed" of in the atmosphere, oceans, and biosphere. The apparent inevitability of the exploitation of the earth's carbon wealth and concomitant transfer of huge volumes of carbon dioxide to the atmosphere pose one of the most interesting questions as to what the present state of our atmosphere and its climate are worth. If one were to apply some sort of "residuals generator" to our current economic and technical processes and extrapolate decades into the future as has been done for carbon dioxide, many other ominous quantities would undoubtedly appear destined to find a home in the atmosphere.

Use for disposal of wastes also raises an issue which one familiarly confronts in identifying the value of natural environments: there is a tendency to regard these environments as having value only when they are assumed to offer a future store of extraction, or, in this case, of assimilation. Problems are often considered in terms of the optimal rate of depletion. However, resources may also have another value, realized only if they are left alone. There is a value from an undisturbed environment. An important set of spatial uses relates to such "environmental" or amenity functions. The atmosphere is an important source of aesthetic and recreational values. Even when left alone, one may assume the atmosphere is generating a service, which is degraded by the accumulation of wastes. Amenity and asethetic values may be perceived in terms of wage differentials and land values. Indeed, one recent study (Kneese and Williams 1980) suggests that maintaining atmospheric visibility may be the key constraint to development of energy resources in the southwestern part of the United States. Some features of weather and climate, including nuisance costs of snow removal and so forth, might also be analyzed in some sort of framework of amenity (and disamenity) uses.

While one can tentatively identify a range of uses of the atmosphere (see Table 1), would it be possible and useful to arrange these into some sort of "atmospheric sector" in the style of national income accounts? National income accounts have traditionally sought spatial unity by country or political entity, and for purposes of policy analysis they are divided into production sectors, usually defined by purposes of intermediate production and final consumption. An atmospheric sector could be seen as a further step in developing the two-dimensional spatial and product matrix of economic accounts which describe the economy (cf. Pontecorvo and Wilkinson 1977). To include an atmospheric sector consistently in the larger set of national accounts, it would be necessary to identify which product sectors have activities originating in both the atmospheric and non-atmospheric spatial sectors and identify what portion of each product sector's output is due to the atmospheric sector. The atmospheric sector might be defined as the element of the overall production vector containing those goods and services whose value added can be directly identified with either an extractive or spatial use of the atmosphere, or more broadly, which directly utilize some characteristic of the atmosphere as an input in their production function.

Table 1. An Atmospheric Sector—Outline.

Major Divisions	Activities
I Resource Extraction or Capture	
A Energy Resources	Insolation Wind
B Mineral Resources	Rain (Net Evaporation) Nitrogen Oxygen and ozone CO_2
C Living Resources	Birds
II Spatial Activities	
A Commerce and transport	Air transport, service and handling; departure to and entry from outer space
B Commercial and other	Recreation and sports (amenity, aesthetic) Scientific research Waste disposal Communication
C Construction	Airport facilities Aircraft
D Government (federal, state, local)	National security Administration of air control Weather forecasting Transportation enforcement

Clearly, some value added from production which is identified with the atmosphere takes place on land. The aircraft industry might be a case of this. Indeed, because of the interdependence of economic and physical systems, all sorts of activities might be said to owe their existence to the atmosphere. So, it is necessary to limit the definition of the sector in some meaningful way. The overall measurement system would need to adhere to consistency and independence conditions. Imposing a consistent spatial definition across productive subsectors might be difficult.

To accomplish the actual measurement of income associated with some satisfactorily defined atmospheric sector, it would be necessary to specify the method selected for evaluation of each sector, and adjust for possible non-equivalence of methods. The need for adjustment raises problems from several points of view. Later, some problems relating to evaluation techniques for climate will be discussed. These are largely problems of different cost measures. But, there are also questions about what and where in the production process to measure. These can be illustrated by considering the difficulties involved in evaluating the atmosphere as a receptacle for waste.

First, there is the question of what is waste, or at what point residuals need to be accounted for economically. Wastes may be defined in contrast to "products." From an economic point of view, products can be sold at positive prices, while wastes cannot, or the cost of recovery is more than the value of the recovered material (Page 1977). Pollution goes beyond mere waste. Rothenberg (1970:35) characterizes it as "a competing and dissimilar use of the environment which alters the characteristics of the environmental resources in a way that is in some sense destructive, and in which there is a uni-directional flow of the costs associated with resource exploitation." Thus, by these definitions, CO_2, until its consequences are better understood, should not be labeled a pollutant. Unfortunately, the distinction between constructive and destructive uses is often not clear cut. Moreover, with slowly accumulating long-lasting residuals it may be difficult to use an accounting framework oriented toward assessing annual flows of wealth.

Obviously, some direct costs of waste collection, treatment, and disposition can be identified and estimated. Putting aside for the moment concern about alteration of the weather and climate or pollution of the atmosphere, one could measure the economic activity deriving from the use of the atmosphere as a receptacle for waste by the sum of the capital and labor employed in dumping. This might be relatively small, consisting mainly of the costs of piping wastes (via chimneys) into the atmosphere. The value derived from this use of the atmosphere would be a proportion of the opportunity cost of alternative sites and modes of disposal, which could be very large.

However, there are arguments to be made about whether these dumping activities should then be part of the atmospheric sector. One could argue for the inclusion of industries which dispose of gaseous or thermal wastes because they utilize a spatial characteristic of the atmosphere as an input in their production processes. On the other hand, one could argue for exclusion because the use of the zone may not be necessary for the survival of the industries in question. If access to the atmosphere were restricted, the industries would remain in production by using alternative non-atmospheric disposal technologies. The economic activity generated by employment of resources in defending any specific quality standard for the atmosphere could, at least in theory, be measured in the national accounts framework either by (a) the increase in the gross product originating in the disposal activities, if the waste costs were internalized into the cost structure, or (b) in the externalized costs of cleaning up (or otherwise compensating) the air. An economic rent for the atmosphere would only be realized if the externalized cost is less.

An interesting conceptual variant of this has been proposed by Ayres (1979:120). He suggests the creation of an "abatement sector," which accepts gross residual outputs from other sectors as inputs, even if no processing is actually carried out. The residuals would correspond, in some cases, to production sectors (industrial wastes), and in others to final private consumption (household wastes). Precautions against double counting could be taken by attributing a negative price to the residuals as inputs. But, if we look at a general equilibrium model including environmental links (Maeler 1974), we immediately see the difficulty of a consistent, unified atmospheric sector. The atmosphere is not simply located in the macroeconomic model (see Figure 1).

For several reasons, then, arriving at good, consistent, overall measures of the level of economic activity generated by using the atmosphere as a dump is complex. In addition to the absence of a framework of analysis, not enough is known about the volume and characteristics of waste disposal in the atmosphere. Partly this is due to monitoring expense and difficulties, partly it is due to the fact that one is dealing with diverse sources coming from both production and consumption processes. Also the "need" or desire to know about the amount of disposal varies. Consequences, to the extent they are known, depend heavily on the nature of the particular waste materials, and their quantity and spatial concentration and distribution. One more difficulty may be added to the difficulties so far mentioned. Suppose we wanted to know the costs of holding waste disposal to some specified level that may be "tolerable," what would tolerable limits of contamination be? If Antarctic or primeval standards of purity are applied, the value of the atmosphere will again be virtually limitless. If standards associated with the various uses are applied, the costs will vary from place to place and from time to time according to the uses to which the atmosphere is put, but this does suggest encouragingly that some more modest measurements can be usefully achieved.

One must conclude, then, that it appears at this first exploration of a full national income approach to an "atmospheric sector," that such an idea remains far away, and perhaps impossible to realize fully. However, such a notion, and its further definition, especially with respect to waste disposal, may still be fruitful to pursue.

EXTERNALITIES AND ALLOCATIVE EFFICIENCY

As we have mentioned, there is a tendency toward overexploitation and degradation of common property resources. As long as the resources, including assimilative capacity, of the atmosphere were for all practical purposes unlimited, there was no confrontation with the problem of how to assign them. As soon as scarcity becomes a problem, a principle is

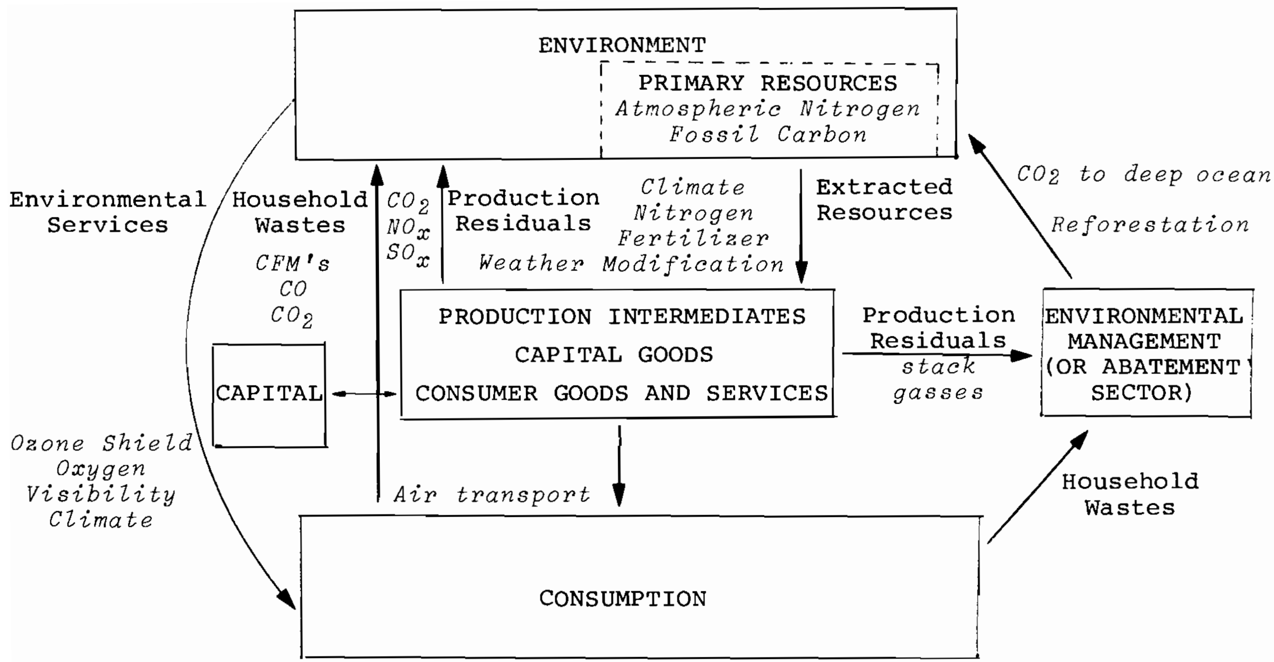

Figure 1. Simple economic model with environment examples related to the atmosphere. (After Mäler 1974.)

needed to determine how scarce goods will be used. Thus, the basic allocation problem is the determination of the socially optimal level of atmospheric goods in all relevant dimensions. One strategy, which we will explore here, is for economic efficiency to govern all allocations. This discussion is phrased in terms of a market economy, but the underlying issue of externalities is endemic to all economic activity, although in centrally planned economies it may not manifest itself primarily as a shortcoming of the price system.

The general efficiency rule is that more atmospheric goods should be provided up to the point at which additional social benefits no longer exceed additional costs. If producers, users of the atmosphere, maximize profits while taking into account "externalities," optimal production allocation can be achieved. Problems arise, however, because the atmosphere is characterized by elusive externalities, and the absence of information provided automatically in market transfers sometimes makes it difficult even to determine the magnitude of the relevant benefits and costs. What are these externalities which tend to be omitted from the decision calculus and confuse the optimal management of atmospheric resources?

"Externalities" is a term used to describe effects on persons or firms who are not directly party to a decision leading to an activity. While the definition has been much argued, and remains in debate, we may offer a variety of descriptions which give a good feeling for the notion. Externalities are the side effects, or spillovers, associated with human behavior, ranging from minor impingements on amenities to major irreversible effects on life. An externality is said to exist whenever an output of one economic agent appears as an input in the consumption or production vector of another, without accompanying payment (Holtermann 1972).

> Externalities arise whenever the value of an objective function, for example, the profits of a firm or the happiness of an individual, depends upon the unintended or incidental by-products of some activity of others (Lin 1976:1).

Heller and Starrett (1976:10) have emphasized the aspect of markets.

> One can think of externalities as nearly synonymous with the existence of markets. We define an externality to be a situation in which the private economy lacks sufficient incentives to create a potential market in some good and the nonexistence of this market results in losses of Pareto efficiency.

For Heller and Starret, the relevant market failures consist of:

(1) difficulties in defining private property or nonexclusiveness of commodities;

(2) noncompetitive behavior;

(3) nonconvexities in transactions sets;

(4) imperfect or incomplete information.

What do these market failures mean? They mean that commodities characterized by externalities will either not have prices or the prices will in some sense be incorrect. The result is that, as Pigou (1932) pointed out, externalities appear as one of the chief causes of divergence between "private net product" and "social net product." As Kneese and Schultze (1975) have argued,

> The problem is not that the price system does not work—it works with marvelous efficiency but in the wrong direction. When the signal it sends out indicates that air and water are free goods, thousands of firms and millions of consumers bend their efforts to use those cheap resources. And so electric utilities dispose of their sulfur residuals from coal and oil not by scrubbing them from their stacks or by other expensive means but by pouring them freely into the atmosphere...And consumers avoid the cost of eliminating hydrocarbon emissions by depositing them in the air.

and:

> In most circumstances the price system provides incentives for economizing on scarce resources. Those who use such resources must pay for them, at a price that reflects scarcity. Goods whose production requires scarce resources in large amounts are expensive compared with those that do not, so consumption of the former is discouraged and use of the latter is encouraged. Business firms, motivated by the search for profits—indeed, by the need to survive—seek ways to minimize the use of costly resources in their production processes. But since the waste-assimilating capacities of air and water as common property resources do not command a price, the private market system encourages their overuse rather than their conservation.

and:

> The free use of the air and water as dumps for residuals, therefore, creates a situation in which the costs and the prices of goods and services diverge in varying degrees from the true costs that their production and consumption

impose upon society. The greater the environmental damage caused by residuals from any particular production or consumption activity, the greater the divergence.

It is easy to see the extreme external diseconomy of several uses of the atmosphere. "Pollution" in a modern industrial economy is the all too pervasive consequence of production and consumption activities of virtually all firms and households. The degree of externality of pollution may vary. Imagine the different responses to a firm dumping its wastes onto its own property, directly onto someone's garden, or into the atmosphere. While the diseconomy is obvious in all cases—consumption of pollution obviously reduces the utility of consumers or the profits of producers—the degree of externality allows varying persistence of divergence of private and social cost and varying amounts of interference with efforts at optimal allocation. But, the question of externalities is not just one of remembering to include some of the often omitted negative element in the decision calculus. In certain cases the external costs may be quite ambiguous. For example, the social costs of a potential climate-altering activity, such as the use of CFM-powered spray cans, may be made up of distinct components, private costs, such as those for labor and capital goods which are directly used in the creation of the product, and external costs, which are probably not only unmeasured, but also could include, in theory, either the reduced *or* increased (and redistributed) output of the economy as a result of climate change.

Just as there are negative and ambiguous externalities associated with the atmosphere, there are also many respects in which the atmosphere, or the use of it, is a public good. Consider an array of all possible goods and services running from pure private goods, where property is private and access is limited by rights which are bought and sold, to common property with open access. One of the principal distinguishing characteristics is the degree of externality involved in their production and consumption. A public good is the service provided by a common-property resource under conditions of no exclusion (or where the difficulty or costliness of exclusion is prohibitive) and demand insufficient to generate congestion or marginal resource costs. It is the positive limiting case or extreme of an externality. Environmental quality is very close to a pure public good. Once provided for one, it can be enjoyed by others in society at almost no cost. But, like pollution and other negative externalities, the positive externalities associated with the atmosphere, including its health, amenity, and possibly climatic values, have tended not to pass through markets or be included in evaluation activities. Of course, the development of air quality standards represents a change in this situation.

One way or another then, one wishes to "internalize" external costs (or benefits). Staying for the moment with the example of negative externalities of production processes, one wants to induce the incentive of the firm to increase (or reduce) production to the point where price equals internal marginal costs and environmental costs. "Transferring social costs to the responsible firms could serve two purposes: It could lead the firm to reduce the pollution aspects of its activities or, as the internalized costs are passed on in higher prices, it could signal consumers, to shift away from pollution-intensive products, or both" (Page 1973:6). There are several strategies to try to bring about the internalization of costs and optimal allocation under conditions of externalities. One school (Coase 1960) has emphasized private bargaining. Another group has preferred governmentally imposed tax or subsidy schemes for achieving efficient resource allocation, especially where decentralized bargaining is expensive or impossible.

Basically, the bargaining solution calls for the formation of a new market. Are markets for the uses of the atmosphere feasible? The fact that such markets generally do not exist suggests that they are not feasible. However, there are indications this situation may be changing. In Long Beach, California, there has been activity which resembles the creation of a pollution rights market (New York Times, 1 August 1977). Firms are being given the incentive of seeking the lowest cost alternative in buying and treating a certain amount of pollution from existing waste sources, which they can balance against new discharges. But, generally, the situation is difficult. Those who wish to buy reduced air pollution are usually not able to call forth a supply response. This kind of market solution requires the existence of enforceable property rights to the environmental resource, and the possibility of contractual agreements between parties affected by the externality and those responsible for its creation.

Moreover, the establishment of property rights may not succeed in resolving the externality problem. A reason often cited is that the transaction costs may exceed the per unit potential profit, for example, in cases of waste disposal. The likelihood of market failure is greater the larger the number of parties involved in the externality relationship, and the more complex the relationships are. In any case, whenever exclusion is costly or impossible, property rights are difficult to define meaningfully, and this is the case with respect to most uses of the atmosphere. In fact, by definition of the atmosphere as a public good for selected purposes, exclusion is an unacceptable policy for certain activities. Heller and Starrett (1976) point out that when exclusion is undesirable, we should clearly not establish a market by assigning property rights to any physical commodity. Thus, with many of the attributes of the atmosphere, we have tended to find various other forms of regulation rather than developing private markets.

Still, it is intriguing to consider whether, for example, a CO_2 market could function.

It is clear that the widespread and persistent presence of externalities is a major obstacle to achieving an efficient allocation of atmospheric resources. But let us put aside this problem for a moment, and see what cost and benefit estimates might still be undertaken and whether they might still lead us closer to an optimal treatment of the atmosphere.

MEASURING ATMOSPHERIC COSTS AND VALUES

We have been suggesting in this paper that, from an economic point of view, the ideal treatment of the atmosphere would identify its highest value in alternative uses. Resources would be allocated to those uses in which social benefits exceed social costs. Efficiency would be achieved by pursuing these activities to the point at which social benefits cease to exceed the social costs at the margin. Presumably, the atmosphere can accommodate several uses, although, as we have seen, there may be conflicts among certain uses or attributes of the atmosphere. Because of the potential of certain uses of the atmosphere to change the supply of atmospheric resources for other purposes, for better or for worse, as with waste disposal affecting the supply of climate, it is desirable not only to analyze current uses of the atmosphere and include or discourage them according to the efficiency criterion, but also to compare the current ensemble of uses with different potential patterns of utilization.

In order to arrive at a highest or optimal value of use of the atmosphere, one thus needs to know the benefits and costs of the various uses, both the current ones, which includes the "production" of our present configuration of macro- and micro-climates, and other feasible ones. What is the present state of measurement of uses of the atmosphere? Can it approach the certainty or knowledge needed for an optimal allocation?

As we have seen, there is little direct measurement of the flow of wealth associated with uses of the atmosphere, and this is true of environmental intangibles in general (Coomber and Biswas 1973). However, while there may be no direct market for air quality or climate, there are indirect ones, for example, for the sites which experience the relevant conditions. To illustrate, an individual contemplating migration to an area with atmosphere N_1, faces a level of *per capita* air pollution costs of C_1, or the average air pollution cost level associated with density N. If he moves to the city, he will have to pay the amount C_1 (plus some small amount added for his own marginal contribution) either in the form of pollution prevention costs, journey to work or, for example, in the form of outright welfare damage to his health and property. He will rationally migrate to the city at this density level only if a sufficiently high wage differential or other net advantage of living in the city compensates him by at least an amount of C_1. Clearly, people will pay to avoid air and climates that are not attractive by travelling long distances, purchasing filtration systems, venturing outside as little as possible, etc. Among others, Hoch (1975) has explored this situation with respect to climate, while Seneca and Taussig (1979) explain the argument in greater detail with respect to air pollution.

With respect to atmospheric goods, it can thus be said that in purchasing a site, an individual is assured the provision of the nonmarketed service as an attribute of the site. There is a kind of weak complementarity between the public good and a private good, with an observable linkage. The problem is to know the relation between objective measures of the level of the services of the environmental common property resource at a site and the individual's perception and evaluation of them. In concept, one can arrive at this relation because it should be possible to measure the marginal costs of meeting certain levels of residuals abatement and thereby increase (or decrease) the availability of the services of the environmental resource. In practice, this kind of analysis turns out to be somewhat more difficult and complex than expected. We shall illustrate the problem with a discussion of cost measures and property rights.

While one line of argument (Coase 1960) has it that resource allocation, explicitly, and resource valuation, implicitly, are invariant with respect to property rights, variation in value corresponding in general to different assignments of property rights can be demonstrated. In fact, with respect to uses of the atmosphere, there are at least three theoretically correct measures of cost. If it is accepted that there are several potentially significantly different measures of the values of these uses, the question of which is appropriate naturally arises, as well as the question of how to combine and compare. First, let us look at the different measures of costs.

One way of assessing the value of things like climate and air quality is by a "willingness-to-pay" (WTP) criterion. For example, the demand curve for clean air may be estimated as the measure of the willingness of the population to give up income for cleaner air. Such an estimate depends on the assumption that the public must pay for the property rights to environmental resources. If the waste disposer has the initial property right, then the consumer, with a given budget line, would be willing to pay an amount which would leave him just as well off as before the transaction for the right to use (part of) the site for its amenity service. Clearly, this measure is not only a function of willingness to pay, but ability to pay. It is bounded by income. While there may be some information on this kind of transaction, in general WTP involves not only the current costs of resources, but also intrinsic preferences or preferences not currently expressed in markets by individuals (d'Arge 1975).

Now, alternatively, begin from the plausible assumption that property rights to the atmosphere (air quality, climate, etc.) reside in the general public and cannot be appropriated by any private parties without adequate compensation. Then, one asks, what is the minimum amount all individuals would collectively be willing to accept as compensation to give up their rights to all higher (better) levels of supply. While the WTP seeks to determine the maximum amount the consumer would be willing to pay to remain in the original regime, this measure of "opportunity cost," here in particular a "willingness-to-sell," (WTS), seeks to determine the minimum compensatory income necessary to render a consumer indifferent. The amount the consumer would accept is largely independent of his income and typically would exceed the amount he is willing to pay. The difference between opportunity cost and willingness to pay is in the presumption regarding property rights, that is, on whom the burden for compensation is to fall. Opportunity cost measures presume the consumer is to be compensated. Willingness-to-pay measures, conversely, presume that the consumer is to pay compensation to prevent a change.

A third theoretically valid measure of value is alternative cost. Alternative cost tries to estimate how much it would cost to provide an equivalent bundle of goods and services by some other means. For example, in the area of water resources, how much would it cost to implement programs and construct required facilities to meet a region's postulated needs during some future period if the climate changed? The difference between net willingness to pay and alternative cost is shown in Figure 2.

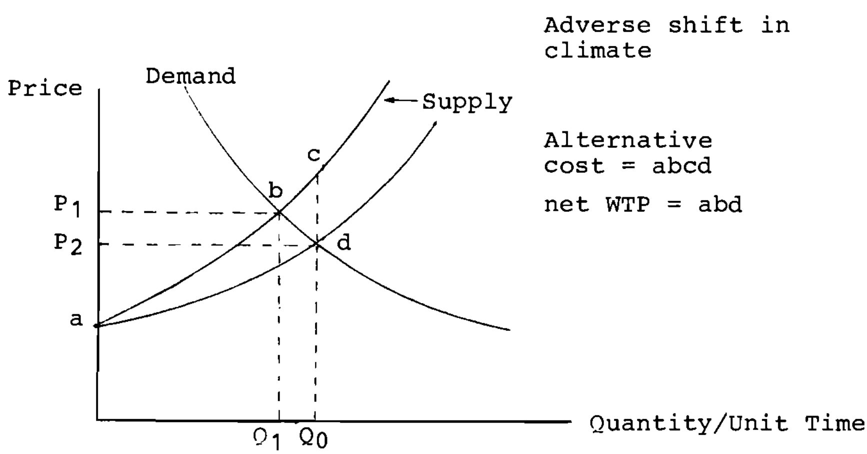

Figure 2.

> The essential difference between the opportunity cost and alternative cost measures is in the applicable constraint. In calculating opportunity cost measures, the individual is constrained to be indifferent; in calculating alternative-cost measures, he is constrained to the same consumption pattern (at least to a subset of the same consumption pattern)(Anderson *et al.* 1975, section 4:5).

One is inclined to think that the possibilities for empirical estimation of alternative cost measures is much greater than that of opportunity cost measures (both WTP and WTS). While estimation of alternative cost measures requires determination of the ways in which consumers can combine goods and services to produce utility-yielding characteristics, this kind of determination is probably less difficult than learning about the basic consumer valuation of the characteristics themselves.

In addition to conflicts arising because there may be several conceptually satisfactory, but quantitatively varying, ways of measuring the uses of the atmosphere, the measurement itself will be drastically inhibited by data difficulties. As Anderson *et al.* (d'Arge 1975, section 4:6) have written,

> Without knowledge of individuals' utility functions or direct experimentation, it is strictly impossible to evaluate either opportunity cost or willingness to pay measures. Use of measures of consumer surplus obtained from empirically estimated demand functions to estimate willingness to pay, as is well known, is only an approximation—and not always a very good one.

Numerical solutions will tend to come from disturbingly simplified cases, and they may be very sensitive to error in functional specification and assumed parameter values.

Moreover, as one estimates the value of the various uses, or performs "impact studies" of climate change, the various different valuation methods will be used, out of necessity. This will be on account of inadequacy or limited availability of data in certain cases, but in others because a good measure for one type of use, for example, the amenity services of clean air, may be a poor measure for another type of use, for example, climatic resources needed in rice production. Because different sets of measures will be used to derive approximations of losses and benefits, consistency among the measures will be difficult to achieve. In some cases, it may be that the difference between using different measures would be trivially small; but in others, it might be significant. Moreoever, realistically, no examination will be comprehensive. In an examination of the value of present climate for agriculture, important crops are likely to be left out or only poorly considered. As one looks at changing ensembles of uses, important effects will not be anticipated. Thus, it will be very difficult to sum the uses of the atmosphere and climate at any given time, much less compare one summation against another. (See d'Arge 1975.)

Moreover, all the measures we have talked about are essentially ones which hold at the margin, that is, for small changes in price and quantity. As changes become larger, or as they interact, the validity of the whole measurement project comes more and more into question. Nevertheless, it may be that for certain policy decisions, the information at the margin is all that is necessary. While for optimal control it is desirable to have information about all the stocks and flows of wealth associated with the atmosphere, for certain decisions much more restricted information may be useful. But there is no getting around the fact that for the larger issues, like those relating to human activities and climate change, one would like a grand piece of analysis: a figure for damages, which would be a summary number over many crops, sectors, and geographic areas, which would be a function primarily of a vector of climate variables, which in turn would be a function of a vector of accumulated emission components, and secondarily of direct effects of the emissions; and also a summary figure for benefits, which would be a function of (a) the vector of climate variables, which would be a function of the emission component vector, (b) direct benefits associated with the emissions, like fertilization of the atmosphere from CO_2, and perhaps (c) some sort of consumer surplus measure associated with emission producing activities, such as the use of fossil fuels, or other means of including costs of prevention or abatement in the calculation.

Finally, there are the uses of the atmosphere which are difficult to monetize at all. Some aspects of nature and human activity are simply not well-denominated by money, while for important changes, which may take place in the environment, people may not be able to have well-articulated preferences, even if the changes are foreseen, which often they are not.

If not dissuaded from certain ambitions by the difficulty of the measurement task, one can still add that even with accurate and detailed information for economic management of the atmosphere there would be perplexing questions from the point of view of "atmospheric optimization." Some recent general equilibrium models have taken the step of seeking optimal policies for economic growth in the presence of resource constraints and a degradable environment, where the degradation is a function of the rate of extraction and consumption. A degradable environment is roughly equivalent to calling the environment an exhaustible resource. For certain purposes one can think of the atmosphere in these terms. For example, the atmosphere might be thought of as having an elasticity with respect to climate as a result of human modification. In the extreme, if human activity were to change the climate of earth to that of, say, Venus, clearly it would be equivalent to exhaustion of climate resources. If one thinks that there is some sort of ceiling then to the use of the atmosphere as a receptacle of waste, whether it is for climatic, health, or other reasons, such a model might apply.

In general, one would expect that extraction and consumption will be discouraged by environmental disamenity (or negative climate change) costs. But, this is not necessarily the case. In one exploration by d'Arge and Kogiku (1973) a rather discouraging result is obtained. Consumption should be sufficient to equate the marginal utility (or shadow price) of consumption to the marginal disutility of the associated waste output, which is assumed to increase as the density of accumulated wastes increases. Consequently, optimal consumption is initially lower when the pollution level is lower. Later it rises as people consume faster to compensate for the disamenity of a high cumulative pollution level. A potential analogy with CO_2 is easy for us to imagine. Carbon is extracted and changes the climate as it is transferred to the atmospheric reservoir. The more the climate changes, the more carbon is extracted to compensate for the changing climate, and the faster the climate changes in turn. This result, symptomatic of some short run optimization, shows that even good information on the uses of the atmosphere might lead to socially unsatisfactory management of the atmosphere. Even if one could treat CO_2 as a big programming problem, distributional questions would have to be faced. What appears optimal here, today, may very well not be desirable in another place, tomorrow.

DISTRIBUTIVE ISSUES

Up to this point we have examined the problems of exploitation of atmospheric resources from the point of view of allocative efficiency. However, there is another major criterion for the formulation of social policy, namely, equity. Are the income distributional impacts of use of the atmosphere an issue, or are they insignificant enough to be safely ignored? The problem here is the traditional one in welfare economics. Any project or policy is likely to result in gains for some individuals, or groups, and losses for others. Schemes of efficient allocation basically try to add, algebraically, all the gains and losses over all the affected individuals to determine the net gain from each of the alternative uses of an area's resources. Thus

> ...underlying any policy prescription from a benefit-cost analysis of a resource use is the potential Pareto, or Kaldor-Hicks criterion, according to which a project is efficient, and presumably therefore desirable, if the gains exceed the losses, so that the gainers could

> compensate the losers and retain a residual gain. Of course, this is not satisfactory to one who is concerned about the actual distribution of gains and losses from alternative use of an environment or any other resource (Krutilla and Fisher 1977: 28-29).

Under such circumstances, the policy maker must select a degree of efficiency, as, for example, measured by output foregone, which he is willing to trade off to achieve a given distributional objective.

While atmospheric resources may be widespread and open for most purposes, they still tend to be subject to more concentrated use by certain specific groups. As with most resources, benefits from using those of the atmosphere tend to be allocated in proportion to the quantity consumed, and consumption has been essentially on a first-come, first-served basis. Thus, questions of equity of atmospheric exploitation depend both on the equity of the present distribution and of proposed alternative patterns. What can be said about the distributional effects, both in time and space, of the present and alternative arrangements?

To illustrate this, let us look at distributive effects of the present climate and a policy to prevent a CO_2-induced climatic change. Present climates have obviously favored human settlement and economic activity in some regions more than others. Those who currently live in pleasant and favorable climates will plausibly gain more from restricting CO_2 than those who do not. At the same time, preventing climatic change will raise the costs of those goods and services whose production, or consumption, may have contributed to a change of climate. The price of electricity may rise, as utilities switch fuel sources. Machinery with CO_2 control equipment may be more expensive to own and operate, and property taxes may rise as municipalities construct and operate CO_2 scrubbers. Overall, costs of climate conservation will probably resemble excise taxes, with the heaviest taxes falling on goods whose production "pollutes" most. The costs of climate conservation will be widely borne by individuals, as producers, consumers, and taxpayers.

A period of adjustment to a climate conservationist position could bring other kinds of costs. Some firms, finding that they simply cannot afford the costs, may have to cease operation and go out of business. Indeed, some industries including ones like coal mining around which whole communities may be based, might have to close down important facilities. In contrast, some areas may have prepared for modifications of their climate. Their investments may prove worthless, while they still have to pay higher prices required to cover the costs of producing goods elsewhere under conditions which do not lead to climate change. (*Cf* Kneese and Schultze 1975.)

Obviously, the benefits of climate conservation will not be distributed equally. For those who make windmills or nuclear power plants, it may prove a bonanza, while for some portions of the labor force and some localities there will be painful transition costs. However, at present we have almost no information in several respects about what the distribution of benefits and losses will be. One can make guesses based on geographical analysis about where people stand to gain or lose. But will the poor suffer more than the rich? Will the urbanite care less than the suburbanite who spends so much effort on a green lawn? Or will he prefer an easy-to-care-for cactus or a tropical fern to today's temperate vegetation? In the long run, industrialized economies should be able to absorb the labor and capital displaced by these adjustments, and various forms of assistance can be devised to ease the adjustment process, but climate conservation could alter the distribution of income, even if both benefits and losses are widely distributed. Would it alter the distribution more or less than climate change?

What is the distributive situation at the international level? We have said that the net benefits of atmospheric use presumably accrue principally to the nations that produce and consume such services. This suggests that the principal national beneficiaries of the CO_2 increase, at least in the short term, are those countries engaged in carbon extraction, trade, and combustion. If we reason that there is a benefit associated with the production of CO_2 emissions, it becomes interesting to ask what is the present origin by region of such emissions. Following Pearson (1979:271), my estimation of the distribution of emissions from burning of fossil fuels and cement production can be seen in Table 2. Similarly, one may look at the world distribution of coal resources as a proxy measure of potential contribution to an extremely serious CO_2 scenario (see Table 3). Clearly, the beneficiaries of the production of CO_2 from an enormously enlarged coal economy are very unevenly distributed.

Table 2. CO_2 emission by region: 1973

	Developed countries	Developing countries	Centrally planned economies	World
Total carbon converted to CO_2 in Gt	2.67	0.48	1.37	4.5
Percentage world totals	59	11	30	100

Table 3. World Distribution of Coal Resources (in 10^9 tce).

Greater than 10^{12} tce ($1{,}000 \times 10^9$ tce)		Between 10^{11} and 10^{12} tce (100 and $1{,}000 \times 10^9$ tce)		Between 10^{10} and 10^{11} tce (10 and 100×10^9 tce)		Between 10^9 and 10^{10} tce (1 and 10×10^9 tce)	
USSR	4,860	Australia	262	India	57.0	GDR[a]	9.4
USA	2,570	FRG	247	South Africa	57.0	Japan	8.5
China	1,438	UK	163	Czechoslovakia	17.5	Columbia	8.3
		Poland	126	Yugoslavia[a]	10.9	Zimbabwe	7.1
		Canada	115	Brazil	10.0	Mexico	5.5
		Botswana	100			Swaziland	5.0
						Chile	4.6
						Indonesia[a]	3.7
						Hungary[a]	3.5
						Turkey	3.3
						Netherlands	2.9
						France	2.3
						Spain	2.3
						North Korea	2.0
						Romania	1.8
						Bangladesh	1.6
						Venezuela	1.6
						Peru	1.0

[a]Mostly lignite.

Source: Based on data after World Energy Conference (1978).

The principal losers, if any, will be those societies in which economic activity will be adversely affected by climatic change, and those, in the case of a preventive strategy of climate conservation, who are left holding untransformed stocks of carbon. Thus, the question of equity appears again: is it just for those favored by geographic endowment or technological capability to act unilaterally (by stimulating the carbon economy) without being held accountable for consequences to other users of the atmosphere? Such action, may, for example, raise the price to others of access to preferred supplies (through a need to shift agriculture to areas without equally good infrastructure), use up those supplies (by increasing scarcity of temperate climates for agriculture), or degrade the quality of future supplies (for example, by increasing variability of climate). Those who cannot themselves exploit atmospheric resources, particularly as a receptacle for waste, may seek to obtain rent from those who can, or at least share the benefits with them. Or, they may try to forestall the use of the resource, until they can develop their own exploitation capability.

Issues of distributive justice have assumed growing importance in arguments about international order during recent years. As d'Arge and Kneese (1973) have pointed out:

> No nation will easily accept international agreements on entitlement of universal common property resources without compensating payments to retain its perception of national wealth. In consequence, the classical answer to externality problems of internalizing the decision-making process for the resource is not easily transferable to these transnational problems. A new overriding element of distributional gains and losses must be simultaneously included in efficiency considerations.

The efficient allocation of the uses of the atmosphere at the national level will probably not resolve the distributional implications of climate change satisfactorily from an international point of view, and perhaps not from a national point of view either.

Lurking in this discussion is the second major feature of the distribution question, intertemporal fairness. This is a serious question with respect to use of the atmosphere. The atmosphere is not only jointly valued by many communities and nations but also by many generations, and in the context of the brief history of industrial civilization the life of some atmospheric problems may be very long. When the present generation evaluates alternative uses of the atmosphere, it is making judgments about the welfare of future generations relative to the welfare of the current generation. On the one hand, measures taken today may reduce the consumption level of those presently alive and raise the consumption level of those not yet born. On the other hand, current decisions may indicate society's willingness to transfer potentially catastrophic or risky prospects to future generations.

As Krutilla and Fisher (1977:39) point out:

> Some of the distinctive and challenging problems for valuation and allocation of the resources of natural environments are dynamic. Clearly, if decisions with respect to the use of these resources are impossible to reverse in a way that ordinary economic decisions are not, effects over long periods of time must be considered.

The problem here is similar to the one of choosing the correct social rate of discount, an indicator of society's willingness to transfer income or wealth over time. This is an extensively argued question in economics, often revolving around the determination of the discount rate for public projects. As Pigou (1932) first suggested, the conservation of exhaustible natural resources might be achieved through lowering of the discount rate in evaluation of projects involving their exploitation. Why should this question of discount rates be at issue?

It is conventionally argued that the market-determined rate of discount (interest) is partially determined by the private time preferences of the present generation of individuals. There are, of course, important ethical implications to the fact that only the present generation of humans participates in the decisions as to what proportion of the natural endowment will be preserved for the future. There is a rampant assymetry in this intergenerational distribution decision which makes its bias dangerous to forget. In addition, one may cite the lively debate in philosophy, involving Singer and others (Singer 1977; Singer and Regan 1976), about the rights of animals. In fact, the questions of environmental preservation and species habitat and distribution may turn out to be major ones, as problems such as climatic change and acid rain could have drastic implications for national parks, wildlife preserves, and so forth. Such issues aside, it may be expected that

> ...individuals with finite life expectancies, among other things, are likely to be guided in their private consumption decisions in a manner that is not necessrarily optimal for a society that has a collective commitment to life in perpetuity. Accordingly, the supply of funds available for investment is at least influenced by private time preferences that depart from what might be a collectively determined social time preference. The rate of discount will be too high and the level of investment too low to make adequate provision for future generations (Krutilla and Fisher 1977:61).

(Of course, we do find counters to this tendency, for example, in the setting aside of parks and in the behavior of some firms, such as timber companies, which may be planting trees that grow on an 80 year cycle.)

Two factors further complicate the question of economic evaluation of the future. The first is uncertainty. In many cases, of which the atmosphere is exemplary, information about benefits and costs of alternative uses is extremely poor, due both to the long period of time over which projections are needed and to technical evaluation problems, such as are connected with common property resources and externalities, as well as to uncertainties transferred from the physical sciences. The second factor is irreversibility. In some sense, of course, all human actions are irreversible, but the term does capture a particular quality of a subset of decision situations. If, for example, a natural environment, once developed or used, cannot for some combination of geophysical, ecological, and financial reasons be restored, then the appropriate social attitude toward decisions regarding it should in some way be different.

What makes irreversibilities important? As Wilen (d'Arge 1975, section 2:113) has written:

> In a world of perfect certainty, whether the consequences of a particular action were irreversible would not really matter. In such a perfectly certain world, decision makers would know the preferences of present and future generations, the physical processes that take place outside of the social systems sphere, and the linkages between physical and social systems. Decisions could then be made that maximize net social benefits over the entire planning horizon; and hence, no decision would ever require reversal of its consequences.

With the atmosphere (indeed, with society), the rule is that information is uncertain, both with regard to physical consequences and economic evaluation. The uncertainties would be of little consequence if the effects of a "wrong" or inefficient decision can be quickly or cheaply reversed. Losses might even be recovered; the overall net from the sequence of wrong decisions plus corrective policies could be positive. However, if the results of an action are irreversible, the possibility of a loss in perpetuity clearly increases. But still, the loss might be of trivial dimensions. Thus, it is important that the costs of the incorrect irreversible decision be potentially large.

In the case of the atmosphere, physical scientists have presented the public with a series of "threats" over the last decade. Possibilities of very large scale costs to health were at one time connected to stratospheric flight. More recently the principal potential threat has been a rise of sea level as a consequence of changes in polar ice caused by extreme climatic change from increases in atmospheric carbon dioxide. Indeed, the consensus of a distinguished group of scientists at a recent workshop (AAAS, Annapolis, 1979) was that a scientifically defensible case can be made that the possibility of disintegration of parts of the Antarctic ice sheet should be taken seriously, through there is no immediate cause for alarm. While the particular causes of disastrous perturbations of the atmosphere may come and go, it is, unfortunately, all too convincing that something very dangerous may be going into the air. Thus, with respect to the atmosphere, the two conditions which are important for irreversibilities, namely the lack of good information and potentially large costs, hold. The significance of irreversibility is further heightened, in this case, by the fact that the atmosphere has common property characteristics: people are not in a position to reject any consequences they do not like. They will be shared.

Arrow and Fisher (1974) have argued that this feature of irreversibility evokes an option value. The passage of time may result in new information about the costs or benefits of alternative uses of an environment, and this knowledge may inform the eventual decision if the decision to develop or use has been deferred. In contrast, since development is not reversible, once a decision to develop has been made, it cannot be affected by the presence of new information which suggests that it would be a mistake in the future. The analysis of Arrow and Fischer (1974) shows that in cases of irreversibility there is a positive option value to refraining from development. Other formulations suggest that this option value can be regarded as a risk premium. (See also Schneider and Mesirow 1976, on an idea of "global insurance.") Intuitively, it is easy to understand such ideas as being indicative of the need for policies which can compensate for the asymmetric implications of intertemporal decision situations.

An example which captures the problems of discounting, uncertainty, and irreversibility, may easily be presented for CO_2. At present, it is very possible that calculations using a positive discount rate (the US Department of Transportation's Climatic Impact Assessment Program used 3, 5, and 8%) would yield the result that the "project" of burning up available fossil fuel reserves for the next 40 years and using the atmosphere as a receptacle for waste would be attractive: net gains would exceed costs. According to Kaldor-Hicks or Pareto criteria the project should be undertaken, because the gainers would compensate the losers and still have something left over. With the project there is a reallocation of goods that would make everyone better off. However, as the present value criterion slides forward through time, future generations may be increasingly less desirous of the project, either because of its costs or because they prefer the services provided by the unused environment.

At some time (t_1) in the future, benefits from the project are less than benefits from foregoing it. The gainers from not having the project could compensate the losers, i.e., all those who would benefit from having the project. It may even be possible that the gainers could compensate all those benefiting in the period between the present and this future decision. Were bargaining possible, conceivably the future generation could compensate the present for not pursuing a project which would otherwise provide net benefits, especially in the period between now and t_1. As in the first case, there exists a reallocation of goods that would make everyone better off, only now it is without the project. Thus, under such conditions, intertemporal welfare tests can yield ambiguous results.

The foregoing discussion is not meant to diminish the validity of discounting. Discounting is merely an implication of, as Koopmans (1979:7) has put it, the

> ...simple fact (that)—short of capital saturation—society can temporarily curtail the production of current consumption goods by transferring some factors of production to the formation of additional suitable capital goods, in such a way as to return a multiple (>1) of the same unit bundle of consumption goods in the future.

The confusion and difficulty arises because, in practice, as Koopmans goes on to point out, present values tend to reflect a curious mixture of the present preference between consumption and production, an assumption about savings behavior of coming generations, and an intertemporal ethical rule. It is the intertemporal ethical rule, perhaps unquantifiable in some respects, that in balancing risks to human life in the present and in the future one is inclined to feel that equal numbers of lives should receive equal weight, making the "present value" of future human life independent of the time at which it is lived, in contrast to the present value of a bundle of consumption goods, that specially complicates the evaluation process.

Clearly then, one can argue that resource depletion and the future long-term quality of the environment, in this case relating primarily to the use of the atmosphere as a receptacle for waste, are not merely problems of market failure, but distributional problems. They may be even more difficult than internalizing cost, because people and nations will not agree on the distributional criteria for societies. Should the criteria emphasize maximization of returns to the international community? Conservation of natural resources? Passing on a stock of environmental wealth *per capita* at least equal in value to the one which was inherited? Or, in contrast, passing on a legacy of infrastructure from development which will minimize the "loss" from environmental change? The decision rules and the population to which they apply remain open questions.

DECISION ANALYSIS

When faced with major atmospheric policy questions such as the threats to the ozone layer or climatic change, is it possible that decision analysis would be applicable to choosing among the uses of the atmosphere? The traditional method of decision analysis essentially consists of determining the monetary value of each potential state of the atmosphere (or ensemble of uses), or some other kind of social indicator or set of them (lives lost, or life span, for example) and weighting it by the probability that the state will occur. What would one need to do this? To begin with, one would want detailed current and projected information on the use of the atmosphere, as, for example, a receptacle for the specific waste. Then one would want valid relationships about rates of residuals emission (and accumulation) and atmospheric effects. Then, one would need information on the cost of residuals control and regulation, and of course, one would need a complete and concise estimate of costs and benefits evolving through time from atmospheric changes according to the different levels of use of the atmosphere as a sink for the waste.

All this is to say, that one would like to foresee every possible event and know all the relevant characteristics of all possible evolving alternative states. Or, as Fischhoff *et al.* (1979:18) have written, decision analysis assumes

> ...all possible events and all significant consequences can be enumerated in advance, that meaningful probability, cost, and benefit values can be obtained and assigned to them; and that the often disparate costs and benefits can somehow be made comparable to one another.

What is the situation with the atmosphere? Clearly we must make decisions "without knowing every potential event or, at best, knowing only a few characteristics of potential states" (Wilen (d'Arge) section 2:114). In fact, the underlying assumptions, with respect to allocations of the atmosphere, must be at the opposite end of the spectrum for what is desirable for decision analysis. Our present knowledge of our use of the atmosphere and the value of these uses, including climate, is very poor. It would be difficult simply to come to a consistent estimate of the value of our current practices. As we try to estimate and evaluate cumulative uses or changing uses, the transfer functions between cause and effect are subject to extreme uncertainty at the times the decisions are being or will be made. Indeed, the assumptions we must make are all of continuing uncertainty. For example, with respect to climate:

— there are large uncertainties in the effects on climate of various emissions. It is sometimes assumed that resolution of these uncertainties would make the question of deciding on how to use the atmosphere easy; but alas,

— there are large uncertainties about translating the effects of changed climate and atmospheric composition into effects on the managed and unmanaged biosphere and other aspects of the environment; and
— there are large uncertainties about how societies and economies would react to these changes, especially in a dynamic context of other major world developments and technological change; and
— it is quite possible that none of these substantial uncertainties will be reduced in the next decade.

In other words, the often assumed process of learning over time may be irrelevant. It is possible we will face virtually the same decision in 10 years that we face now, with only slightly more reliable information.

While all of these problems undermine decision making based on the estimation of the value of uses of the atmosphere, there is a companion problem that is often ignored. Suppose we have, in some sense, a good estimate of the value of continuing to put CO_2 in the atmosphere, a forecast of the climate 50 years from today, a good deal of information about redistribution of biota, and so forth. There would still be an enormously difficult issue of evaluating use for climate-changing waste disposal. People can hardly be said to have well articulated preferences about the uses of the atmosphere. As Fischhoff *et al.* (1979:33) have pointed out, on new and complex issues people's values may in some fundamental sense be incoherent. They may be unfamiliar with the terms (social discount rates, miniscule probabilities, megadeaths) in which the issues are formulated, and they may not even know how to begin thinking about some issues (gradual rise in sea level). They may have contradictory values (desire for environmental preservation and desire for energy-intensive existence), and vacillate between incompatible, but strongly held positions (need for regulation and importance of minimal government). Finally, "their views may change over time (say, as the hour of decision or the consequence itself draws near), and they may not know which view should form the basis of a decision." In fact, people occupy different roles in life which will continue to produce clear-cut but inconsistent or conflicting values.

Is there still some method society can apply to the kinds of atmospheric policy issues we have mentioned? Some way to try to value the consequences of decisions involving potentially severe or even catastrophic outcomes, when the outcomes can only be barely sketched, if at all, and probabilities of such outcomes are unknown or anticipated to be low? It may be possible to utilize a hypothetical set of outcomes and probabilities to get a feeling for the problem. After all, doing nothing about analyzing and comparing the uses of the atmosphere is effectively the same as deriving an expected value measure for the question by weighing the "unknown" outcomes with a zero probability, and present concern over issues is evidence of unwillingness to do that. Normally, "decision analysis attempts to accommodate the uncertainties inherent in the assessment of problems and of the variables involved through the judicious use of sensitivity analysis." The calculations of expected costs and benefits are repeated using alternative values of some troublesome probability, cost, or benefit. If each reanalysis produces the same relative preponderance of expected costs and benefits, then it is argued that these particular differences do not matter. (Fischhoff *et al.* 1979:19.) But with respect to the atmosphere and climate change, there may be a danger than even if one does not make unrealistic assumptions about the availability of data needed to complete the analysis, the decision analysis may begin to attain some kind of autonomous reality on its own. Thus, in this area decision analysis may be illustrative and helpful in some way, for example, in eliciting or helping to form preferences, but it will be far from a basis on which a decision could actually be made.

POLICY AND MANAGEMENT

A policy discussion must concern itself both with appropriate techniques for incentive and control and with institutions for formation and implementation of these techniques. While almost all atmospheric policy issues may eventually involve the design of a regulatory mechanism to promote more rational management of atmospheric resources, the economist's conventional wisdom about external effects, equity, and social policy may be followed in many ways, according to the specific characteristics of the problem and the atmosphere in general. Moreover, because the history of regulation of the atmosphere, to the extent that there is one, has not been one of clear management goals, proper regulations, and adequate information, it is worthwhile to look broadly at possibilities. Given the nature of the users, receptors, sources, and characteristics of the externalities in question, what are the available strategies? And what level and kind of government should determine and enforce controls? In fact, should it at all? As Mead (1979: 356) has pointed out,

> ...the presence of a net externality is not a sufficient justification for government intervention. The costs of correction, including the costs added in the legislative compromise process and actual administration..., must be less than the cost of the net externality to be corrected. Failure to meet this test will lead to even greater misallocation.

There are a variety of approaches for achieving particular goals with respect to the atmosphere. Focusing on issues with respect to waste disposal, one can suggest following Kneese and Schultze (1975):

- Change the way economic activity is carried out so that it generates less residual to begin with. For example, shift away from fossil fuels.
- Treat the residual as it emerges so as to render it less harmful. For example, use catalytic converters on automobiles.
- Increase the capacity of the environment to absorb residuals, or change discharge points in a way that does less damage to society. For example, do not allow emissions in the stratosphere or plant trees to absorb CO_2.
- Divert the residual to a different environmental medium. For example, dump CO_2 into the deep ocean.
- Make society less dependent on (products which are damaged by wastes accumulating in) the atmosphere. For example, shift resources from climate-sensitive activities to climate-insensitive activities.

The number of specific policies to implement these approaches is quite large, but the types of policies traditionally considered and discussed by economists are comparatively few in number. Daly((d'Arge) section 2:127), following Kneese and Bower (1968), offers this list of general alternatives:

- to do nothing, allowing voluntary negotiations to materialize aided by specification of property rights (i.e., assigning liability for damages)
- system of charges, for example, in the form of an effluent tax
- payment of subsidies to discourage the creation of the external effects, for example, subsidizing the installation of abatement equipment
- enforcement of quality standards for the environment and/or quantity standards regarding, for example, the amounts of particular effluents
- auctioning of a predetermined quantity of rights with respect to the particular activity being considered
- merger or other form of coalition between inflictor and receptor
- various hybrid schemes involving some combination or combinations of the above techniques

While a wide array of control techniques and policies may be available, few are likely to satisfactorily fulfill the various performance criteria which may be proposed. First, we have emphasized allocative efficiency. To produce economic efficiency, the tax or effluent charge (or other selected method of regulation) has to be set to equal the marginal external damage caused by effluents. This presupposes knowledge on the part of the regulatory body, of the precise nature of the damage function, and of the costs of regulation. It is, thus, difficult in many cases, for example, CO_2, to imagine adoption of such a scheme. This also raises a second issue, that of flexibility. What control techniques are capable of responding to changing situations, so that we are not locked into a choice which itself may be characterized by lack of good information on costs or consequences? For example, dumping CO_2 into the deep ocean may appear desirable at the moment, but it may only be because the risks have not been explored. A third criterion revolves around effectiveness and enforceability. Seneca and Taussig (1979:74) explain the difficulties here:

> Consider the problem of sanctions against lawbreakers in any hypothetical market for air pollution rights. That is, suppose that contracts to provide cleaner air were somehow negotiated in spite of the large information and transaction costs discussed above. Successful delivery of clean air to buyers would depend critically on the ability of the police and the courts to enforce the terms of such contracts. Effective enforcement would depend among other things, on detection of innumerable potential violators on the sellers' side of the contracts. Enforcement probably would be prohibitively expensive, especially if the general public feels that everyone has an inalienable right to burn his garbage or drive his car and refuses to cooperate with law enforcement officials.

Moreover, the question of enforcement raises again the basic issue that part of the process of regulation is specification of the ownership and rules for exchange of property. The selection of rules and institutions to guide the use of atmospheric resources, no matter how efficiently and fairly it may be done, cannot be accomplished without new encroachments on common property resources which some may be reluctant to see further defined or enclosed. The intrinsically multinational character of many of the externalities associated with the use of the atmosphere further suggests the limited applicability of much of the literature on regulation in economics. This literature usually assumes the existence of a governmental entity with both the information and authority to regulate efficiently the activity in question. Taxation powers, for example, are often assumed, for purposes of discussion, of potential national policies. Internationally, there is almost no power to tax firms or individuals within nations. Moreoever, suggestions of such authority are almost always received as an unwelcome attack on the sovereignty of nations.

The existence of an effective international organization to concern itself with the management of the atmosphere might, in some respects, be desirable. Unfortunately, the history of international organizations and a look at analogous areas, such as the oceans, suggest that progress in this respect is uncertain and likely to be slow, and, indeed, developments are potentially regressive, both from a technical and a managerial standpoint. This is not to suggest that interested organizations, such as the UN Environment Program, the International Council of Scientific Unions (ICSU), and the World Meteorological Organization (WMO) are lacking in talent or incapable of influencing events. It is to suggest, however, that the powers presently available to these bodies will not assure efficient or equitable use of the atmosphere in the senses we have been discussing. Because the fundamental legal and political entities of the world are sovereign nations, regulation must almost certainly begin with national mechanisms and cooperation among the nations who are the most concerned and concentrated users of the atmosphere. But, this just returns us to the discouraging situation of confronting global issues with fragmentary national resources.

While there are specific problems of policy design as discussed so far, there is also the broad question whether we are considering issues from the correct point of view. The tendency in resource management has been to organize functionally defined units across spatial or physical regimes. But, is it best to organize management primarily around geopolitical "space" (the oceans, atmosphere, Antarctica, outer space) rather than around the functional areas (waste disposal, etc.)? It should be noted that this is an issue both at the global and national level, where concepts like "ocean management" have not always served well. Some have argued that as issues and relationships become more complexly linked, the tradeoffs and choices must be made in a way that is impeded by defining institutions in spatial terms. Morse (1977:18) proposes,

> ...it would be better to link issues via regimes according to the purposes the issues are to be put or the uses made of them (e.g., "industrial policy," or "protein") rather than according to a "natural system" into which they seem to fall (e.g., grains, oceans, population, trade, etc.).

Certainly, CO_2 is an issue of competing uses of the atmosphere, but it is also an issue of energy paths, and of waste disposal, and it may be more important to redesign policies from these points of view than from the spatial point of view.

This critique does not mean there is no place for something like "atmospheric management" or attempts at optimization of the uses of the atmosphere. It suggests, rather, that different types and degrees of interdependence of issues call for different kinds of regimes. Some regimes will simply aim at problem definition, some at standardization and harmonization of policies, while others may, in fact, need to play a dominant role in managing activities. While the spatial organization may be a particularly convenient way of confronting governments with issues, the issues will probably most of the time need to be considered in terms of broader policy bundles. And implementation of relevant decisions (on energy, land-use policy, and so forth) may take place through quite different mechanisms.

Morse suggests there is a continuing need for evaluation of linkages of activities so as not to create a multipurpose spatial regime which is in practice merely eclectic. A spatial regime can serve usefully in delimitation of property rights, determining rights of access and limits of exploitation of resources in shared areas that are characterized by interdependent relationships. Having fulfilled this purpose, such a regime may become of questionable value. Morse (1977:19) gives the following case of functional versus spatial conflict:

> A food regime, for example, would involve some ocean space questions (fisheries), some trade issues (commodity agreements) and investment issues if its main purpose were to assume minimal equity in the distribution of food. The development of an adequate food regime would be impeded by the establishment of an all-encompassing "ocean space" regime. In terms of "functions," some aspects of ocean space would require little more than regulatory mechanisms—e.g., the establishment and maintenance of traffic patterns...

In the end, one might have a faulty commons and a dysfunctional management principle by simply emphasizing ocean space. There is no resolution to the debate other than, as Morse suggests, to continue to evaluate where the linkages in spatial terms are so strong that management from that point of view should dominate. In any case, one form of management need not preclude the other. Different angles of authority and function, if coordinated, might serve well.

In conclusion, one does get a sense from the broad kind of survey offered in this paper that several issues relating to the atmosphere have not received sufficient attention, definition, and comparison, and methods for development of relevant information and resolution of conflicts are insufficiently advanced. The most difficult questions all revolve around the massive return of residuals to the environment. The institutions of private property and exchange that are normally used for determining the value of resources and providing incentives for their efficient allocation do not, and perhaps cannot, function successfully for this purpose with respect to the atmosphere, as the atmosphere maintains many of the characteristics of a common property resource, at global and lower levels. The problem is compounded by the very poor information available and by equity questions, of spatial, as well as, intergenerational character.

Some experts have argued that a partial solution to the problem lies in giving preference to nondamaging uses of common property resources over damaging ones. Page (1973) has advanced an argument for justifying a hierarchy of rights based on the difference between rights to the use of the services of a common property resource which does not impair its substance, and rights to consumption, preemption, or destruction of the resource itself. While there are difficulties about information here, and ambiguities may arise, as, for example, with the contention that in some areas climate change may produce benefits, this would seem to be a persuasive argument, as long as there is some confidence in evidence or forecasts of detrimental effects. As Krutilla and Fisher (1977) comment, such arguments take one out of economics and into ethics.

Of course, it is precisely the ethical issues which are among the most compelling reasons for coming to terms with problems like climatic change, acid rain, and destruction of the ozone layer, since causing these problems is clearly not consistent with most concepts of environmental stewardship or the proper relationship of man to nature. But these concepts are philosophical and not economistic, and in spite of the inadequacy of economic analysis of the atmosphere, much of the battle over management of atmospheric resources will be fought out on economic (and political) issues and not ethical ones. Reducing residuals is expensive. It will add to the costs of production, slow exploitation of resources, and ultimately appear in the form of higher prices for consumers. Moreover, the costs of residuals control tend to rise steeply as targets for environmental preservation become more ambitious.

Given the scientific and economic uncertainties about many of the uses of the atmosphere, and the structure of control and management, or lack of it, both nationally and internationally, it is hard to believe that society will be able to come to grips in a decisive way with major atmospheric issues in the next decade. Even supposing, for example, unanimity among atmospheric scientists about the severity of CO_2 effects, much advanced work on the impacts of climate change and CO_2 enrichment of the atmosphere from ecologists, agronomists, and others, and more reliable analysis from economists, the underlying structural and philosophical reasons for present policies toward exploitation of atmospheric resources might well rule out successful preventive or compensatory action. Nonetheless, it is clearly important to study and pursue the possibilities for various control techniques for atmospheric issues, and for viable national and international regulation. But, it may be as important to continue to think about living with, and adjusting to, an ever more irrationally exploited and degraded atmosphere.

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CHALK ON THE WHITE WALL? ON THE TRANSFORMATION OF CLIMATOLOGICAL FACTS INTO POLITICAL FACTS

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SCIENTIFIC FACTS AND POLITICAL FACTS

It is not necessary for a scientific fact to be at the same time a political fact, since we are only faced with a political fact when a political situation is changed. Of course, scientific discoveries may bring about changes in political situations, and the conditions of life in the modern world to a very considerable degree depend on scientific facts. However, in scientific papers it is generally the scientific facts themselves, conceived in the language and terms of physics or of the other sciences, that are published, and not the political facts to which scientific discoveries may give rise.

Sometimes a scientific fact is very easily transformed into a political fact. The discovery of nuclear fission, for instance, even if originally expressed in terms of nuclear chemistry, almost immediately meant to everybody concerned an important political change in energy, as well as weapons, technology. Many scientific facts, however, have not yet or may never become political facts in the sense of bringing about changes in political situations.

At present it is interesting to ask whether or how the political situation is changed by scientific statements on climatic changes which will happen or which may happen as a result of human activities. On being told about the possibility of CO_2-induced climate changes, for instance, many people will conclude *prima facie* that such changes should be prevented, and prevention then means the substitution of fossil fuels by nuclear energy or by energy conservation. In fact, the CO_2 issue has become an important argument in the nuclear controversy. Notwithstanding the quality of this argument, one should be aware that the quick step from climatologically expected changes in temperature, precipitation, and so on, to politically recommended preventive measures is by no means the only step to be taken into account here. The spectrum of political response is far more sophisticated than is recognized in the simple conclusion taken from the confirmation of some particular energy policy as a result of the dependence of climate on the carbon cycle. Care must be taken when transforming or translating scientific facts into political facts.

Statements on expected changes in climatic parameters are, as such, irrelevant to a politician who is concerned with implementing certain goals in a given situation. Approached by a climatologist who is reporting his latest results in terms of temperature, pressure, and humidity, the politician will ask, "All this may be so, but what difference does it make to me? I am concerned with achieving goals in a given situation, and how does the climate come in here?" Obviously the climatologist cannot answer this question within the framework of his scientific discipline. He may, however, hand over the question to the geographer and to the ecologist, since these researchers are concerned with the habitat of mankind and other species, and can interpret climatological parameters through their disciplines as impacts on the conditions of life.

Now the ecologist and the geographer will talk to the politician about bugs and worms, as well as about erosion and human settlements. Again this will not be politically conclusive, but from here the politician will probably turn to an economist and to some technologists and ask them:

- about the economic implications of changes in human habitat, brought about by temperature/pressure/humidity changes (or otherwise);
- about technological strategies to make use of the expected changes or to do something about it.

By now the original scientific fact has been almost advanced to political perception. The line of thought established so far is comparable with a chain of dominoes. Only one more domino is missing, namely the answer to the question whether the conceived changes in economic as well as in technological options would give rise to any changes in people's behaviour or attitudes. If it did not make any difference to the people, the politician would still be justified in concluding that the temperature/pressure/humidity fact from which the domino chain has started does not cast any shadow on his field of concern.*

The conclusion so far is that climatological facts are not political facts in themselves, and also may not generally be expected to have a bearing on the political situation,

*I am not suggesting that we should omit consideration of implications with respect to other species. Such implications should make a difference to people and thus be taken into account by human concern.

that is, become political facts and elicit political response. This being so, the transformation of temperature/pressure/humidity facts into political facts turns out to be a task which in every case should be taken care of with interdisciplinary expertise. Now—as in the earlier stages of the domino chain—the final step into politics, by way of political science, again depends on the range of perception in the field of arrival. Thus we have to determine—and this is what I am going to discuss here—which kinds of political reactions can be conceived in response to climatological facts that cast a shadow on the field of political options. These are the climatological facts that will change the political situation and, therefore, become political facts.

THREE POSSIBLE POLITICAL REACTIONS

Basically, the political choice seems to be whether a change in the political situation which depends on changes in climatic parameters should be accepted or prevented, or partly accepted and partly prevented. The question of prevention arises in particular, since most of the climatic changes which are presently discussed are anthropogenic. The situation is, however, much more complicated than the simple dichotomy between prevention and acceptance, or adaptation, suggests. Considering CO_2-induced climatic changes, for instance, one may prevent such changes by:

— preventing additional CO_2 generation to begin with (substituting fossil fuels by other energy sources);
— preventing not generation but only additional CO_2 emission into the atmosphere (alternative disposal of stack gases);
— preventing neither CO_2 generation nor emission, but only preventing increases in the atmospheric CO_2 content (compensation of additional sources by additional sinks).

On the other hand, adaptation to climatic change may range from passive acceptance to global efforts of compensating for the—potential or actual—undesirable impacts of that change on all peoples. Thus, there is no clearcut distinction between 'active' adaptation and the prevention of implications. To avoid a conceptual muddling of different strategies, in my view it seems reasonable to introduce a third category between prevention and adaptation, namely compensation (or abatement) and to define:

— prevention as prevention at the origin (change in human behaviour);
— compensation as a suspension of undesirable effects by global efforts (international activities and budgets);
— adaptation as responses to undesirable effects of climatic change on the national or individual level.

The specific difference between the first two strategies is, therefore, given by suspending the cause or only preventing effects, while the latter strategies differ in the level of response and payment (international versus national or individual). The reason to draw the second distinction with respect to the coordination and payment level is that climate is international, so that adequate countermeasures against climatic changes must be internationally coordinated, while programs below the international level can be only piecemeal reactions and may suitably be called adaptation. At both levels, however, anticipatory as well as *ex post* reactions are possible.

It is important to realize that prevention, compensation, and adaptation are basically equivalent options, so that it would be a mistake to consider, for instance, prevention as being in principle better than adaptation. What is 'better' only depends on the (social) costs involved, as long as one is not making the distinction between 'better for mankind' and 'better in nature,' including mankind. These costs, however, may differ considerably among the three strategies, and these differences do not only depend on the facts of the particular case with which we are concerned, but prevention and compensation from the outset—or *a priori*—seem to be charged with a *malus* in favour of adaptation.

PREVENTION

If human activities lead to undesirable implications, the most sensible conclusion *prima facie* will be generally that a change in human behaviour is required. Unwanted results of an action indicate that something is wrong with the action. Despite the obvious rationality of this argument, prevention and compensation tend to be less practical as political solutions than adaptation. With respect to climatic changes, three basic drawbacks of preventive strategies depend on the internationality of climate.

(1) A decision can hardly be identified as the relatively optimal solution without referring to what a future optimum would look like. Since the different parties—especially in international relations—usually do not agree on common goals, the 'least marginal action' (least change in behaviour) will be favoured, which in most cases is expected to be adaptation.

(2) The different options may in general, or in most cases, turn out to be options of the different parties involved, so that, for instance, the question is whether country A takes a step for prevention, or whether country B takes a step for adaptation. International activities for compensation will also be viewed differently by the different parties involved. Obviously, international bargaining does not necessarily bring about the best solution, which would be the objective of an international authority.

(3) Few changes are to the disadvantage of everybody. There are likely to be quite a few countries, including some in the Third World, which are going to receive net benefits

from climatic change. Therefore, the political conflict may as a first order effect turn out to be a distributional conflict, even within the Third World, with some countries, for example, developing migration pressures with respect to others.

Can we expect that the structural bias in favour of adaptation will be counterbalanced by comparative savings of preventive or compensatory strategies in relation to the costs of adaptation—be it only in the interest of the whole, an entity which is not represented by any of the different individual parties? I am afraid that even a hypothetical international authority would in most cases hardly decide in favour of prevention. Two basic reasons are the following:

(1) The three options—prevention, compensation, and adaptation—are connected with quite different time scales. Prevention by its very definition takes place much earlier than compensation, while adaptation may again generally be left to a later future than compensation. Therefore, by way of discounting future costs to the present, the already given bias in favour of adaptive strategies will be even more enhanced by the time argument.

(2) Political responses with respect to climatic changes are marginal with respect to the given pattern of interests and incentives. Considering CO_2-induced changes, for instance, one finds that there are already strong national incentives to reduce the consumption of fossil fuels, and these incentives are only slightly enhanced by uncertain assumptions about climatic changes in distant times at distant places. Or, to be more explicit, if the actual oil crisis does not convince the American people that oil should be substituted by conservation (capital investment) and by alternative (carbon or noncarbon) fuels, and that this is economically reasonable as well as technically feasible, prospects of climatic changes will not convince them either. Is it not most improbable that the industrialized world will slow down economic activity by energy restrictions for reasons beyond those which already exist and that other countries will stop burning forests to prevent CO_2-induced climatic changes? After all, events like the Sahelian drought or a Peruvian El Niño irregularity should be considered bad enough to elicit action. Thus, the irregular becoming regular probably will not bring about changes in human behaviour either. Different reasons or causes for similar results do not seem to change the situation.

The conclusion is that prevention can only be expected when there are comparative advantages even after the given drawbacks are taken into account. Such advantages may also result by way of a joint production of benefits. For instance, by piggybacking CO_2-oriented measures onto measures which are accepted for other reasons, the costs of which do not rise significantly by bringing about that additional benefit, preventive steps may reasonably be expected. The joint production of benefits from reducing oil consumption (and thereby perhaps imports) and CO_2 emissions at the same time is a good example of a piggybacking strategy for certain countries.

COMPENSATION

Considering the *a priori* drawbacks of any strategy to prevent anthropogenic changes in climate, one may turn to compensatory measures as the second best solution. If nothing can be done with respect to the cause, at least the undesirable effects should be suspended. This is a field where considerable amounts of technological fantasy and imagination are called for. With respect to CO_2-induced climatic changes, for instance, Marchetti's famous Gigamixer is a most ingenious proposal to suspend undesirable effects by a technological fix. His idea is to put the stack gases from electricity generation as well as from heat generation centers (by burning fuels with pure oxygen or by filtering out CO_2 and other components) into a current which is at the ocean surface at Gibraltar and then disappears in the deep sea. The CO_2 is then supposed not to show up again within the next five hundred years, after which time overloading the atmosphere with CO_2 will not be a problem any more, because mankind will have run out of fossil fuels. A similar idea is to use the stack gases as a fluid for tertiary recovery in exhausted oil fields (Marchetti 1979).

Generally, the most appealing idea to the modern mind—appalling, however, when accepted as a general principle—may be to venture into 'global climate management,' so that undesirable implications of human activities may be suspended. In fact, having agreed on so much resource management already, be it water, energy, or the environment in general, there seems to be no conclusive reason why our domination of nature and our treatment of nature as a 'resource' should not be extended to climate. On the other hand, we are beginning to realize that technological solutions of problems are generally tied up with social commitments and that there are good arguments in favour of the recommendation to consider these social commitments even more carefully than the technology itself (Meyer-Abich 1979).

Apart from these more philosophical considerations, the chances of compensation measures depend on the costs involved and on agreement among the different parties as to who will be charged which share of the total costs. As with prevention, we are again faced with the problems both of poorly defined or not generally accepted goals and of cost distribution in a pattern of international competition. To begin with the price of technological fixes, Marchetti has estimated that electricity production would become about 30% more expensive if the stack gases were transferred to his Gigamixer. Global climate management, basically cloud and rain distribution management, will also not be a cheap solution. These costs, however, are not high or low by themselves, but are high or low with respect to the benefits in question.

The benefit of counteracting climatic changes by technological compensation may be defined as the opportunity costs minus the benefits of a climatic change (if there are any). The opportunity costs are to be understood as the additional benefits which would have occurred if the climate had not changed, or as losses brought about by climatic change. Within the Climate Impact Assessment Program (CIAP), d'Arge (1974) has ventured to calculate such opportunity costs for some parts of the global economy, on the basis of a scenario with a 1 °C decrease in mean annual temperature. To pretend any accuracy and reliability at all for such (partial or further extended) calculations has been strongly criticised by Margolis (1978), and I agree with him. This criticism even applies to calculating opportunity costs of climatic changes with respect to present activities with given objectives in a given climate. It applies, therefore, even more to the following two points:

(1) To future activities the goals of which are unknown, so that nobody knows whether climatic changes can be held responsible for missing political goals to this or that extent or whether they contribute to achieving them. Or, if goals were made explicit, it would again be an open question as to whether they will be missed on account of climatic changes. A country, for instance, might claim to have been prevented by climatic changes from becoming the wealthiest country in the world. It may well be that this claim, 'iffy' as it is, can hardly be refuted.

(2) To stating deviations with respect to a reference case which is ill-defined in itself, since the climate is also changing by natural developments. The benefit of compensating for anthropogenic effects on climate is obviously ill-defined when natural fluctuations of the same order of magnitude may be expected and which nobody can predict or exclude so far. The benefit of compensation strategies is, therefore, only poorly defined, and this is a rather serious problem when high expenses are at stake.

Finally, it must be pointed out that, even if the opportunity costs and benefits of climatic changes were known or at least conceptually defined, the political problem of charging different parties with costs of the technological fixes in relation to their particular responsibilities, as well as to their costs and benefits, would be practically insurmountable. Climate cannot be nationalized. It is essentially an international concern, so that any climate management or compensation strategy involves economic externalities—positive or negative—with respect to national borders. Investments to compensate for climatically harmful activities, therefore, will be almost without returns generally if not endeavoured as much as possible on the basis of international cooperation and exclusion of 'free rider' policies. The implication is that something like the 'polluter pays principle' from environmental policy should also be applied in climatic matters.

It is at this point that the question of different national liabilities with respect to climatic change arises. Since not even the benefits of technological compensation strategies can be determined, however, the question of cost distribution according to differential national liabilities may be considered irrelevant. Also it may be argued that costs should be distributed according to the expected benefits instead of the shares in pollution.

ADAPTATION

That which impedes prevention and compensation supports at the same time the conclusion that adaptation will be politically the most sensible strategy with respect to expected changes in climate. Adaptation, in particular,

- does not require an agreement on long-term goals but is rather flexible when goals and values are changing;
- does not require long-term international cooperation but allows a maximum of self-determination in evaluating costs and benefits;
- allows the appropriation of positive externalities of climatic changes, if there are any;
- allows one to confine oneself to the least marginal action at present;
- allows deferment of expenses most distantly into the future;
- is the line of least resistance with respect to present patterns of interest and incentives.

These comparative advantages reduce the price of adaptation in relation to the other two strategies. The price of adaptation itself is

- migration into those regions which are favoured by the climatic changes in question (though it is very hard to live as an immigrant, this is the traditional solution to such problems in the history of mankind);
- vocational reeducation and—most probably—industrialization.

To what extent migration and industrialization must be expected depends on the particular properties of the climatic change in question. Qualitatively, however, it can easily be shown that migration and industrialization will be the basic implications of any climatic change, since the political situation can be changed by climatic developments only insofar as it depends on climate or is sensitive to climatic parameters. Obviously, there is only one basic dependency of human societies on climate, namely with regard to agriculture. Change in agricultural productivity means that the ratio of population density per agricultural productivity is changed, and such changes can be compensated by corresponding changes in the population density (migration) or by increasing agricultural or other economic activities (reeducation and industrialization).

There is no doubt that the adjustment of economies adapted to the present climate to a different climate and the migration of perhaps hundreds of millions of people imply considerable costs. Taking into account time-spans and the above given comparative advantages, however, as well as the kind of climatic changes by human activities which have been discussed so far, I do not see any reason whatsoever why adaptation should not be the most rational political strategy. Also the costs of adaptation are highly dependent on early information about the developments to be expected, so that forecasting climate—allowing for more active or 'preventive' rather than passive adaptation—can reduce these costs enormously.

Looking more closely at the different vulnerabilities of different parts of the world against climatic changes, one finds even more that adaptation proves to be the most rational political solution. The reason is that the vulnerability of a country with respect to climatic changes depends no less on its social, institutional, and technological structure than on the particular character of the change in question. This may result in a twofold disadvantage for the developing countries, since not only is their technological potential less advanced than that of the industrialized countries but also it must be expected that the CO_2-induced changes in climatic parameters for the developing countries have to be represented economically as a more severe change in agricultural productivity than for the industrialized world. In fact, the European peoples are not only privileged with respect to wealth, but also insofar as changes in the mean temperature by a few degrees Centigrade at present appear less likely to influence precipitation patterns in a way that will cause serious overall change in European agricultural productivity. In addition, changes in the energy budget of the atmospheric processes seem to be the common denominator of anthropogenic effects on climate. Most of the developing countries, on the other hand, are highly vulnerable to even minor variations in water supply, since they are already working at the margin of productivity, and water is the main limiting factor of vegetation all over the world except for a few areas, among which only the humid tropics are in the developing world. To some extent the argument also applies to the industrialized world, since, for instance, Kazakhstan in the U.S.S.R. is situated in a semiarid area, and food surplus areas of the U.S.A. and Canada are vulnerable to changes in rainfall. On the whole, however, it may be concluded that

— the rich countries do not only possess the more advanced technologies to cope with changes in agricultural productivity, but they also are less liable to get into a situation where these means would have to be applied;
— while the poor countries do not only lack technological response capacity, they are also the ones which would probably need such capacity.

Finally, by recalling that agriculture is a relatively minor part of the economic activity of many industrialized countries while in most of the developing countries the whole economy is still basically dependent on agriculture, it must be concluded that the conflict potential between North and South could be considerably enhanced by climate changes, because the already existing inequalities in distribution of wealth may tend to be increased.

Apart from agricultural losses—which may amount within a few years to very considerable shares of the former productivity if precipitation falls below a minimum—the developing world may also be affected by losses in hydroelectricity (which again depends on rainfall) and by changes in marine productivity.

Considering the industrialized countries, I certainly do not want to suggest that they will be unaffected. Obviously we feel climatic variability—and as a first order approximation the same would apply to climatic change, or variation—in food prices, tourism, heating expenses, etc. Also the construction business (buildings, roads, etc.) like agriculture, is dependent on seasonal changes. However, in the long run the basic dependency of mankind's cultural and economic development on climatic change, as may be assumed for the past, in my opinion most probably does not apply to the future of the industrialized world. One cold winter, for instance, may be bad for the construction industry, but many cold winters or any other climatic changes, including increases in variability, may even be an economic incentive, especially if corresponding information is available early.

CONCLUSIONS

If climatic changes must be expected to hit mainly the Third World and not the industrialized world, the situation probably becomes more critical than if it were the other way around. At the same time, paradoxically, the problem tends to fade out as a distinctive problem—like chalk on a white wall or like a particular darkness in the night. The reason is that if it is mainly the developing countries that are affected, climate-oriented policies become part of development policies in general. In the context of present development debates, however, it seems that with respect to the next 40-50 years:

- we are not confronted with a new problem, since the overburdening of productive capacity by high population densities is the problem now, as well as having been the problem for some time;
- no monetary transfers are involved that would change the present situation as far as development policies are concerned.

Compared with the already existing problems in development policy, the possibility of climate changes, therefore, seems to be a 'marginal' problem in the sense of not being qualitatively different, while not significantly increasing quantitatively the already given tensions. For example, the recommendation to increase food reserve (requiring higher production in the industrialized world), reasonable as it is with respect to possible climatic changes and food shortages, is eminently reasonable with respect to the present situation as well. And the same applies to Elise Boulding's (1979) recommendation "to draw on skills that are now hidden from policy makers," reviving "traditional knowledge stocks of peasant and nomadic communities, of ethnic groups in industrialized societies, or minority-status groups in all societies, including particularly women and children."

Of course, nobody can exclude that crop yields in some developing countries for reasons of climatic change will drop by, say, 50% within five years. A 50% decrease in productivity corresponds to a 100% increase in population density, and this—at a rate of 2% per annum—would be reached in only 35 years, so that the assumed climatic change comes out to be something like 'seven times worse' than that population increase. Even if we are certain of a climatically caused drop in crop yield at some future point in time, we could not do better from a policy point of view than do what we already know should be done for other reasons.

While being far from negligible, the costs of adaptation are still, therefore, only marginally charged on an account which is grossly imbalanced anyway. While the costs of prevention and compensation were either basic changes in the industrialized way of life or enormous technological investments to get an unknown share of an ill-defined benefit, adaptation allows at the same time for least marginal action with respect to present patterns of interest and for piggybacking discounted future costs on long range development policies. The situation would be different when for reasons of climatic change

- catastrophic developments of the same kind and order of magnitude as those which have to be expected already now, or
- undesirable developments of a new quality

are seen to be emerging beyond the next 40-50 years. As Flohn (1977, 1979) and others argue, this may very well be true, even if it is to some degree uncertain at the present state of our knowledge. Nevertheless, it remains true that climate change is not a political issue or does not require additional political decisions now.

Adaptation, therefore, for the time being seems to be the most rational political option, also the option requiring least marginal action (i.e., action specifically for reasons of climatic change and not mainly justified for other reasons). No problems have been identified so far that are additional problems which emerge uniquely as a result of

CO_2-(or otherwise) induced climate change, and all of the problems associated with climate change should be emphasized and taken care of at least as much for other reasons. This, however, should be taken only as a first order representation of temperature/humidity/pressure changes at the political level. Much more consideration will have to be given to interactions among the different levels of the domino chain to achieve an adequate assessment. The next step may be to look the other way around for climatological representations of political conflicts, taking into account, for instance, that the industrialized world:

— in the nuclear energy controversy is experiencing profound doubts with respect to traditional technology and human needs, doubts which to some degree seem to have been shifted into climatic issues;
— may be blamed for food shortages in the developing countries as being induced by industrialized economies, even if there is no sound climatological justification;
— is generally experiencing a growing concern about being responsible for social and technological commitments of mankind in the very distant future, so that the concern about climate may be only one element or a symbol of a more deeply rooted uneasiness.

In this sense, the climatic concern may become beyond itself an important focus for social and political concern about not adequately doing what should already be done now for other reasons. Even if reasonable political conclusions do not become more reasonable by additional confirmation from climatic reasons, this confirmation may politically emphasize those conclusions in a particular situation. When discussing such conclusions, one should be careful, however, in regarding them as being more than occasioned by climatological facts.

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CROP-CLIMATE MODELS: A REVIEW OF THE STATE OF THE ART

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Although this may seem a paradox, all exact science is dominated by the idea of approximation.

Bertrand Russell

INTRODUCTION

There are two main ways to determine the effects of climate on crops: detailed ecological studies and crop-climate models. Ecological studies involve assessment of the behavior of crops under different climatic norms and prevailing local conditions. Accordingly, the production function for corn, which may be defined as the mathematical function providing the interrelationships between resource inputs and crop yields, will vary from one geographical location to another, depending on: soil types, availability of fertilizer, pesticides and water control, climate and other management techniques. While many of these resource inputs can be controlled, others like climatic variables are beyond man's control. Furthermore, the timing of the resource inputs is an important factor, which significantly affects crop yield. This is because all crops have critical stages, irrespective of the location where they are grown. For example, ecological and physiological studies have identified three stages of growth for sorghum: preboot, bootheading and grainfilling. In terms of yield, lack of soil moisture during the bootheading stage is the most critical stage, followed by grainfilling and preboot. In other words, in terms of timing, water availability during the bootheading stage affects crop yield the most, and thus is an important factor to consider in developing policies and operational practices for yield optimization.

Crop-climate models attempt to relate climatic variables to production data through statistical techniques. Different forms of multiple regression techniques have mainly been utilized so far. This type of model was initially developed to determine at which stages of growth crops were more vulnerable to different forms of climatic inputs (Johnson 1976). A review of many of this type of model can be found in Baier (1973a, 1973b, 1979) and Hillel (1977). In recent years, however, crop-climate models have been developed to analyze the broader issue of estimation of the effects of climatic fluctuations on agricultural production. The present paper reviews some of the more important models developed for this purpose.

CROP-CLIMATE MODELS

Several crop-climate models have been developed in recent years for different types of crops and also for different geographical locations. Among the more notable ones are those developed by Thompson of Iowa State University (1973, 1970, 1969a, 1969b), McQuigg *et al.* for the National Oceanic and Atmospheric Administration (NOAA 1973), Williams of the Department of Agriculture of Canada (1975), and Haigh for the Charles F. Kettering Foundation (1977). The basic approach to all these models has been the "black box" technique, in contrast to models based on the understanding of the different interacting physical processes. The crop-climate models developed thus far are mostly of multiple regression type, and use empirical relationships derived from historical crop yield and climatic data to predict potential future yields from different climatic scenarios.

Thompson Models

The models developed by Thompson are for corn (1969a), wheat (1969b), and soybeans (1970) for certain areas of the United States. Multiple curvilinear analysis was basically used to estimate the influence of climate on the crops considered. For example, for the study on soybeans, Thompson (1970) considered the data available from five states, Illinois, Indiana, Iowa, Missouri, and Ohio, and took account of the following six climatic variables: total precipitation from September to June; July precipitation; August precipitation; June temperature; July temperature; and August temperature.

State-wide averages of monthly mean temperature and monthly mean precipitation were used as climatic variables. It was assumed that climatic variables were related to yield in a curvilinear pattern resembling a parabola, which means that there is an optimum value of the climatic variable in the sense that, at that value, the crop yield is maximized. A linear time trend was included in the regression analysis, and it was further assumed that the yield of soybeans had been increasing at a constant rate, and that the year-to-year fluctuations, i.e., departure from the normal, were due to climate. The dependent or predicted variable was the crop yield, and the independent or predictor variables were the climatic parameters, and technological trend variables. The period analyzed was from 1930 to 1968. Thompson (1970) concluded that, "The record yields of 1961 and 1968 were associated with near normal temperature in June, below normal temperature in July, near normal temperature in August, near normal preseason precipitation, and above normal rainfall in the July to August period."

The models for corn (Thompson 1969a) and wheat (Thompson 1969b) were very similar to the one developed for soybeans. For corn, Thompson concluded that, "The highest yields have been associated with near normal summer temperatures and near normal precipitation from September through June. Exceptionally, high yields have been associated with higher than normal July rainfall, with near normal summer temperatures." Similarly, for wheat, it was found that warmer than normal temperatures in early stages of growth and cooler than normal temperatures in the later stages of growth are desirable, but no single climatic variable explained much of the yield variation. However, climatic variables and technology trends accounted for 80-92% of the wheat yield variability in the six states considered.

Haigh Model

More sophisticated models of the characteristics of corn, soybean and wheat production in selected parts of the United States were later developed by Haigh (1977) for the Charles F. Kettering Foundation. The study considered both the total output and the year-to-year variability of that output for corn and soybeans in Illinois and Iowa, winter wheat for Kansas, and spring wheat for North Dakota. The study attempted to answer two basic questions:

(1) What changes, if any, have occurred in the year-to-year variability of crop weather and crop yields and their relationship to each other?

(2) Is the hypothesis that the trend in yields has leveled off in recent years correct?

Haigh attempted to answer these questions by developing structural models to separate the total year-to-year variability of crop yields into weather and management components. Changes in the coefficient of variation of yield (CV_y) were compared with changes in the coefficient of variations of weather (CV_w) over time to analyze yield sensitivity to weather. If the ratio of CV_y/CV_w increased over the period under consideration, it was assumed that there was evidence of an increase in the sensitivity of yields to weather, and vice versa. Four measures of weather were considered: precipitation and temperature; precipitation minus potential evaportranspiration; soil moisture; and growing degree days.

Monthly values of these four parameters were considered for those months regarded most important to crop yields.

Results of the study indicated that:

(1) There is no evidence that technology has reduced the sensitivity of grain yields to weather.

(2) Statistical evidence exists of a leveling off in the rate of increase of corn, soybean and hard winter and spring wheat yields in recent years.

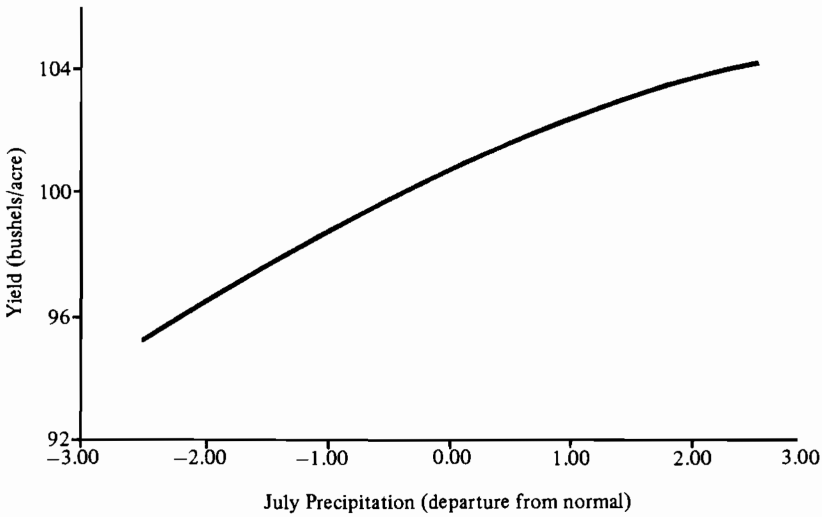
Haigh, however, properly adds a word of caution to such interpretations. For example, with regard to the second conclusion, there is no doubt that year-to-year crop carry-over levels affect government acreage set-aside programs of the United States, and thus the total area of land planted. Hence, when the reserves are high, less area is under cultivation, which means that the farmers take the less productive marginal land out of production. When carry-over stocks are depleted and acreage restrictions are relaxed, as was the case in the early 1970s, these marginal lands are brought back into production. Under these circumstances, it is quite possible that yields in marginal lands are more susceptible to weather, and such use of marginal land in recent years could possibly explain the leveling off in yields that has been observed during such years.

Haigh used the models to estimate the percentages of yield variations that could be accounted for by management, weather, or their interactions. For example, for Illinois corn, it was estimated that management accounted for at least 62.1% and at most 82.2% of the variations, whereas weather accounted for at least 11.6% and at most 31.7%. The yield-weather responses, in terms of July precipitation and August temperature, for the Illinois corn are shown in Figure 1. In general, for all the crops considered, yield variations explained by management were roughly two to three times the percentage explained by weather. The results are summarized in Table 1. Haigh points out that a limitation of the analysis was a residual percentage showing, at least statistically, an interaction between management and weather. This interaction term ranged from 10 to 20% of the total yield variation.

Williams Model

Williams (1975) developed crop-climate models to evaluate the potential impacts of adverse climatic trends on the Canadian grain production. He also used a multiple regression approach, which incorporated factors like technological trends, soils, topography, and 12 climatic variables.

His model indicates that if the climate became wetter, substantial reduction in yields may occur, if the seasonal precipitation increased by 25% or more, as shown in Figure 2.



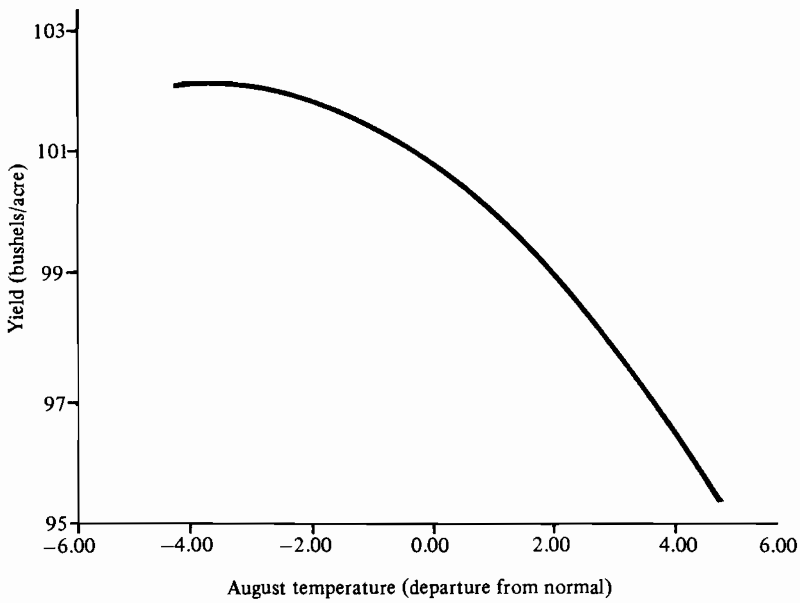


Figure 1 Yield weather response for Illinois corn.

Table 1. Separation of yield variation into management and weather components (Haigh 1977).

Crops	Variation in yield percentage			
	Management		Weather	
	Maximum	Minimum	Maximum	Minimum
Illinois corn	82.2	62.1	31.7	11.6
Iowa corn	78.0	62.4	25.3	9.17
Soybeans	78.2	68.0	15.6	5.4
Kansas winter wheat	77.4	59.7	26.2	8.5
North Dakota spring wheat	67.9	51.2	21.9	5.2

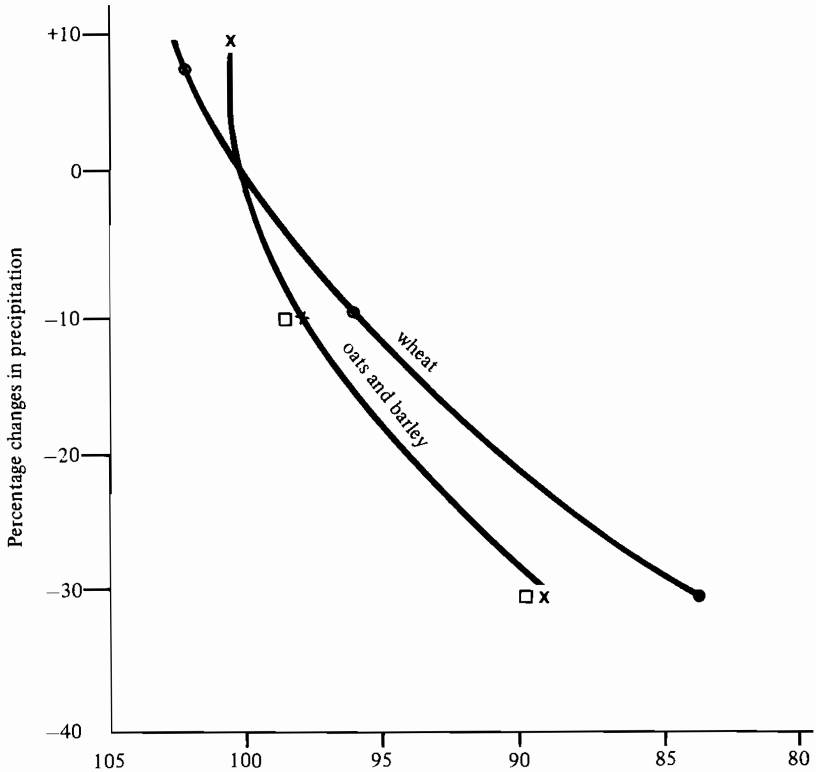


Figure 2 Change in crop yield (%) due to changes in mean precipitation.

Higher precipitation could have adverse effects on spring planting, rates of growth and harvesting. In more humid areas of Canada, where oats and barley plantations tend to dominate, the effects could be more serious. Furthermore, availability of more moisture in mid-summer in the wheat-producing areas could improve yields, thus offsetting early and late season disadvantages.

Williams (1975) also attempted to estimate the probability of crops reaching maturity in an area of some 80 square miles between the Peace and Wapiti Rivers in northwestern Alberta. He found that under "normal" circumstances barley could be grown at 94% of the locations considered. If there is a cooling trend, and the temperature drops by 1 °C (average throughout the growing season), it could be grown at 73%

of the locations. However, with a drop of temperature of 3 °C, it could be grown only at 2% of the 84 points considered. Similarly, under normal circumstances, wheat could be cultivated at half the locations considered. With a 1 °C cooling, it would mature at 15% of the locations, but with a drop of temperature of 3 °C, it would not mature at all. These results are shown graphically in Figure 3. The figure also shows that a 1 °C cooling would reduce the growing season from 9 to 15 days at 5 locations where wheat would mature, and that a 3 °C cooling would reduce the growing season by 39 to 42 days at the two locations where barley would mature. In other words, a cooling trend could significantly alter the present land-use pattern in the Canadian West by making wheat an uneconomic crop. It should, however, be noted that, in all probability, the conditions for wheat cultivation in the southern parts would improve under similar climatic conditions.

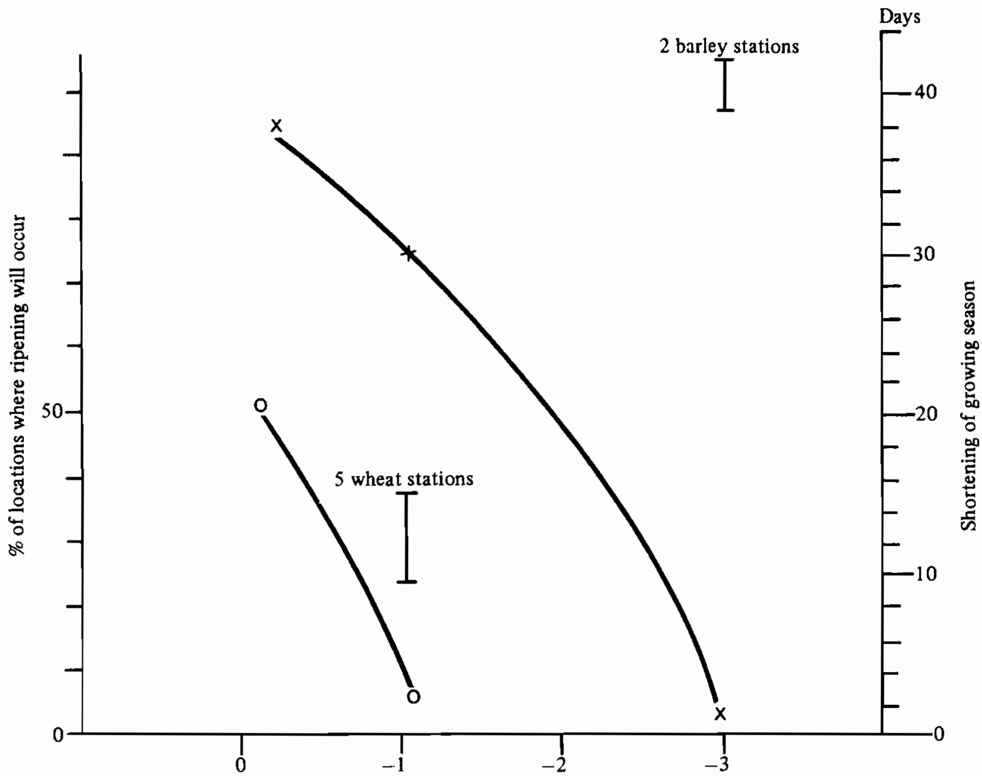


Figure 3 Mean departure from normal crop season temperature (°C):
(a) Percentage of locations at which wheat (o) and barley (x) will ripen in northwest Alberta;
(b) the shortening of the freeze-free season with cooler seasonal temperature.

MAJOR PROBLEMS OF MODELING

While there has been a great deal of interest in crop-climate models in recent years (in addition to the ones mentioned earlier, see also DeWitt 1975, NOAA 1973, Menon and Bowonder 1978, Michaels and Scherer 1977, Thompson 1975, Walther 1977a, 1977b), it is important to note some of the major disadvantages of these types of models. These problems will now be briefly discussed.

First, as mentioned earlier, statistical analyses of multiple regression types basically lead to the development of black-box models, without full understanding of the interrelationships of the different physical processes involved. In other words, it does not necessarily follow that the models developed would have realistic structures (Katz 1977). Thus, spurious correlations and unrealistic structures could present major problems in terms of model validation.

Second, the coefficients of these types of models are statistical estimates, and are not universal constants. These may be subject to several sources of error, most important of which are correlations between climatic predictor variables, and the nonlinear relationships between crop yields and different climatic parameters, both of which will be discussed later.

Third, the square of the multiple correlation coefficient R^2 is often used as an indicator of the quality of the models, and this statistic is assumed to estimate the percentage of the total variability explained by the model. However, R^2 is only an indicator of the statistical significance of the model, and since it is a black box statistic, it does not give any information on the structural accuracy of the model.

Fourth, the relations between crop yields and different climatic variables are seldom linear. Thompson accounts for the nonlinearity by assuming a parabolic relationship. A linear term, departure from normal, and a quadratic term, square of departure from normal, are used as predictor variables for each climatic variable. This necessitates estimation of additional coefficients, and the problem becomes more difficult if the period of data available is short (a real problem for most developing countries), and thus may not constitute a representative sample. This means that the data used may not contain enough extreme climatic fluctuations, and thus it becomes difficult to ascertain if the appropriate functional relations have been used (Katz 1977). For example, there is no quadratic term for May temperature in the wheat model developed by Thompson (1969b), since multiple regression did not generate a realistic coefficient for that term. Furthermore, if the nonlinear relation is represented by using both linear and quadratic terms as independent variables, correlations often arise between linear and quadratic terms, as shown in Table 2 for the Kansas wheat model of Thompson (1969b).

Table 2. Correlations between linear and quadratic terms for Kansas State wheat model (Katz 1977).

Variable		Correlation
Total precipitation,	August-March	0.21
	April	0.68
	May	0.56
	June	0.41
	July	0.63
Average temperature,	April	0.16
	May	-0.03
	June	0.25
	July	0.21

Fifth, in the classical linear regression analysis, a fundamental assumption is that the independent variables are not closely related to each other. This, however, is not correct for meterological variables. For example, mean monthly values of temperature and precipitation, for a given period, often show high negative correlation, which in some cases could be more than 0.40. If an analysis of the climatic data used by Thompson (1969b) for the Kansas wheat model were to be made, it would show increasing correlation with the advance of the growing season, as shown in Table 3.

Table 3. Correlations between monthly total precipitation and monthly mean temperature for Kansas State wheat model 1920-1968 (Katz 1977).

Month	Correlation
April	-0.14
May	-0.28
June	-0.69
July	-0.73

In addition, high correlations often exist between the values of average temperature and precipitation for months adjacent to each other. These, in certain instances, could exceed 0.30. These two correlations, in combination, could introduce severe multicollinearity in the analysis, so much so that they could often be higher than the correlation between meteorological variables and crop yields. Such a situation will naturally introduce major errors in the analysis to the extent that even the signs of the coefficients could be erroneous (Snee 1973).

Last but not least is the difficulty of separating increases in yields due to different components, i.e., management, technology, and climate. It is generally agreed that the most important factors in increasing crop yields during the last 40 years or so have been technology, increases in the use of pesticides and fertilizers, improved genetic quality of seeds, investment in machinery and better water control. The problem, so far as crop-climate models are concerned, is to separate to what extent yields have increased due to changes in technology, management, and climate. At the present state of the art, it is not possible to separate such components of yield completely and realistically (Haigh 1977). Furthermore, technology is neither given nor can it be expected to remain constant over time. Neither can it be assumed that the actual production techniques used in the field are necessarily equivalent to the present state of the art. From past and present experiences, it can be assumed that even in cases where investment required is minimal, certain farmers will adopt the technological changes relatively quickly, while others will take a much longer time. Hence, any technological change in such analyses will appear empirically over a period of time. The technological trend, of course, can be represented in such models by segmented linear trends, but the actual process of location of the points of change is not an easy task. In addition, the average farmer may not have much influence on the price of his crops or climate, but he often does adjust resource use compared with relative prices or anticipated weather. In other words, farmers are changing the pattern of resource use in agricultural production, due both to technological changes and changes in the relative prices of the crops. Separation of these components, especially within a modeling context, is a very difficult task. An example would be useful to illustrate this point. If crop prices remain as they are at present, but energy costs increase significantly in the future, it is likely that current energy-intensive farming practices will change because of economic reasons. It is quite possible that farmers may decide to use less fertilizer and/or pesticide, which will obviously have a major impact on the recent observed patterns of yield increase.

Finally, some comments on the Haigh model are necessary, since it is the only model that is based on a ridge regression technique, designed for multicollinear data for stabilizing estimates of coefficients. The standard errors obtained in this case are somewhat larger, when compared with results from many of the other models. For example, for North Dakota spring wheat, it was just over 14% of the current yield levels, rather a high figure. This, as Haigh himself points out, is to be expected because ridge regression leads to a larger standard error if $k > 0$. On the other hand, if $k = 0$, it should be realized that the ridge regression coincides with the ordinary least squares solution.

Institute of Ecology Model

The scenarios for this study were selected to represent the extremes in weather-influenced yields (Institute of Ecology 1976). The example chosen included when agricultural production was:

(1) severely reduced by stress, 1933-1936;

(2) moderately reduced by stress, 1953-1955;

(3) very high because of favorable weather, 1961-1963;

(4) up and down because of unusual variability in weather from one year to the next, 1971-1975.

The Thompson models for corn, wheat, and soybeans were used to identify the weather-years for these scenarios. The study considered ecosystems producing corn, wheat, sorghum, and soybeans in the United States and wheat in Canada.

Of the following three major variables in food production, the first two were kept constant to demonstrate the influence of the third:

(1) area cultivated, planted and harvested;

(2) use of agricultural technology, including varietal selection, chemical application, and mechanization;

(3) weather during the planting, growing, and harvesting season.

In other words, the scenarios used were developed on the basis that the total crop area cultivated remained constant at the 1975 level, and so did the 1973 technology for agricultural production.

On the basis of such analyses, the scenario yields for US corn were estimated; these are shown in Figure 4. It clearly indicates the gap between climatically favorable and adverse years, and also emphasizes the year-to-year variability in yields. The annual corn production in the United States for the scenario years, on the basis of yield figures, is shown in Figure 5. It indicates that except for one scenario year, 1936, the domestic annual consumption level of 1975-1976 in the United States can be easily met. Similar

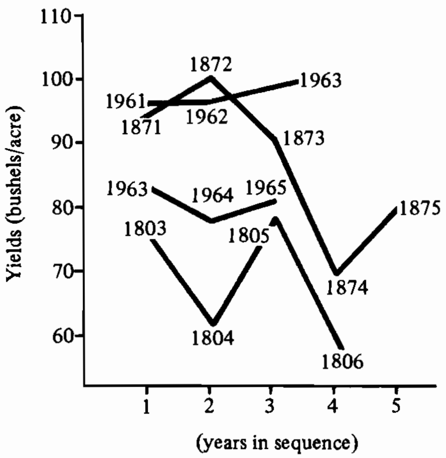


Figure 4 Scenario yields for US corn.

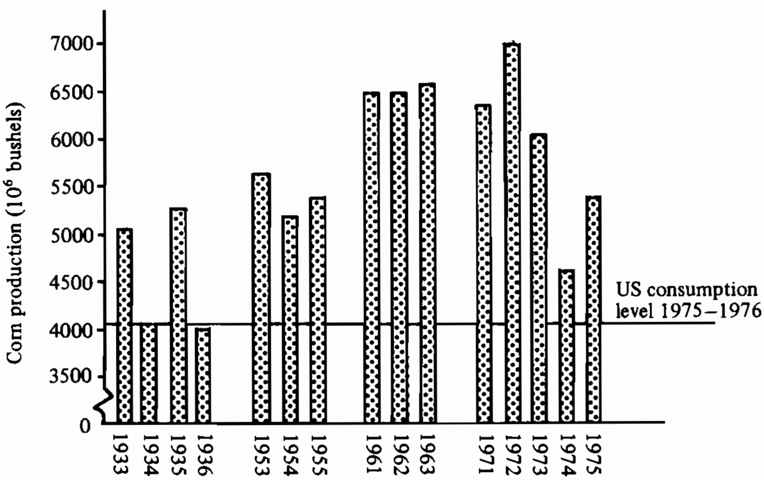


Figure 5 Scenario production of US corn.

production figures for other crops in the United States for scenario years were obtained for wheat, sorghum, and soybeans. An interesting conclusion was that sorghum production is most influenced by climatic fluctuations, followed by corn and wheat. Soybean production seems to be the least affected as shown in Figure 6. If wheat production scenarios for the US and Canada were compared, it can be concluded that, "Although there is some tendency for good conditions in one part of the region (of Canada, where wheat production is concentrated in an area of 24 million acres) to compensate for poor conditions in another, this is much less effective in reducing the variability of annual yields than is the case in the much more extensive and climatically heterogeneous US wheat region of 169 million acreas." However, if only the US spring wheat crop is considered, the situations in Canada and the US are not very dissimilar.

The study also considered annual fluctuations in crop yields in both absolute and relative terms. Absolute deviations were expressed in yields per unit area or in total weight or volume of the departure from the expected norm, whereas relative yields were defined as a percentage of the mean or norm. The study concluded that so far as major North American grain crops are concerned, the absolute variability has increased, but the relative variability has decreased during the period considered. These variabilities were indicated by the standard deviation and coefficient of variability for each decadal period (Institute of Ecology 1976). The year-to-year relative variability seems to have been reduced between 30 to 40% during the period 1935 to 1975. It was, however, not possible to separate the causes of such a development: whether it was the good climate of recent years or technological developments that provided a buffer. The two are of course interrelated, and with the data available, the two factors could not be effectively separated.

The scenario model building by the Institute of Ecology is an interesting development since it did not assume any climatic change, rather the emphasis was on what would happen to the production of certain crops if certain climatic variations, observed in three to five year periods since 1933, were to reoccur. It did not attempt to prepare the best or worst case scenarios.

CONCLUSION

The crop-climate models discussed herein are still in the early phases of development. They already provide some interesting insights on the effects of climatic variables on crop production. However, further developments, both in terms of modeling sophistication and our understanding of the interrelationships between the different processes involved, are essential before their potential can be fully realized, and the models can actually be used in decision-making and planning processes.

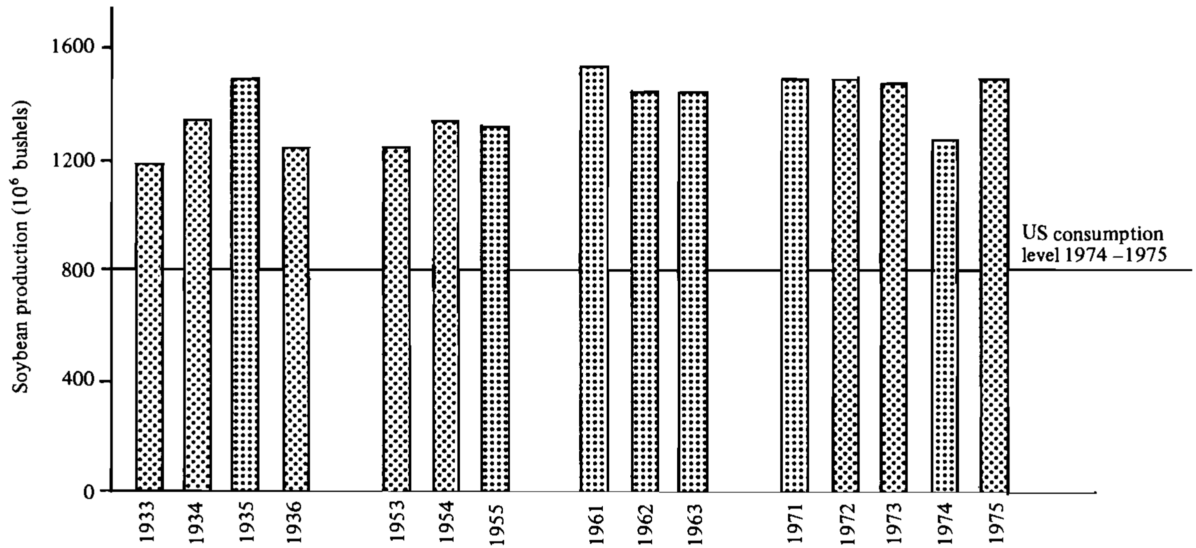


Figure 6 Scenario production for soybeans.

One of the main difficulties of estimating the net effects of climatic variables on crop yields is the desirability of having precise information on the actual timing of the occurrence of different meteorological conditions at specific locations. Generalized climatological statements, while interesting, are at present not very useful for planning and operational purposes. This can be illustrated by a study that was carried out by the South Dakota University (1973) on the effect of an additional inch of precipitation on the yields of wheat during the growing season due to weather modification. Analyses of data from experiment stations around the state indicated that yields of wheat in experimental plots, where all known technology is used, would increase by 5.3 bushels per acre. Similar data from commercial farms indicated that the additional water availability would increase yields by only 1.8 bushels per acre.

Similar analyses for corn indicated that, if the precipitation was distributed throughout the growing season, the commercial yield would increase by only 1.0 bushel per acre. However, if this additional source of water could be somehow concentrated between the one month period of 15th July and 15th August, the predicted increase was 12 bushels per acre, a 1200% increase over the previous condition. Similarly, if the additional water availability was extended over a two-month period, between 15th June and 15th August, the predicted increase was 12 bushels per acre. These facts indicate that generalized statements of climatic fluctuations are not very useful for agricultural production purposes. It could also be concluded that relatively little is known about the net effects of changing climates on crop production and water resource planning. From a modeling viewpoint, it seems that the next development should be consideration of much shorter time periods than a season. This should provide better information and understanding than has hitherto been possible.

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DROUGHT IN THE GREAT PLAINS: A CASE STUDY OF RESEARCH ON CLIMATE AND SOCIETY IN THE USA

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INTRODUCTION

Assessment of the effects on society of climatic variations is a complex task. Methodological approaches for such assessments are in formative stages of development. The meeting of the IIASA Task Force on Climate and Society Research is a reflection of this fact. Within the research community there exists a growing realization that we need to take stock of available methods, existing case studies, and current research efforts before pushing ahead in new directions. This paper is intended to stimulate thinking about the opportunities for further inquiry in the emerging field of research on the relationship between climate and society. Two conceptual models of relationships between climate and society are presented, and they are illustrated with a case study of drought in the United States Great Plains. The case study is part of a continuing research effort by the Climate and Society Research Group at Clark University (Worcester, Massachusetts, USA).*

THE US GREAT PLAINS AS A CASE STUDY OF CLIMATE AND SOCIETY

The Great Plains comprises all or part of ten states within the mid-continental United States (Figure 1). For several reasons the region provides a unique setting for examining the effects of climatic variations on society. It is a semi-arid agricultural area, alternately plagued by prolonged droughts and blessed with periods of plentiful

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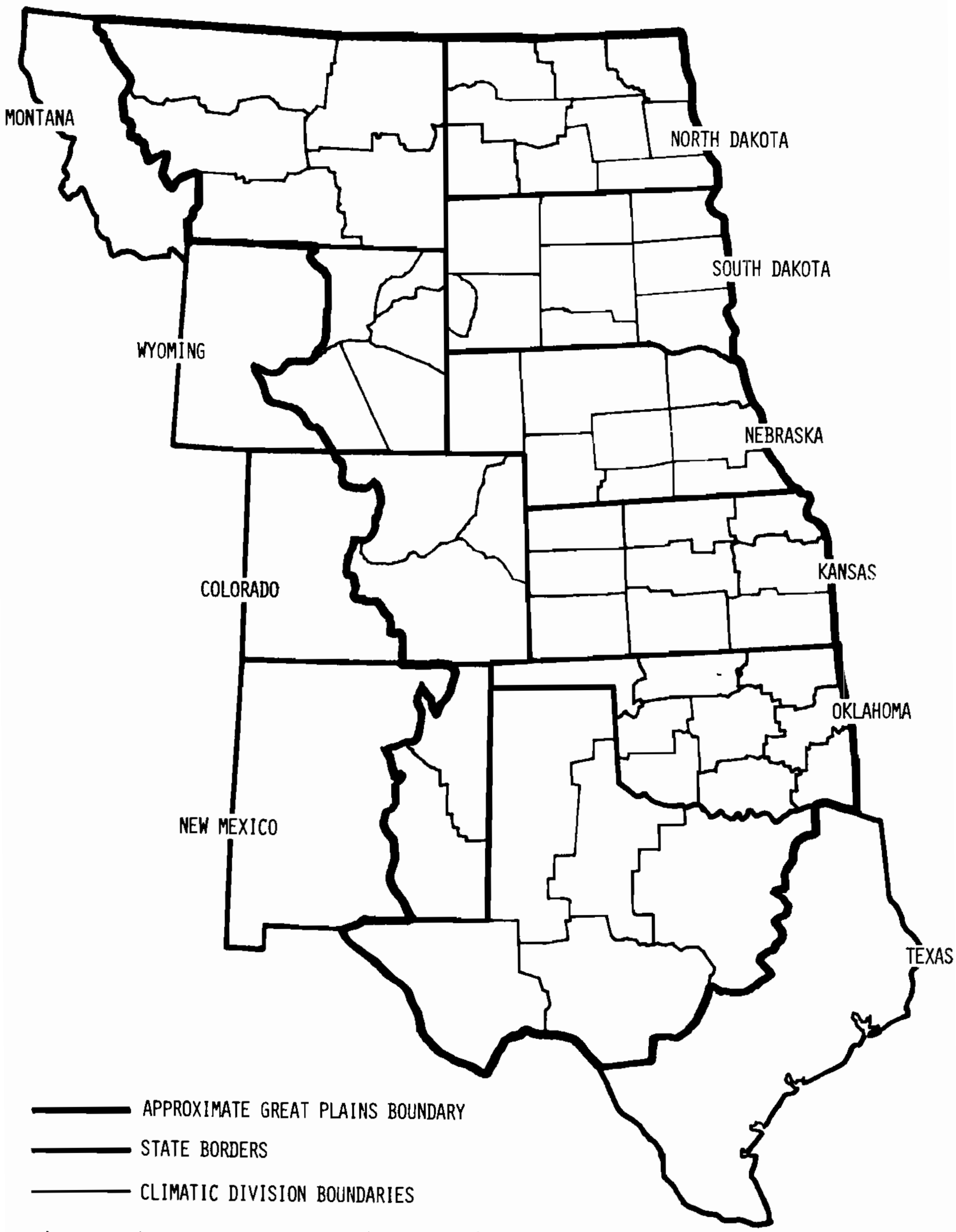

Figure 1 The Great Plains Study Area.

rainfall. The history of agricultural settlement within the region encompasses only a century, but it is a dramatic one, characterized by boom and bust and by remarkable changes in livelihood patterns and technologies. From the tentative steps of the region's first sodbusters during the latter half of the 1800s, the Great Plains has grown into a center of agricultural activity which contributes about 45 percent of the total wheat trade among nations. Furthermore, the early settlers who moved into the Plains were largely unfamiliar with the climate and did not know to expect the periodic fluctuations, which have proven detrimental to agricultural pursuits; thus, from the point of view of perception of climate, the Great Plains settlement may serve as an illuminating historical analogue to the possible problem of an imminent climatic change whose features are unknown. Finally, unlike other, similarly interesting areas of the world, there exist relatively abundant data on agricultural change and drought, on which the researcher can draw. This setting is thus a good one for investigation of broad hypotheses about the relationship between climate and society.

THE "LESSENING" HYPOTHESIS AND A CONCEPTUAL MODEL OF CLIMATIC IMPACT ASSESSMENT

Two major hypotheses are posed by Clark University's Climate and Society Research Group. The first states that persistent and adaptive societies, through their technological and social organization, *lessen* the impacts upon the resident population of recurrent climatic fluctuations of similar magnitude, and indirectly *lessen* the impacts on the entire society. Thus, over a period of time, such societies are seen to exhibit markedly diminished effects from similar climatic fluctuations. This has been dubbed the "lessening" hypothesis.

However, the second hypothesis states that success in insulating a livelihood system from recurrent climatic fluctuation comes as a result of increasingly elaborate technical and social systems, which *increase* the vulnerability to catastrophe from both natural and social perturbations that occur less frequently. In relatively closed livelihood systems, such vulnerability may be marked by recurrent system collapse, evidenced in major population declines. In more open and enlarging systems like the Great Plains, such vulnerability may be devolved or shared ever more widely, rippling into previously unrelated areas or societies.

The focus of this paper is the first—or lessening—hypothesis. Hereafter, the term "lessening" will be used as an abbreviation for the hypothesis itself.

In order to investigate lessening in the Great Plains, an initial simple conceptual model of climate-impact assessment, as shown in Figure 2, was adopted. It is a straightforward approach (called an "input-output" model by Kates (1979)), which has characterized a major portion of the work

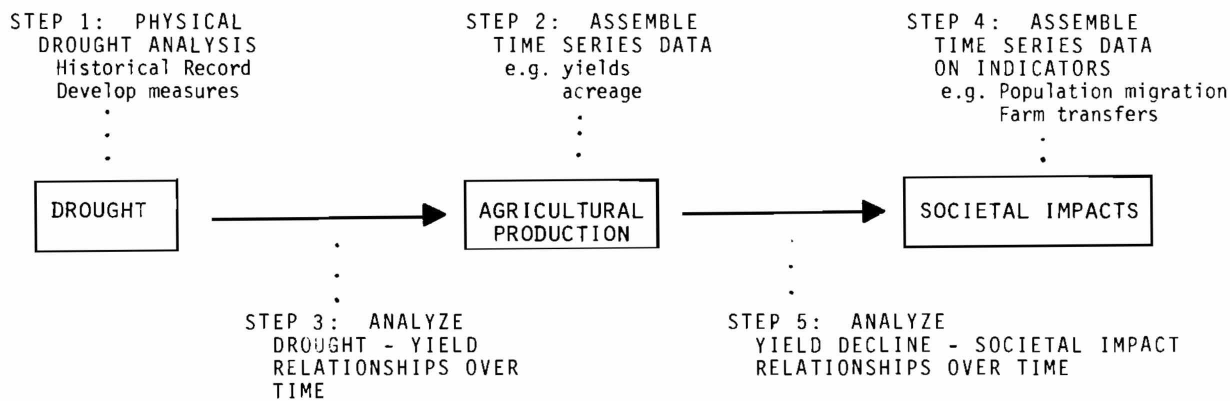

Figure 2 Great Plains Case Study methods.

in climate-impact assessment to date. According to this conception, a climatic event (drought) affects some sector of society (agricultural production) and "causes" societal impacts. Within this framework, the investigation of the lessening hypothesis for the case of the Great Plains involves five steps: 1, constructing the historical record of drought occurrence; 2, assembling time-series data related to agricultural production; 3, examining the drought-yield relationship over time for evidence of lessening; 4, assembling time-series data on societal impacts; and 5, examining the agricultural drought-societal impact relationships over time for evidence of lessening. Let us examine each step in turn.

STEP 1: THE HISTORICAL RECORD OF GREAT PLAINS DROUGHTS

Major droughts have occurred in the Great Plains four times since the 1890s (or five times if one includes the drought in the western US during the mid-1970s): in the 1890s, 1910s, 1930s, and 1950s, or roughly every 20 years. For the 1890s, instrumental records and historical sources indicate that, during the years 1894-1895, widespread severe drought conditions prevailed over major portions of the Plains. Evidence of more localized droughts is found for the period 1887-1896. During the 1910s, it is difficult to identify a drought covering the entire Plains area. Droughts observed in 1910, 1911, 1913, and 1917-1919 were short and severe, but rather spatially constrained. The 1917-1919 drought was especially severe in Montana and the Dakotas.

From 1930 to the present, records of climatological data are much more consistent and uniform, thus allowing for a greater comparability of historical drought events. The Palmer Index, a measure of soil moisture and groundwater conditions based on evapotranspiration (Palmer 1965), has been calculated (by the National Climatic Center, National Oceanic and Atmospheric Administration) for climatic divisions in the Plains, utilizing area-averaged precipitation and temperature data. These values were obtained and compiled for the period 1931-1977. The entire pattern of drought occurrence over time and space is displayed in Figure 3, where 64 climatic divisions, oriented north to south, are plotted against time, in years. The data represent growing-season averages of monthly Palmer-Index values. Only values indicating drought conditions were plotted: the darker the pattern in Figure 3, the more severe were the drought conditions.

The duration and spatial patterns of the droughts in the 1930s and 1950s are easily distinguishable. The drought conditions of the 1930s persisted for nearly a decade and affected virtually the whole of the Plains. The drought of the 1950s matched that of the 1930s for severity in certain portions of the central and southern Plains. Isolated droughts occurred in the 1960s: for example, 1961 was a particularly dry year.

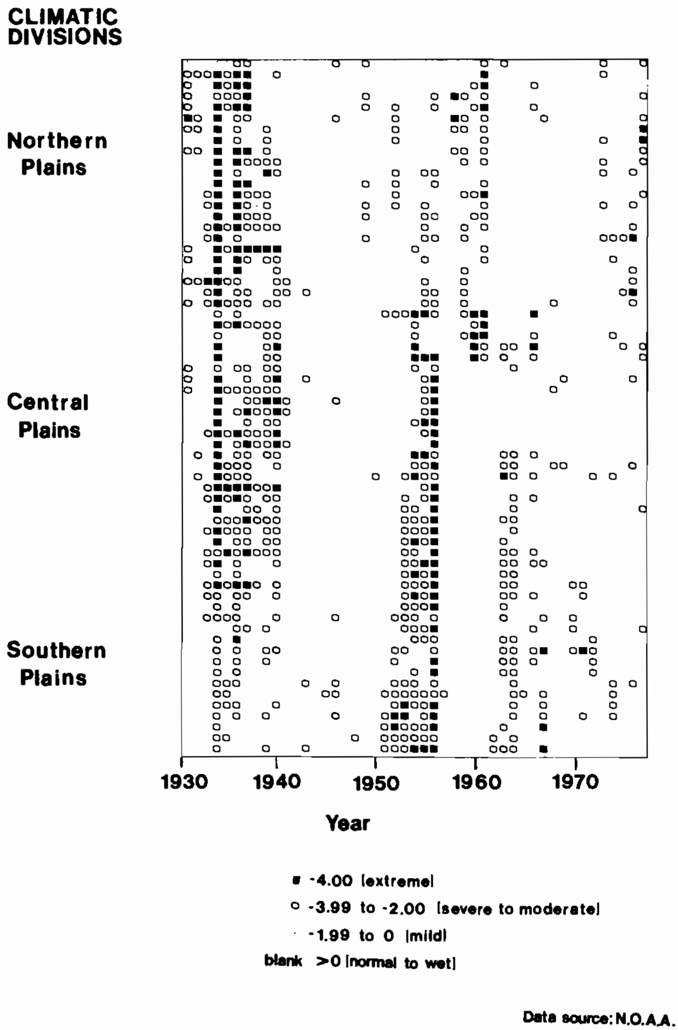

Figure 3 Patterns of Great Plains droughts. (Based on Palmer-Index values averaged over four months, May through August, by climatic division.) (Data Source: NOAA.)

The 1970s again brought dry conditions, although they were not as extensive as earlier droughts. The years 1974, 1976, and 1977 witnessed spatially limited desiccation in the southern Plains and even some blowing soil in the famous Dust Bowl area. In North Dakota, 1977 was a year comparable to the worst year of the 1930s. Severe drought also developed during the 1970s from the continental divide westward to the Pacific Coast.

One way of portraying the severity of drought is by accumulating the number of climatic divisions displaying Palmer drought of a given magnitude or greater during each month of the growing season, as shown in Figure 4. For any given year, these "division-months" reflect areal extent, as well as magnitude and seasonal persistence, of drought. The severity of the 1930s drought (as represented by the area under the curve) is strikingly evident. In fact, recent analysis of dendrochronological data spanning several centuries suggests that the 1930s drought was the worst single drought event since about 1600 A.D. (Mitchell, *et al.* 1978). This finding is supported by statistical analyses of instrumental records in the northern Plains by Eddy and Cooter (1978) whose frequency simulation suggested that the 1930s drought in western Kansas has a return interval of about 360 years.

Although comparable data are not available for the entire 90 years under study, it is likely that the ranking of major droughts from most to least severe is as follows: 1930s, 1950s, 1890s, 1910s, and 1970s. However, in terms of division-months of Palmer growing-season droughts, the 1970s do not appear any drier than the 1960s, notwithstanding widespread media coverage of drought in the Plains during 1977 (Warrick and Bowden 1980).

STEPS 2 AND 3: WHEAT YIELDS AND DROUGHT RELATIONSHIPS

Time-series data on wheat yields were assembled to provide a continuous record from 1890 to 1977, as shown in Figure 5. Wheat was chosen because it is sensitive to soil-moisture conditions and because it is a principal agricultural product of the Great Plains. The percentage of acres planted but not harvested is also shown, because poor crop prospects due to drought (or other causes) often lead to crop abandonment. The curvilinear yield-trend line was constructed from a polynomial regression fit to the actual wheat-yield data. The broad bands in Figure 5 roughly designate drought occurrence and duration. It should be kept in mind that, especially during the 1910s and 1970s, droughts were often scattered, single-year events.

During each major drought decade, yields plunged below levels expected on the basis of long-term trends. The longer, sustained declines are most evident for the 1930s and 1950s, when drought was more persistent. Of course, yield declines are not necessarily due to drought alone; for example, in the 1970s, acreage expansion to inferior areas and weather phenomena were influential. The percentage declines from

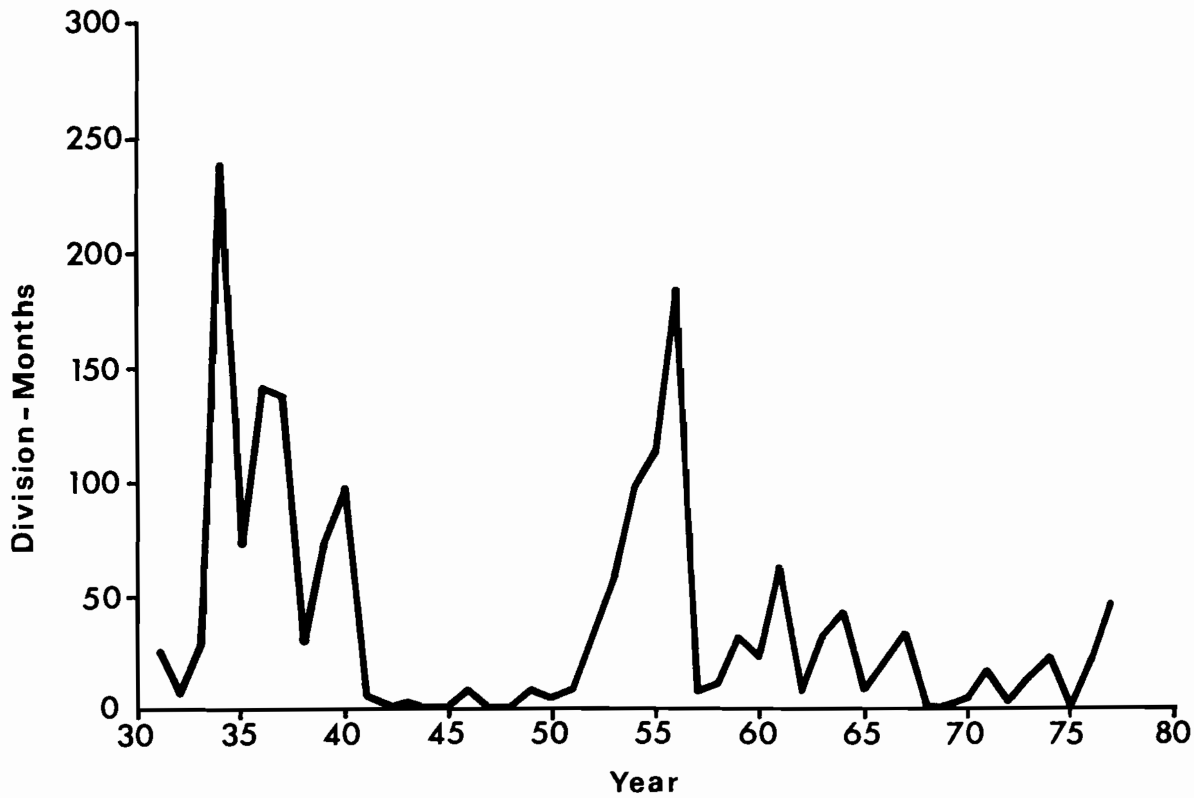

Figure 4 Great Plains droughts, 1931-1977. (The number of divisions exhibiting severe 01 extreme drought (≤ - 3.00) conditions, based on Palmer-Index values summed over 5 months, April through August. Data source: NOAA).

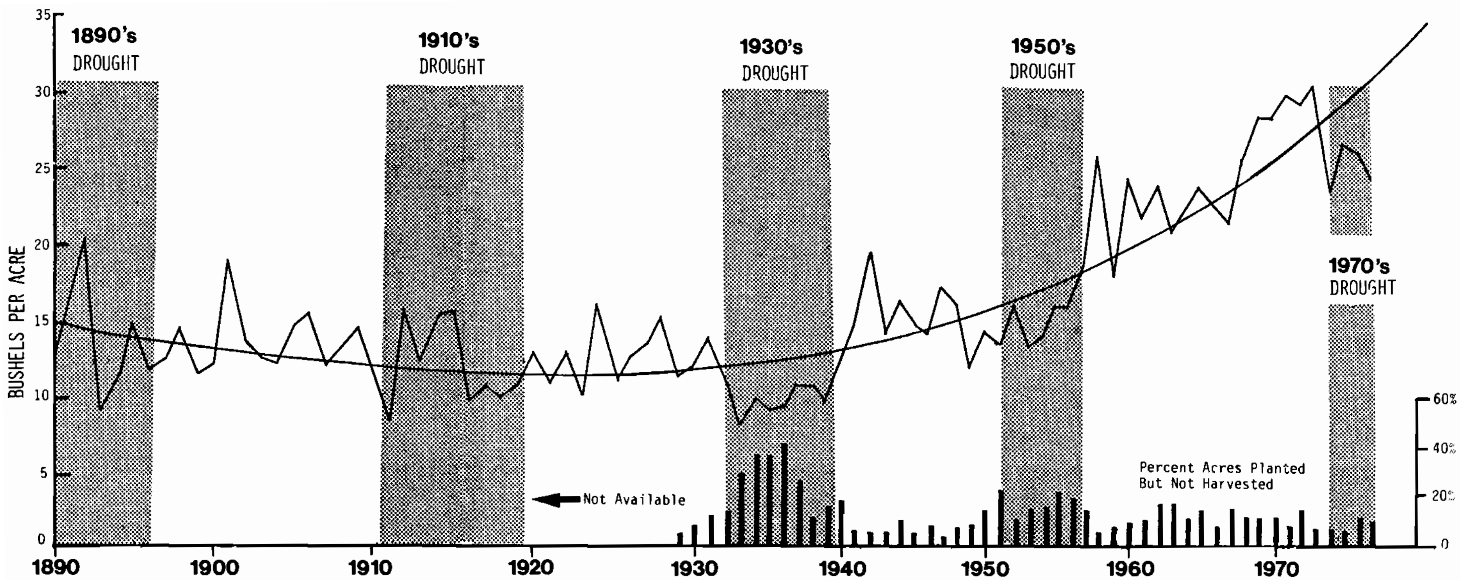

Figure 5 Wheat yields in the Great Plains, 1890-1977. (Data source: U.S. Department of Agriculture.)

expected yields for each drought period are depicted in Table 1. Each entry represents the average of the two worst years in the period concerned. Have wheat yields become less sensitive to droughts?

Table 1. Relative wheat-yield declines for historical droughts.

	Drought Decades				
	1890s	1910s	1930s	1950s	1970s
Percentage decline from trend[a]	26	24	29	19	17
Percentage decline per division-month of drought (x 100)[b]	—	—	8	6	7

[a]Average of the two worst years in each decade.
[b]≤ -1.00 on the Palmer Index, summed over all climatic divisions during the March-July growing season.

Since the 1930s, when the decline was about 29 percent, the declines have dropped to 19 and 17 percent for the 1950s and 1970s, respectively. However, it is also true that measurements show that each successive Plains-wide drought since the 1930s was less severe from a physical point of view. One crude way of taking into account these differences in drought severity is to divide the percentage decline in yield by the number of division-months of Palmer drought for each set of years. As depicted in Table 1, the resulting declines per division-month of drought are rather similar and do not suggest a lessening impact over time. The results of this approximate procedure suggest that we should look elsewhere in the literature for evidence of lessening.

The literature on weather-yield relationships is inconclusive on trends in the role of meteorological factors in agriculture. The arguments fall into two camps. On the one hand, there are those who conclude that drought (or weather, principally) has had a definite decreasing influence on yields due to "technology." For example, Newman (1978) examined yields of several grains for the United States and Canada in terms of running averages of coefficients of variability (CV) over a period from 1930 to the present, and demonstrated that the CVs decline for all grains. Wheat, for example, showed a decrease from 11 percent for 1936-1945 to 9 percent for 1966-1975. Corn, sorghum, and soybeans showed more definitive reductions in CVs. Newman maintains that the possible effects of decadal differences in weather on this observed decrease are largely cancelled out by the geographical diversity of wheat production and by the fact that the Canadian Plains' weather is often out of phase with that of the US Plains. He concludes, in short, that sensitivity of yields to drought has been reduced and that technology is responsible. The US Department of Agriculture agrees with this conclusion.

The opposing interpretation is that yields are still subject to sharp declines from poor weather, and that any observable trend toward decreased variability is due to an unusual streak of favorable weather—and not to technological prowess. Perhaps the most ardent support for this view comes from McQuigg *et al.* (1973), whose approach holds "technology" (as defined by an upward yield-trend curve) constant while simulating historical records of yields using weather-yield models developed by Thompson (1969). At a constant 1973 level of technology, yields of recent years are still high, suggesting a strong influence of favorable weather. Furthermore, at a constant 1945 level of technology (Figure 6), simulated yields correspond well to actual yield data. This suggests strongly that weather, not technology, has been the dominant factor in shaping the recent pattern of high, consistent yields, or, in short, that lessened drought impact on yields is simply an illusion caused by fortuitous weather conditions. This conclusion finds support from Schneider and Temkin (1978) and Haigh (1977), among others. Several studies, including those by the Institute of Ecology (1976) and Gasser (1976), emphasize the importance of both weather and technology.

One major barrier to reaching firm conclusions about trends in weather-yield relationships is the somewhat stubborn problem of separating weather and technology: both are time-dependent. This problem is especially acute at the large scales of nations and regions on which most studies have been conducted. Perhaps a more promising approach would be to focus on states, crop-reporting districts (which, incidentally, conveniently coincide with climatic divisions for most of the Plains), or even counties. At these smaller scales of analysis, one could take advantage of variability in local weather in order to capture a broader range of climatic events over time. By selection of a more deliberate distribution of drought events, it might be possible to control systematically for weather in order to examine yields for evidence of lessening drought sensitivity. Weather-yield models developed for smaller spatial units—like the University of Wisconsin models which employ crop-reporting districts (Michaels 1978)—are currently being scrutinized for this purpose.

In this regard, a preliminary analysis at the state level has been conducted. The State of Kansas was chosen because it is the center of winter wheat production and because a number of drought events have occurred since the 1950s. A continuous record of Kansas wheat yields from 1890 to the present was assembled, and a third-degree polynomial curve was fitted to describe the trend. On the basis

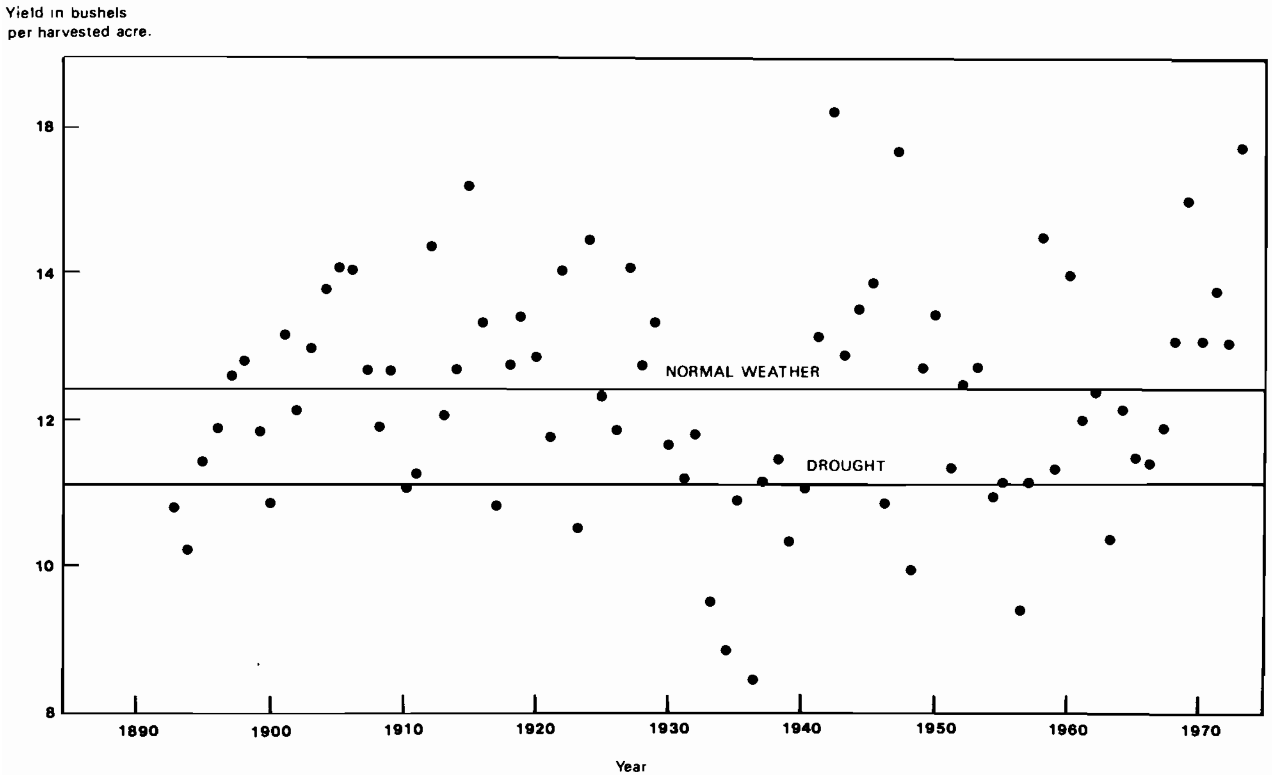

Figure 6 Simulated weighted-average wheat yields using 1945 technology and based on regression of actual yield/weather data, 1874-1945. (Data source: NOAA, 1973.)

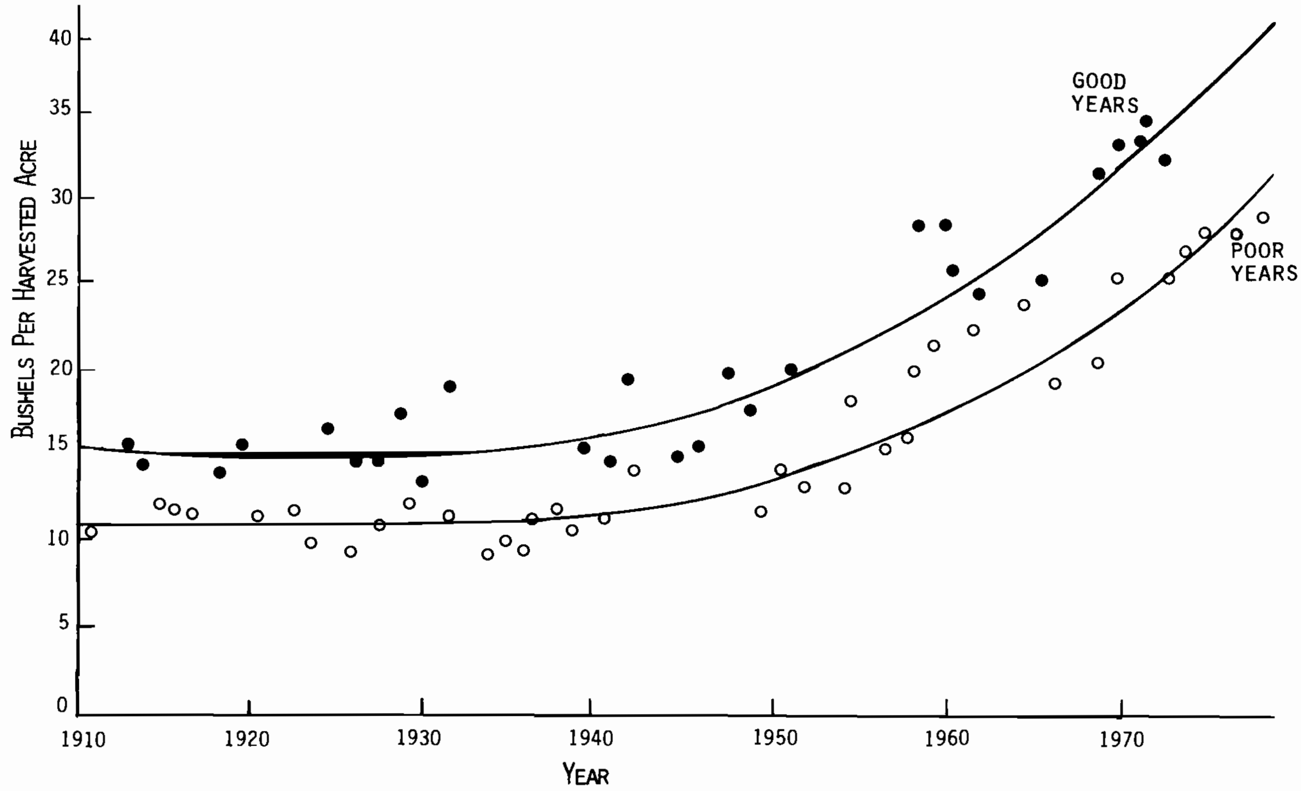

Figure 7 Kansas wheat-yield trends. (See also Table 2.)

of the trend curve, years of "good" yields and "poor" yields were selected, being defined in terms of positive and negative residuals (residuals being the difference between observed and expected yields). As shown in Figure 7, separate trend curves were then fitted to the good and poor years, on the assumption that if lessening were occurring, one would detect a relative convergence of the two curves. In other words, if our agricultural system has become better at dealing with drought conditions, the relative difference between expected good yields and expected poor yields should decrease over time.

In terms of absolute bushels, the trend curves actually diverge, as reflected by the values for 10-year intervals shown in Table 2. This is an obvious consequence of the overall increase in average yields, meaning that we can anticipate greater average loss during poor years, in actual bushels per acre, than in previous years—in one sense, a "worsening." But our notion of drought impact is concerned more with losses in relation to some expected "good" yield—a *relative* decline. The relative declines shown in Table 2 were calculated for the same 10-year intervals from the formula

$$\text{relative decline} = \frac{\text{expected good yield - expected poor yield}}{\text{expected good yield}}$$

Is lessening occurring? Apparently not. Assuming that drought is a major contributor to poor yields, the small differences in these values suggest that the relative impact of drought on yields has remained rather stable over time.

While firm conclusions about the drought-yield link cannot yet be reached on the basis of this (or other) analysis, the strong possibility that lessening is not occurring has enormous implications for drought-management strategies. The conventional wisdom seems to assume uncritically that the arsenal of technological adjustments designed to buffer yields against unfavorable weather have been highly effective, especially those adopted since the 1930s. Many point to the

Table 2. Kansas wheat-yield trends. (See also Figure 7.)

	1925	1935	1945	1955	1965	1975
Absolute difference (bushels per acre)	4.0	4.2	5.2	6.3	7.7	10.1
Relative difference (percentage of good-year trend)	26	28	29	29	27	27

Dust Bowl crisis as evidence of the progress made in drought protection. This observation often serves as justification for further application of similar technologies for the future. But, if further research demonstrates that, on the contrary, sensitivity of yields has not been reduced, one could evaluate the past efforts as failures. Could it be that we have spent millions of dollars and years of effort for naught? If such is the case, prescriptions for the future of "more of the same" should be assessed with a very critical eye.

STEPS 4 AND 5: THE IMPACTS ON SOCIETAL WELL-BEING

Ultimately, it is not yield declines *per se* that concern us, but rather the adverse consequences that they may bring to human well-being. How did the agriculturalists of the Great Plains fare during each of the major droughts of the last 90 years? The evidence suggests that the impact has been decreasing markedly since the 1890s. This lessening impact is reflected in data on migration, farm transfers, government relief payments, and health effects. We will now examine the available data for each drought decade.

The 1890s

The physical displacement of people is an indicator of drought stress that reflects a set of adverse conditions severe enough to prompt relinquishment of home and place of livelihood. Patterns of population declines have been reconstructed for each decade from 1890 to the present, using decennial county population data published by the US Bureau of the Census.* Estimates of population declines for the drought decades of the 1890s, 1910s, 1930s, and 1950s are displayed in Figure 8.

The decade of the 1890s witnessed massive outpourings of agriculturalists from large areas of the Plains. Net displacement may have amounted to as many as 300,000 persons. Many areas experienced a dramatic loss of 50 to 75 percent of their population. This sudden out-migration reversed the trend of many years in which settlers flooded into the uncultivated margins of the Plains frontier. Of course, it is highly probable that the population would have levelled off, perhaps even declined, in the 1890s, with or without drought;

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*The estimates were adjusted to account for the systematic bias caused by using decennial population figures alone. Since major droughts have usually occurred mid-decade, drought-related population loss is underestimated in earlier decades, when the trend in population was upwards, and overestimated in recent decades of general rural population decline in the Plains. To account for this, pre-drought and post-drought decadal trends were projected into the decade in question; the drought-related population drop was measured as the absolute difference between the two projected curves over the period of drought occurrence.

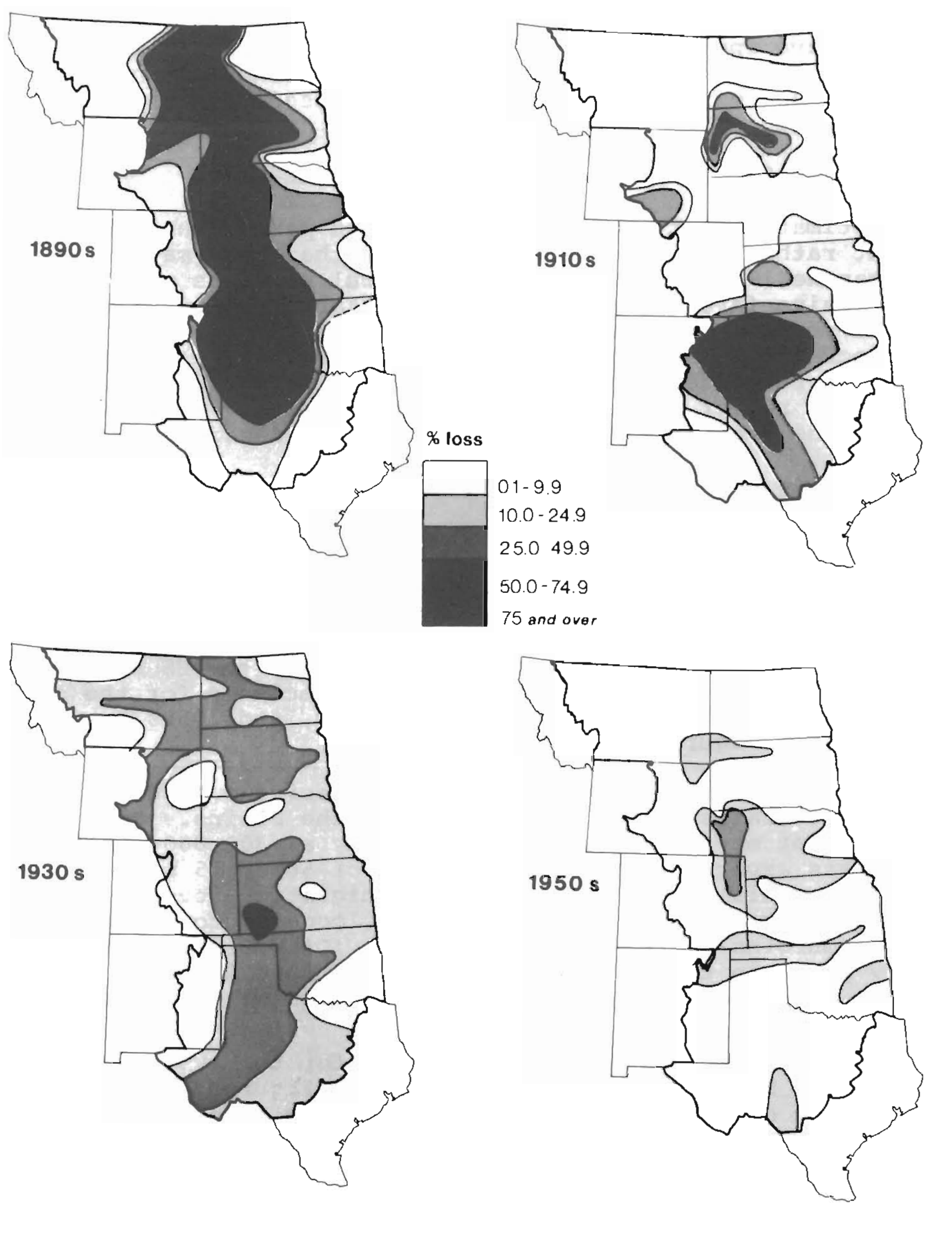

Figure 8 Population declines. (Data source: U.S. Bureau of the Census.)

prices for agricultural products had plummeted as economic depression penetrated the region. But there can be little doubt that severe drought greatly exacerbated the troubles of the agriculturalists and sent thousands scurrying back to more familiar and favorable environments.

The situation of the 1890s was overwhelming enough to affect the health of Plains settlers. Many of those living on the Plains frontier were newly-arrived homesteaders who brought little with them and who were existing on a thin margin of reserves. When drought and depression struck, many were left without means of support or sustenance. Malnutrition was not uncommon, particularly in portions of the central and southern Plains, and starvation was the fate of many (Bowden 1977).

For several reasons, the possibility of extending public relief was dismissed by state and local government. On a philosophical level, the notion of public assistance was difficult for governments to accept, given the deeply entrenched beliefs in the efficacy of laissez-faire capitalism. The agriculturalist—the victim—was viewed as responsible for his plight; it was not the duty of the taxpayer to bail him out of his difficulty. On a more practical level, local governments were fearful that public assistance would advertise to the outside world the fact that their state was facing serious troubles. Plains states had carefully cultivated a strong promotional image to attract people and money inside their borders, and news of drought disaster could irreparably tarnish that image (Baltensperger 1974).

In sum, during the 1890s the impact of drought must be described as severe. With no public assistance of any significance, severe adverse health effects—even death—were experienced, and massive out-migration of settlers took place. The fact that the drought of the 1890s was perhaps only half as severe, from a physical point of view, as that of the 1930s underscores the vulnerability of those early settlers to climatic perturbations. By any definition, the drought years of the 1890s were disastrous.

The 1910s

During the drought of the 1910s, circumstances similar to those of the previous drought episode existed. The preceding decade brought good weather, good prices, and agriculturalists back to the Plains. Population was increasing nearly everywhere. During the early 1910s, the liberalization of the Homestead Act, rising prices, and the opportunities for wheat farming afforded by new technologies stimulated the last homestead rush to the northern Plains. But like the prior generation, settlers were without reserves and so were ill-equipped to deal with unexpected setbacks from the weather. Thus, when drought in the northern Plains became apparent in 1917, intensified in 1918, and culminated in the disastrous year of 1919—when Montana wheat yields averaged 5 bushels per acre—agriculturalists once again found themselves in serious trouble. And, once again, state governments were reluctant to extend relief aid to needy agriculturalists, for basically the same reasons as described above.

For example, in 1919, the Montana governor convened a special session of the legislature to consider the drought problem. In addressing the assembly, the governor urged the members to:

> ...not let it be understood that the state of Montana is or that the people are as a whole, in destitute circumstances...Montana does not need outside help. The Red Cross and other organizations, when called into relief work, raise their money by drives, stating the specific purpose for which it is sought. If we delegate any considerable part of our problem to these organizations, we will directly or indirectly ask for outside help and advertise the State as seeking charity abroad...I am one who believes firmly that Montana will take care of herself...*

In other words, droughts were bad for business. Nevertheless, local fund drives were initiated and there were signs of softening toward the notion of public assistance. Other states had similar experiences. While there may have been drought-related health effects at local levels, there were no reported deaths from starvation, as there had been 20 years earlier (Toole 1972).

The stresses associated with drought-afflicted crop yields, however, were serious enough to dislodge many agriculturalists from their farms. Extensive areas in the western Dakotas and southern Plains experienced a net loss of between 25 and 50 percent of their population. A massive wave of out-migration also took place in eastern Montana.** Although these population dislocations were not as severe as those of the 1890s, it must be emphasized that the drought of the 1910s was not complicated by poor market conditions. In fact, these population movements took place despite all-time-high wheat prices, forced upwards by World War I.

The 1930s

The 1930s drought, still deeply embedded in the memories of Americans through experience and images of "the Dust Bowl," was physically the most severe yet experienced. However, despite the persistent and extreme desiccation, blowing soil,

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*Governor Stewart of Montana, Message to Extraordinary Legislative Session, 1919. From Montana State Library Archives.

**This exodus is not reflected in Figure 8 because the greatest influx of homesteaders occurred after the census count of 1910, and because the census count of 1920 caught most emigrants on the eve of their departure.

years of poor crop yields, and rock-bottom prices which prompted the exodus of thousands of bankrupt farmers, the percentage decline in population in hard-hit drought areas was considerably less than those of previous droughts. Of course, this does not mean that the population losses were insignificant, particularly in the light of the fact that the total population of the Plains had grown considerably since 1890. Net losses in population amounted to roughly 6 percent over the entire region. In Oklahoma, the decline approached 18 percent of the 1930 population, and several counties in the Dust Bowl area—Morton, Grant, and Stanton in Kansas, and Baca in Colorado, among others—experienced a 30 to 50 percent reduction in their total population (Worster 1979).

Financial distress among the rural Plains agriculturalists was a serious problem by the mid-1930s. Although there were scattered incidences of malnutrition amongst the most destitute, and persistent ill-effects from blowing dust, the threat of widespread health impacts was quickly abated by an unprecedented influx of governmental assistance for relief and rehabilitation. The Great Depression had helped to soften deep-rooted, hard-line attitudes of free enterprise, individualism, and the passive role of government. A large array of New Deal programs was established for depression-fighting, and these offered a convenient framework into which drought-relief programs for the Great Plains could be placed. With the philosophical ground already broken, federal funds were appropriated and distributed. By 1936, 21 percent of rural families throughout the Plains were receiving federal emergency relief (Link 1937). In hard-hit counties, the level of assistance reached 90 percent of families (Kifer and Stewart 1938). Total assistance (in unadjusted dollars) may have reached $1 billion (Warrick *et al.* 1975). By the mid-1930s, government payments comprised nearly 20 percent of all farm cash income (Borchert 1971).

During the 1930s, farm-transfer rates also reflected distress in the agricultural sector. In earlier years, farms were often simply abandoned when conditions became stressful because prospective buyers were largely non-existent. In later years, farms were sold or foreclosed. The numbers of transfers per thousand, including voluntary and involuntary (forced sales and related defaults) transfers, from 1930-1977 are displayed in Figure 9. In the mid-1930s, the abject combination of drought and depression surfaces in the high rate of farm transfers; about one farm in ten changed ownership at the peak, and half of these transfers were involuntary.

The 1950s

Twenty years later, the situation had altered remarkably. Evidence of stress during the drought of the 1950s is not apparent in data on migration and farm-transfer rates. The percentage declines in population during the 1950s are essentially indistinguishable from those of the wetter 1940s and 1960s. A slow, steady, net out-migration has been characteristic of the rural Plains since the 1930s; apparently, severe

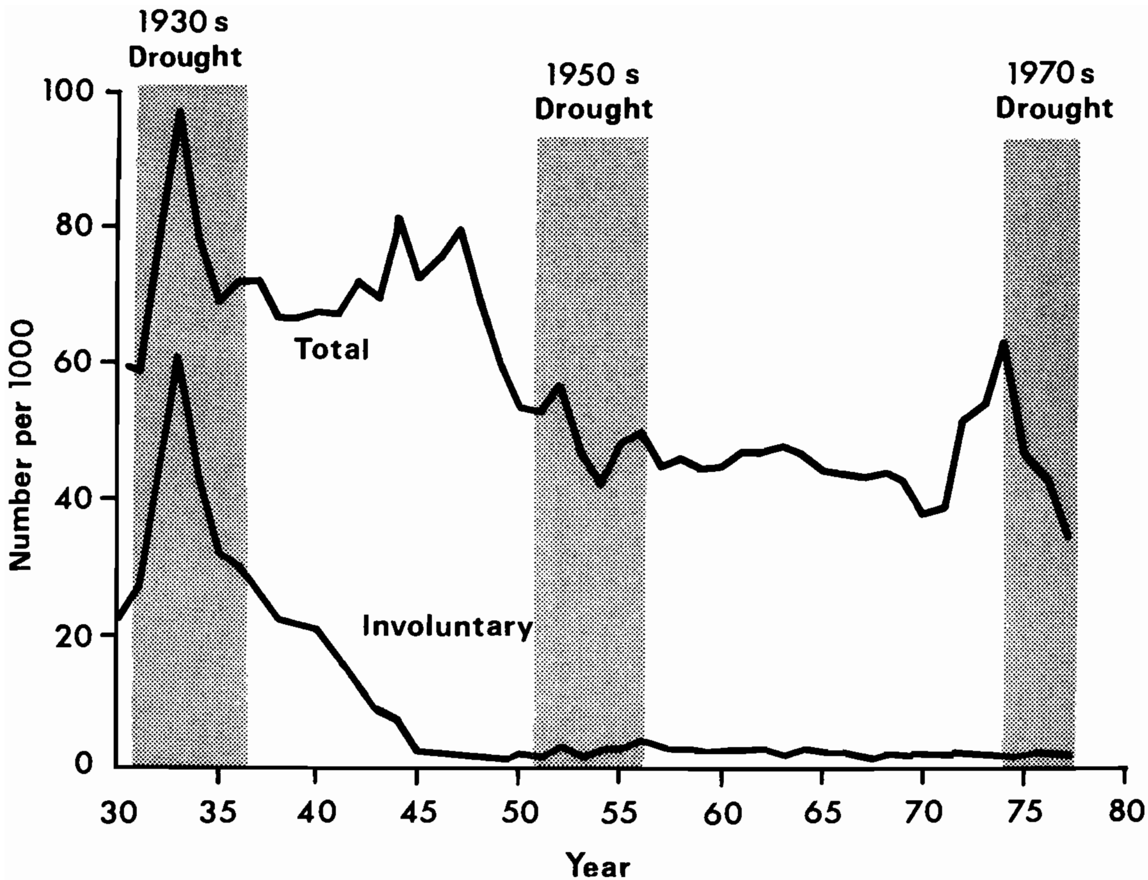

Figure 9 Farm transfers, 1930-1977. (Data source: U.S. Department of Agriculture.)

drought, such as that occurring in the central and southern Plains in the mid-1950s, had little effect upon the on-going process. Similarly, farm transfers did not increase during the 1950s drought as they had 20 years earlier, despite the fact that farm income suffered (Warrick 1975). In fact, the transfer rate from 1950 onward suggests that there may be an emerging tendency for farmers to maintain their position in the face of drought or other adversities. This notion finds support in the works of Malin (1944, 1947), Hewes (1973, 1975), and Bremer (1974), all of whom studied population mobility and turnover rates in the Plains. Their work suggests a trend, since early settlement, toward greater persistence among the resident rural population from one decade to the next. In central Kansas, for example, only about 35 percent of the inhabitants present in 1890 still remained by 1900; by the time of the 1950s drought, the decadal persistence rate was closer to 60 percent. This increasing persistence may well be symptomatic of the development of a greater resilience in Great Plains agriculture, a resilience which may reduce vulnerability to climatic events such as drought.

Certainly, the quick response of the federal government helped to alleviate the mounting potential for extreme financial hardship during the 1950s drought. By 1954, conditions were deemed severe enough to warrant federal drought assistance. The concept of public assistance to drought victims was now quite acceptable to a nation which had recently survived on a vast diet of federal programs conceived under prior conditions of drought and depression. Total expenditures amounted to $400-750 million, depending on the data source used.*

The 1970s

In the mid-1970s, the machinery of government was again activated and funds flowed west from Washington. While it was clear that the western United States—particularly California, Utah, and other far-west States—were being scorched by severe drought, the case was less clear for the Great Plains as a whole. In 1977, selected portions of the northern Plains were indeed experiencing drought reminiscent of the 1930s; several years earlier, portions of the old Dust Bowl even saw some blowing soil. However, whether drought occurrences in the 1970s were really any different from those of the 1960s, or whether agriculture in the Plains suffered unduly, can be legitimately questioned (Warrick and Bowden 1980).

Nevertheless, a 1977 Western Governors' Task Force on Drought—whose membership included Plains states—was successful in pushing through a $1 billion federal drought-relief package with unprecedented speed (Crawford 1978). As much as $200 million of this amount may have been allocated

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*US Department of Agriculture (1957) and Special Assistant to the President for Public Works Planning (1958), respectively.

to Great Plains states, although precise data are not available. Whether this amount was warranted by the physical and social circumstances of drought is, again, a matter of debate.

THE PATTERN OF DROUGHT IMPACTS

Over the period of 90 years studied, substantial evidence exists to support the hypothesis of lessening impacts. Although difficulties are encountered in accounting for differences in drought severity, and in separating drought effects from economic effects, the overall picture which emerges is one of progressively lessened impact upon the local agricultural residents. The most severe disruptions to livelihood and health occurred during the earliest periods, in which incidences of malnutrition and even starvation are recorded, and in which major sections of the Plains were decimated by population out-migration. During the more severe drought of the 1930s, it is argued that population dislocations—though dramatic—were relatively less pronounced than in previous droughts. Farm transfers (perhaps the modern equivalent of farm abandonment and migration) were, however, chronically high. Stress is not evident in these same indicators during the 1950s and 1970s. On the other hand, the concept of governmental relief and rehabilitation evolved from total rejection to federal institutionalization, to the point where the response to the 1970s drought might be considered premature or disproportionate to the degree of drought stress.

Thus, the pattern of impact has shifted, over a period of time, to encompass a broader social network. Local stress has been reduced and the willingness to spread the costs throughout society has grown substantially.

While the societal impacts diminish, it is not clear that this reduction results from a lessening in the drought-yield linkage. The data are ambiguous. It can be proposed, tentatively, that the bulk of lessening has not been achieved by technological mechanisms (e.g., fallowing, crop varieties, tillage practices, stubble mulching, etc.) which intervene between drought and yields. Rather, it is more likely that lessening has occurred because of intervention to protect societal well-being from the effects of yield declines, for example, through maintenance of financial reserves, availability of loans, stabilized prices, crop insurance schemes, federal farm policies, and the like (many of which are incidental to conscious drought response). This is a proposition which deserves further exploration.

The conceptual model presented at the beginning of this paper, however, is inadequate for examining this proposition, for it largely ignores societal response, the social basis of vulnerability, and the dynamics of adjustment. To incorporate these factors we turn to an alternative formulation.

AN INTERACTIVE MODEL OF CLIMATE AND SOCIETY

The model presented in Figure 10 is of the generic "Interactive Model with Feedback" type, as described by Kates (1979). This particular model was devised as a framework to assist a group interested in identifying promising areas of research on the question of social and institutional responses to CO_2-induced climate change,* and it therefore has a strong informational/decision-making component. Such a framework is also applicable to the study of drought in the Great Plains and may be generally useful in considering climate impact research.

From this perspective, impacts are as much a product of social organization as of climatic perturbation. They result from an interaction of climate and society. (Contrast this to the first model which portrays a unidirectional causal relationship.) Thus, the characteristics of society which fashion vulnerability are just as pertinent to understanding impacts as are the physical mechanisms of climate perturbation. With respect to drought, for example, certain societal sectors (like agriculture) are most visibly affected, but the effects may spread in less obvious ways through the pathways and linkages of the social system. They are reflected ultimately in some combination of human impacts, both positive and negative. For example, drought in the Plains initially affects agricultural yields, but may diffuse through regional economies, food supply systems, market mechanisms, or local community organizations; the resulting impacts could range potentially from malnutrition in a distant developing country, to high food prices in the northeast USA, to financial hardship for Plains agriculturalists.

The way in which climatic events, their impacts, and the range of alternative actions are perceived and interpreted influences the formulation of strategies for coping with the problem. Final response (or selection of strategies) is guided by a complicated array of societal constraints and incentives. For example, one could argue that for the last four decades, Plains drought was perceived primarily as an environmental problem—a lack of moisture—with impacts falling most heavily upon the individual agriculturalists. From the range of potential response, the strategies which are considered seriously are those designed to rectify the problem as perceived: namely, in terms of irrigation, desalination, soil cultivation practices, resistant crop varieties, evapotranspiration retardants, and so on. Some strategies, like desalination, were rejected due to economic constraints. Others, like irrigation schemes, were strongly favored owing to institutional bias existing among agencies like the US

*A panel concerned with delimiting research needs on the social and institutional responses to a possible CO_2-induced climate change, sponsored jointly by the US Department of Energy and the American Association for the Advancement of Science (Annapolis, Maryland, 1979).

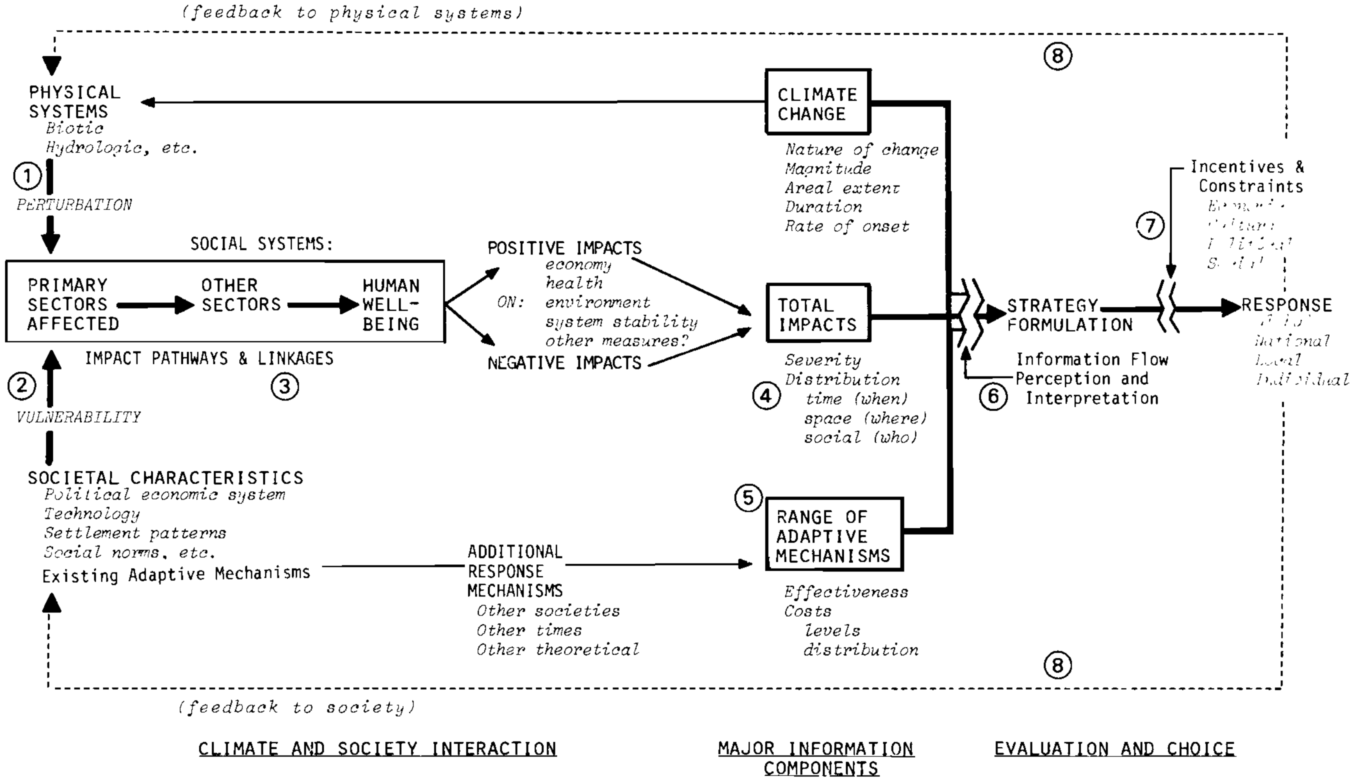

Figure 10 An interactive model of climate and society, emphasizing decision information and response.

Bureau of Reclamation or Corps of Engineers, or due to the preference of political entities motivated by patronage benefits. Still other strategies, like land-use regulation, were eliminated effectively in the first round, because they implied a different cause of drought problems and because they were antithetical to social attitudes about private property and individual rights.

The resultant patterns of response alter either physical systems, social systems, or both, and, in so doing, transform the interaction of climate and society over time. The relationship is clearly dynamic. It is this aspect of climate/society interaction that is particularly difficult to take into account in both research and planning. Usually climatic impact and response are treated statically (as in the first model). Yet, in order to anticipate better the consequences of our actions and to avoid unexpected or counterintuitive consequences, we need to understand the likely feedbacks over the long run. For example, would the widespread adoption of cloud-seeding weather modification in the Great Plains lead to alteration of crop varieties, land-use patterns, and agricultural production in such a way as to increase vulnerability to drought occurrence in the long term?

Although more realistic, the interactive model is unquestionably more complex, and studies which attempt to understand its workings *in toto* are often viewed as "fuzzy and idiosyncratic," in the words of Kates (1979). It is usually easier and more manageable for climate-impact assessments to adhere to simpler models, as illustrated by our Great Plains study.

Conclusions

For the purposes of this meeting, it may be helpful to conclude by raising several broad research questions which are suggested by the more sophisticated conceptual model. These are presented below in outline form. The numbers correspond to the circled numbers in Figure 10, and indicate the location of the question in relation to the model. The parenthetical questions are examples which apply specifically to the Great Plains. These are followed in each case by some brief comments related to the major questions.

1. What are the *relationships between fluctuations* or alterations in the physical systems resulting from climate change, and the *sectors of society* at risk?

(e.g., What are the patterns of, and potential for, economic disruptions from declines in wheat production under varying conditions of climatic fluctuation in the Great Plains? What would be the impact today of a recurrence of the 1930s drought?)

While we have models of climate and models of economies, very little work has been done in linking them together. This interfacing of physical and socioeconomic systems may offer a research opportunity with potentially large returns.

2. What are the *characteristics of society* that determine *differential vulnerability* to climate change?

(e.g., Historically, what were the underlying social characteristics and processes which fashioned the degree of vulnerability of Great Plains agriculturalists to droughts, and how and why do these change?)

The key concept is "vulnerability." Cross-cultural comparisons—e.g., comparative studies of market and centrally planned systems—may lead to the identification of the structural dimensions which ultimately determine, to a large extent, how vulnerable societies are to climatic fluctuations.

3. What are the *pathways* through, and *linkages* between, sectors which translate climatic perturbation into impacts on human well-being?

(e.g., Whereas the impacts of Great Plains droughts in the past were limited to local levels, there are indications that they may now be manifested in larger regional, national, or even global systems. What are the pathways to impact? And what are the key linkages by which these impacts are transmitted?)

The eventual human impacts of climatic change depend upon the ways in which direct effects on certain sectors filter through the political, social, and economic fabric of society. Knowledge of these pathways and linkages, and how they change over time and differ across cultures is fundamental to the evaluation of strategies for dealing with anticipated climatic events.

4. What is the *level and distribution of total impacts* arising from given climatic events?

(e.g., *Who* carries the burden of drought impact in the Great Plains? Who may gain? And why?)

While society often keeps careful records of aggregate economic gains or losses from climatic fluctuations like drought or flood, the question of the distribution of effects is usually left unaddressed. Knowledge of this sort could provide insights into the reasons for vulnerability and thus possible strategies for its reduction.

5. What is the *range of mechanisms* by which societies adjust to climatic fluctuation or change? And what are their costs and effects?

(e.g., What are the mechanisms by which vulnerability to drought in the Plains has been reduced? What are the more insidious social costs—in terms of dislocated families, bankrupt farms, and dying communities—which may be associated with larger farm sizes, higher technologies, and agricultural rationalization in an adapting Great Plains region?)

As society faces the prospect of a possible climatic change in the future from CO_2 or other causes, the issue of what mechanisms could be employed to cope with the effects has more than academic implications. Understanding of adjustive mechanisms can be gleaned from other times and places, for example, through historical case studies or cross-cultural comparisons.

6. How is *information* (scientific and otherwise) on climate change and its impacts *perceived, interpreted, valued,* and *channeled* into strategy evaluation?

(e.g., In the modern Great Plains, how is information about drought and, more generally, weather interpreted and utilized within an agricultural system which is increasingly technological, economically integrated, and commodity-conscious? Whom does such information benefit? And does it lead to differential vulnerability within the agricultural sector?)

Information on climatic events, impacts, and response mechanisms gets filtered in a variety of ways. The significance of climate change, for example, in the form of information generated by Global Circulation Models on possible CO_2-induced climate change, may be interpreted quite differently by the scientist and the policy maker. We know relatively little about the consequences for policy of different types of scientific information or of different modes of presentation. The ways in which information is incorporated into the decision process has critical implications for eventual decision outcomes.

7. What are the *conditions of choice* which guide societal response to climatic change?

(e.g., Throughout the history of societal adjustment to drought in the Great Plains, what were the guiding factors—for instance, financial institutions, market mechanisms, social attitudes, economic incentives, etc.—which favored the development of particular response mechanisms over others? Can understanding of these processes of the past provide predictive or prescriptive insight for future drought response in the Plains?)

Critical to the understanding of societal response to climatic variation is knowledge about the major incentives and constraints which influence choice. This applies to all scales of response. For example, at the individual level, there is a body of literature on the cognitive limitations of decision makers on matters of risk and uncertainty. At the social system level, important constraints to effective response may be inherent to political and economic systems: economically-dependent developing countries may be severely limited in response choice by the constraints imposed by a global capitalist market economy, or by their own systems derived from colonial roots. In the future, North-South conflicts may limit significantly the range of practicable global strategies for dealing with climate change.

8. What are the *dynamic feedback effects* of response patterns to natural environment and society?

(e.g., How have adjustments to drought (and other climatic risks) in the Great Plains altered vulnerability through time? Can any underlying processes in the Great Plains be identified which would contribute to a broader theory of climate and society interaction?)

This is the ultimate question: how does the whole system work? Methodologically, the question is difficult to address, although systems modeling has potential for combining the major components and examining their dynamic feedback effects. In contrast, questions 1-7 posed above largely address separate parts of the problem, and thus have the quality of being more focussed and precise. Yet understanding of the entire interrelated process and how it functions as a complex system of feedbacks and interrelationships is the ultimate goal of climate/society research.

Additional issues are raised by Figure 10, but the points outlined above are sufficient to suggest the range of questions which are integral to understanding climate and society as an interactive system, whether in the Great Plains or elsewhere.

In considering potential research, this Task Force convenes at a time when interest in societal impacts of climatic variability and change is high. The coalescing problems of CO_2, fluorocarbons, droughts, and food supply have focussed attention on climate as never before, and even stimulated the creation of a global climate research program (World Meteorological Organization 1979). However, our present research capabilities for unraveling the complexities of the interactions of climate and society appear inadequate. Researchers are well-grounded in either a natural or social science discipline, but little research endeavors to bridge the gaps between disciplines. Yet this is what sound climate impact assessment requires. It is hoped that further exploration of models in the context of specific research, for example, on drought impacts in the US Great Plains, will help generate creative ideas for future directions in climate and society research.

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DROUGHT AND SELF-PROVISIONING*

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INTRODUCTION

Drought cannot be defined in absolute terms, since it is by nature a variation and dependent on other sets of values. Associated with a "normal" distribution of the water supply, drought is, by the same token, associated with an economic and socio-technical system based on that norm which resiliently admits variations in distribution up to certain thresholds. Once these thresholds have been crossed, the system can no longer function in the usual way for a given time or as a stable whole with respect to certain elements.

When thrown out of an equilibrium which enables the system to keep reproducing itself, the system, in order to regain its balance, tends to draw on internal reserves of energy and/or to resort to external energy forming the internal reserve of a system wider than the system initially described and encompassing it. The restored balances and their thresholds of tolerance are not necessarily the same as the initial balances or thresholds of tolerance.

During a drought crisis, if internal reserves are insufficient, the original system may also become a qualitatively different system. When the crisis has passed, the system, whether quite visibly changed or seemingly only at a different level of balance, may be significantly more fragile or more resistant to changes in water supply. In the first instance, a situation which was previously considered normal may now be below the new threshold of tolerance and will become a drought situation; in the second instance, a situation which was previously considered as drought, but which

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*This is an adapted version of a much longer work entitled "Drought Reserves and Social Classes," prepared for the International Federation of Institutes of Advanced Study (IFIAS) Drought and Man Project, Geneva, 1979.

is differently located within the new range of acceptable variation, will be accommodated as a normal situation.

What is true of a relative shortage of water, is equally true of a relative excess, namely, flooding. A river in spate, up to a certain level, is considered to be normal, and it is used in a rational manner for the production of flood plain crops. Egypt provides the best-known example of this practice. The spate becomes destructive when it exceeds certain curves, and it is then called flooding. Below other curves, an insufficient spate is again identified with a drought situation.

Drought is thus integrally linked with society, although it is often convenient for analytical reasons to consider it as an independent variable. In this paper, I shall not deal with the direct impact of drought on crop production but will rather try to explore the potential consequences and seriousness of drought by analyzing the structure of the economy of a particularly relevant social group. I will examine the impact of plausible shortfalls in production on the producers' food consumption in a social system of cereal production in which consumption by the producer—self-provisioning—still plays a major role.

This model of social organization is still the one most commonly found in the Third World. Based on private ownership of land and the means of production, it is the peasant system as defined by Shanin (1971, p. 24):

> The peasantry consists of small agricultural producers who with the help of simple equipment and the labor of their families produce mainly for their own consumption and for the fulfillment of obligations to the holders of political and economic power.

I shall consider producer consumption mainly in terms of cereals. Cereals are peculiar in that the harvest cannot begin until a precise moment has been reached in the vegetative cycle, and, once this moment has been reached, the crop must be harvested as quickly as possible in order to reduce losses caused by seeding, mould, and the inroads of various predators. Moreover, the vegatative cycle of cereals is, at least traditionally, relatively fixed in relation to the annual climatic calendar. In contrast, the cultivation of tubers such as manioc, potatoes, or sweet potatoes can be staggered over a much longer period. The special problems related to livestock production (annual feed surpluses or shortages, discrepancies between resources and labor) will not be dealt with here. Also, in order to simplify and clarify the situation, I envisage the case of a single annual harvest of cereals. However, the conclusions we can draw from this extremely simplified model can be applied without difficulty to the more frequent case of two annual harvests of cereals, or even to cases of more than two harvests.

MODEL OF A SELF-PROVISIONING SOCIETY

Food has a dual nature, as a basic need and as merchandise. In a self-provisioning society we find both efforts to extract food away from the producers and efforts to retain it. The forces of extraction are of a composite nature—from cash requirements to land tenure relations, of which sharecropping is the most extreme example. The mechanics of the extraction of surplus food cannot be understood without taking into account the countervailing resistance of the self-provisioning peasant. As long as peasants of the Third World cannot control the prices of the produce which they sell on the market and the prices of what they have to buy (agricultural inputs and food), their attempt to retain some food for self-provisioning is an attempt to stay alive in an environment of fluctuating yields and prices. The idea of forces of retention conflicting with forces of extraction must be the heart of a model of the food sector of a self-provisioning peasant system. This conflict shapes the drama of millions of people in the world today.

To illustrate the dual nature of food and to demonstrate the forces at work, let us assume that one hundred units of food are produced in year 1, and a reduction to ninety units occurs the following year due to a drought. If in year 2 the level of self-provisioning remains the same, this means that the forces to retain food for self-provisioning are stronger than the market forces of extraction (Table 1). If in year 2 the level of "surplus"* remains the same (Table 2), it means that the forces of extraction are stronger. An indication of the balance between extraction and retention is therefore shown by the way in which the decrease in production is traded off between self-provisioning and marketing.

Table 1. Case in which the forces of retention are stronger than the forces of extraction (units of food).

	Production	Self-provisioning	Surplus
Family X			
Year 1	100	50	50
Year 2	90	50	40[a]
Family Y			
Year 1	100	80	20
Year 2	90	80	10[b]

[a]A reduction of 10% in production corresponds to a reduction of 20% in the marketed surplus.
[b]In the case of Family Y the same reduction of 10% in production entails a reduction of 50% in the marketed surplus.

*The term "surplus" is used for convenience. For a discussion of this concept, see Spitz (1980).

Table 2. Case in which the forces of extraction are stronger than the forces of retention (units of food)

	Production	Self-provisioning	Surplus
Family X			
Year 1	100	50	50
Year 2	90	40[a]	50
Family Y			
Year 1	100	80	20
Year 2	90	70[b]	20

[a] In this case the impact of drought, reducing production by 10%, is to reduce the level of self-provisioning by 20%.
[b] Under the same conditions, the level of self-provisioning is only reduced by 12.5%.

The fact that a decline in production has greater repercussions on the marketed surplus when the latter represents only a small proportion of production is well known, and has often been studied at the level of international trade. In contrast, this phenomenon seems to be less well understood at the national and, above all, at the microeconomic level in an agricultural situation where self-provisioning still plays a major role. Surplus and producer consumption are, in fact, often treated implicitly as if they were linear functions of production, which they never are. At the most, as in the simplified example we propose, they may be related functions, where production equals the sum of producer consumption and marketed surplus, to each of which is attached a varying coefficient of retention or extraction.

Drawing on the results of a 1962/63 survey in northern India,* I wish to take further the simple exercise presented above and to develop a new approach to the relationships between food production fluctuations, prices, and food availability. This approach is based on an indicator used locally by the peasants themselves to establish their own place and that of others in the socioeconomic hierarchy. This indicator is the number of months of self-provisioning. The use of this indicator makes it possible to give a calender dimension to the problem of the impact of drought—essential in an economy shaped by seasonal variations. This indicator also highlights the problem of stocks.

*The survey was carried out in the district of Hazaribagh, a part of the hill-plateau area known by the name of Chota-Nagpur. The district occupies the southern half of the State of Bihar.

The number of months M of self-provisioning may be expressed as follows:

$$M = \frac{1}{UC_m} \sum_{i=1}^{j} a_i y_i - S$$

where M is the number of months of self-provisioning, C_m is the average monthly consumption by consumption unit, U is the number of consumption units, a_i is the area of fields under cultivation (by surface unit) r_i, y_i is the yield per area unit of fields having a surface area s_i, and S is the surplus.

A fundamental fact is that M can be arrived at *directly*, without any calculations, in the course of a survey, for it constitutes a classifying category in the minds of the persons interrogated; the question "For how many months were you able to feed your family last year from your own production?" elicits an immediate response. If there is a deficit in production, the exhaustion of the cereal stocks at the beginning of the tiding-over period necessarily entails the purchase of basic cereals, and this comprises 80 percent of the budget when converted into monetary terms. The exact moment at which expenditure had to begin is clearly fixed in the memory of the persons interrogated, even if a source of income prior to that date has enabled them to build up some monetary reserves. In the absence of earlier income, they have to seek work or draw on their capital (in the broadest sense), or even borrow.

Two families with a capacity for six months' self-provisioning in basic cereals may not use their resources in the same fashion; the families may not be of the same size nor have the same level of consumption. However, once their food reserves are exhausted, they face the same situation in that they must find the necessary resources to enable them to live for the six months that remain until the next harvest. This they will be able to do more or less easily, depending on their circumstances, in particular, the possibility of sale of agricultural produce, craftsmen's products, or labor.

The fact that M may be arrived at directly makes it unnecessary to adopt a restrictive hypothesis of average consumption per family; real consumption is not constant throughout the year and unless it can be followed from week to week or from month to month, it can be arrived at only with difficulty; similarly, consumption may vary by unit of consumption. A fairly good approximation of total production $\sum a_i y_i$ may also be arrived at directly, and this is a means of corroboration. However, exact knowledge about the surface area is not only difficult to obtain, but also has little significance in view of the wide variations in yields to which we may draw attention. The concept of yield itself is not a category present in the minds of the persons surveyed, and, in the absence of direct measurement, it would be illusory to evaluate a_i and y_i.

The variable M gives us no information about the level of consumption. Consumption may be very high for a short period if there is additional income, and it is therefore necessary to examine such additional income. It may be connected with a traditional activity, such as a craft, and may be stable; or it may derive from an activity outside the village, of a more or less specialized nature, depending on whether or not there is guaranteed work, whether the work is permanent, semi-permanent, or temporary, and whether the pay is on a monthly, weekly, hourly, or piece-work basis. The stability of the income varies, often reflecting a greater or lesser degree of specialization.

Even in the case of highly stable employment, circumstances may be such that the source of additional income dries up. The most obvious case is that of a fairly long illness. Since highly stable employment is rare, its interruption, apart from cases of illness, is most often the result of the curtailment of the employment itself. Several examples of such curtailment were observed in the area surveyed, such as the closure of certain mines at Giridih with no opportunity for reemployment, and a similar reduction in jobs resulting from a crisis in the mica industry. In such cases a retreat to the most stable base of employment, namely farming, occurs. Consumption pressures then arise, and the period of self-consumption of supplies is extended; if M is below 12 months and if there is no other income, debts clearly must be incurred.

How does a "rational" farmer behave once he has completed his harvest? From his past experience, and with possible readjustments because of changes in the composition of his family, he calculates the number of months of supplies available for self-provisioning at the level of consumption to which he is generally accustomed. If this number is under 12, he will have to consider the possibility for obtaining additional income and, on that basis, choose his consumption level. He can readjust this level periodically according to new factors or new expectations. The way in which a farmer actually behaves appears to be not far removed from such rational behavior, aimed at minimizing the risk of being simultaneously without both food and resources during the tiding-over period.

Even given equal probabilities of obtaining additional income, substantial differences may be expected between the economic behavior of a farmer who sells food in any year and that of one with a permanent deficit in cereals. In order to assess economic behavior, therefore, it is necessary to stratify the field under study by average production characteristics (in relation to family characteristics, consumption levels, and work opportunities in the outside world), and also to take account of the variability of such characteristics in different years (i.e., basically according to climatic variations), the distribution and size of deficits and surpluses, and the probabilities associated with them.

AN APPLICATION OF THE MODEL OF SELF-PROVISIONING

As reference years, we take agricultural years between one harvest and the next. To show the effects of drought, we have to study three consecutive years:

- year 1, a good year from the point of view of agricultural production
- year 2, a bad (drought) year from the point of view of agricultural production
- year 3, a good or bad year from the point of view of agricultural production

In the area in which the research was carried out, no security stocks were built up in good years to provide for unfavorable years, even in the richest families. We will therefore not take such stocks into account. On the other hand, as climatic conditions deteriorate in year 2, forecasts are made about the volume of the coming harvest. Such forecasts induce those who still have stocks available to reduce their consumption level, so as to have a carry-over stock to add to the harvest. We will assume provisionally that consumption is reduced starting only at harvest time. We will therefore consider that self-provisioning for year 2 is "normal" and that it is reduced only for year 3, following the drought year.

Let us make another hypothesis for purposes of simplification: the production available to each family productive unit is reduced by the same proportion, namely, one-third. However, because the richest families generally have better land and more control over water, their production is in reality usually less affected than that of the poorer families. The disparity between rich and poor farmers during a drought is therefore even greater than that which is described below.

Take the case of three families (A_1, A_2, A_3) which, in year 2, have respectively the equivalent of 36, 24 and 21 months of self-sufficiency, i.e., a 24, 12 and 9 months surplus (see Table 3). Their production in year 2 is equal to 24, 16 and 14 months of self-provisioning. We shall work under the hypothesis (to be revised later) that the reduction in production affects only the surplus, or in other words, that *these families maintain a constant level of self-provisioning*. (See Table 1 above, case in which the forces of retention are stronger than the forces of extraction.)

Table 3. Months of self-provisioning and months of surplus available to families A_1, A_2, and A_3 in year 2 and year 3.

Family	Year 2 (drought year, still good from the point of view consumption)		Year 3 (bad from the point of view of consumption)	
	Year 1 production available in year 2	Surplus	Year 2 production available in year 3	Surplus
A_1	36	24	24	12
A_2	24	12	16	4
A_3	21	9	14	2

The effect of the drought is to reduce the surplus of A_1 by 50 percent, that of A_2 by 67 percent, and that of A_3 by 78 percent. The smaller the percentage of marketed surplus in relation to production, the more this surplus is reduced in a drought year.

A 33 percent reduction in production therefore leads to a 50, 67, or 78 percent reduction of the surplus (Table 4). Even assuming constant demand, this reduction in market supply will consequently lead to a considerable rise in prices, the more so as—given unequal land distribution—A_3 families are generally larger than A_1 families.

Table 4. Surplus in relation to production, families A_1, A_2, and A_3 in year 2 and year 3.

Family	Marketed surplus as a percentage of production $\frac{\text{Surplus}}{\text{Production}} \times 100$		Percentage reduction of surplus between years $\frac{\text{Year 2 surplus -3 surplus}}{\text{Year 2 surplus}} \times 100$
	Year 2	Year 3	
A_1	66	50	50
A_2	50	25	67
A_3	43	14	78

FAMILY A_1

. . . .

Year 2 FSP   Year 2 surplus (24 months)

. . . .

Year 3 FSP   Year 3 surplus (12 months)

FAMILY A_2

. . . .

Year 2 FSP   Year 2 surplus (12 months)

. . . .

Year 3 FSP   Year 3 surplus (4 months)

FAMILY A_3

. . . .

Year 2 FSP   Year 2 surplus (9 months)

. . . .

Year 3 FSP   Year 3 surplus (2 months)

Figure 1. Reduction of surplus family food supplies following a drought, in the case in which the forces of retention are stronger than the forces of extraction. The dots represent units of food production. FSP is food for self-provisioning.

Let S_2 and S_3 be the surplus and p_2 and p_3 the average selling prices of cereals in years 2 and 3. To maintain the same income derived from the sale of the surplus, it is sufficient that

$$S_2 p_2 = S_3 p_3$$

i.e., for A_1, that $p_3 = 2p_2$, for A_2, that $p_3 = 3p_2$, and for A_3, that $p_3 = 4.5\ p_2$.

Let us suppose that the average selling prices of cereals are doubled or trebled in year 3. Let us then examine three cases with regard to the level of producer consumption: in case 1 the consumption level remains unchanged (forces of retention are stronger than forces of extraction); in case 2 the level of food consumption is reduced by one-third (forces of extraction are stronger than forces of retention); in case 3 the level of food consumption is reduced by one-sixth (intermediate trade-off between forces of extraction and retention). Table 5 summarizes the consequences of these hypotheses in terms of changes in income from the sale of surplus food. These changes are expressed as a plus or minus percentage of income in year 2.

If prices are doubled, A_1 can maintain the same level of consumption, while A_2 must reduce its consumption by 17 percent and A_3 by 21 percent in order to maintain the income derived from the sale of the surplus. That is to say, families A_2 and A_3 must cover year 3 with the equivalent of 10 months and 9.5 months respectively of producer-consumption in year 2. Any reduction in the level of consumption beyond these thresholds increases the income derived from the sale of the surplus.

Table 5. Changes in income from the sale of surplus cereal in families A_1, A_2, and A_3, for three cases of change in producer consumption, assuming a doubling or a tripling of the average selling price of cereals in year 3.

		Doubling of the average selling price in year 3			Tripling of the average selling price in year 3		
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Change in producer consumption from year 2		0	-17%	-33%	0	-17%	- 33%
Percentage change in family income from year 2	A_1	0	+17%	+33%	+50%	+75%	+100%
	A_2	-33%	0	+33%	0	+50%	+100%
	A_3	-56%	-11%	+33%	-33%	+33%	+100%

If prices are trebled and producer consumption levels stay the same, the income of A_1 increases by one-half and that of A_2 remains constant. In order to maintain its income, family A_3 must reduce its level of producer-consumption by 8 percent. In order to increase family income by one-half, A_1 does not reduce its consumption, A_2 reduces it by 17 percent, and A_3 by 21 percent.

Subject to the hypotheses we have adopted, such price increases consequently enable farmers of type A to maintain or improve the income derived from the sale of cereal surpluses, possibly at the cost of a slight decline in the level of their own cereal consumption. Moreover, a drought situation enables them to obtain manpower at lower costs and to reduce their annual payments as Rao (1974) observed in respect to the Andhra Pradesh drought of 1971-1973:

> While the drought situation was disadvantageous to the lower sections of the society who mainly depend on manual labour, the well-to-do sections...found it advantageous to them. As they were getting labour at a cheaper rate, they took the opportunity to get their irrigation wells repaired and new ones dug at a much lower cost.

As we shall see below, families of type A can also take advantage of sales of land, cattle, and agricultural tools at distress prices. Finally, because of their political and social power and the economic guarantees they can offer, they are the first to benefit from low interest bank loans which enable them both to make these advantageous purchases and to re-lend the money at usurious rates.

POORER FAMILIES AND THE PEAK PERIOD PROBLEM

Let us now envisage the case of the additional families B, C, D, E, and F. The characteristics of these families in terms of cereal production are shown in Table 6.

Table 6. Number of months of self-provisioning in year 2 and year 3 (following a drought), in the case in which the forces of retention are stronger than the forces of extraction.

Family	Year 2		Year 3
	Production	Surplus/Deficit	Production
B	18	6	12
C	12	0	8
D	9	-3	6
E	6	-6	4
F	3	-9	2

If family B fails in year 3 to reduce its level of self-provisioning, it is faced with the situation that it cannot sell any surplus. The hypothesis that the reduction in production affects only the surplus (which was not unlikely in the case of family A_1) becomes altogether unlikely in this case. With the money earned from the sale of six months' surplus in year 2, family B was able to afford a certain level of expenditure; some of the expense items typical of "good years"—improvement of housing, agricultural investment, ceremonies (particularly marriages)—can be reduced, cancelled, or postponed. The requirements for cash expenditures in year 3 are so compelling that the forces of retention of food for self-provisioning are insufficient to maintain the level of consumption of the previous year. In families of type B, which represent the upper stratum of peasants of average means in the survey area (Hazaribagh district, State of Bihar), education of children is, for instance, considered particularly important. To give an education to a son is to give him the assurance of employment outside the peasant community, in which life is subject to growing uncertainty because of the scarcity and high cost of land, while property is whittled away with every inheritance. Education therefore represents a "must" and the level of producer consumption will be reduced to cover its cost. More generally, the attainment of a relatively high income in a good year creates a consumption model which tends to be upheld, though of course at a lower level, in difficult years. Because of this "ratchet effect"* observed in the survey area, the hypothesis that the entire decline in production is reflected in the amount of surplus therefore cannot be upheld. The level of producer consumption is inevitably reduced. To obtain a surplus equivalent to two months' producer consumption (reduction of the surplus to one-third of the year 2 surplus) means reducing the level of producer consumption by one-sixth.

The fact that family C does not sell any surplus in year 2 (a "good year" from the point of view of consumption) means that it has some income, from whatever sources, to meet cash requirements. Assuming that these resources do not diminish in year 3, a very favorable hypothesis, this family will at least try to stretch its self-provisioning period until the next harvest. In order to achieve this, it must reduce its consumption level by one-third.

In order to maintain self-provisioning for the same number of months, families D, E, and F must reduce their consumption by one-third. However, they are faced with a price increase following the drought. Again adopting the

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*F. Modigliani (1949) was the first to introduce into fluctuation models the idea that consumption depends both on the income for the preceding period and on the maximum income that may have been obtained in the past. A. Smithies (1957) has used this "ratchet effect" at the macroeconomic level.

highly favorable hypothesis that their income is maintained, these families will not be able, with their unchanged income, to buy more than one-half or one-third of the cereals that they bought in the good year—depending on whether the price doubles or trebles. They will have to reduce their self-provisioning level of consumption by one-third, and in addition will have to reduce the amount of cereals purchased for consumption by one-half or two-thirds.

In the Chota Nagpur region, the varieties of rice grown in 1962-1963 had a vegetative cycle of about five months (more recent varieties have a shorter cycle). If the months following the harvest are numbered from 1 to 12, the first soil preparation work begins with the monsoon in month 7 (May-June). The peak period for agricultural work is in month 8. During this period, a production unit has its full complement of labor. Family members who work away from the village return, and those who are engaged in a craft interrupt that activity. Month 8 is therefore a month in which monetary income is at its lowest. It is also the month in which food consumption is at its highest both because of the number of workers and because of the increased consumption level resulting from the hard physical labor required of them. Observation has shown that, in order to cope with this situation, families of types E and F tend to build up food reserves for this period. Self-provisioning is voluntarily stopped whenever monetary resources can be found; these resources are then used to buy basic foodstuffs, particularly cereals, at a lower price than they would cost later, since prices rise steadily up to harvest time.

The purchase of basic cereals therefore does not necessarily mean that granaries are empty, since stocks may be kept for this peak period of agricultural work, as well as for festivals or other anticipated events. The building up of such intra-annual reserves (which are distinct from inter-annual security stocks) depends of course on the size of the harvest and on the possibilities of finding paid work, whether permanent or temporary, anticipated or casual. Families with permanent work outside the village are the ones who most frequently build up cereal reserves for the peak agricultural period; those who can rely only on casual work find themselves without reserves and even sometimes without any seed by June or July. They therefore have to resort to loans in cash or in kind. In the latter case, the loan is repayable at harvest time, four or five months later, with interest in kind of 50 percent, or, in the case of seed, 100 percent.

In year 2, family D has nine months of self-provisioning, and is consequently in a state of self-provisioning during the peak period of agricultural work. Family D thus does not normally have to build up stocks for this period. Consequently it finds itself facing a shortage after a bad harvest, with the result that its period of self-provisioning would be reduced to six months if it kept its consumption for year 3 at the same level as for year 2. Family D therefore has to reduce its consumption so that its period of self-provisioning is extended to cover the peak period of agricultural work.

If the first signs of a drought situation appear four or five months before the harvest, family D (and for the same reason also families C, B, and A) may have to reduce certain expenditures in view of the difficult year ahead. Family D cannot, however, reduce its level of self-provisioning so as to build up a carry-over stock, since it no longer has sufficient reserves to tide it over to harvest time and at the same time to possess a significant surplus. Family C, on the other hand, has this possibility and so, of course, do families B and A. Only in the case in which sufficient reserves are available can carry-over stocks exist.

SOME REFLECTIONS ON ANALYZING DROUGHT IN PEASANT SOCIETIES

Our survey of the influence of drought on self-provisioning and on the surpluses of various groups of agricultural producers has not used the classical and apparently sophisticated tools of microeconomic analysis. Instead, on the basis of fundamental observations, we have tried to highlight a number of elements whose interaction appears to help in explaining the functioning of the food system of an economy still largely dominated by the phenomenon of self-provisioning. This approach may lay the foundations for a more complex study, taking account of the relationships between ownership and production, relationships created by indebtedness, relationships between food and non-food agricultural production, between rural agricultural and non-agricultural income, between rural and urban income, and so forth.

The approach used in the research described in this paper makes a basic distinction between the self-provisioning sphere and the monetary sphere, on the one hand, and on the other relates the analysis to the human time scale of agricultural production, in terms of the calendar of the different seasons and dissimilar years. These two dimensions are closely linked in the economic system which we have taken as a reference point. This system is largely dominated by the self-provisioning of family units of production and consumption, and operates in the framework of individual land ownership, in a world in which land is a scarce factor; it is a system perpetuated at a low level of productivity, making it extremely sensitive to variations in that productivity, whether of climatic, economic, or social origin. While monetarization remains incomplete, any analysis must separate the economy based on payment in kind, whether related to self-provisioning or unpaid family labor, from the monetary economy.

It is, of course, possible to make these two sectors into a single sector by assigning prices to the non-monetarized part of the economy. A merger of this kind makes it possible to use seemingly sophisticated analytical tools, which have been developed in the context of the rural economies of industrialized countries. Self-provisioning plays only a minor role in such economies. For them, seasonality becomes a simple problem of cash-flows and no longer has the same central character as in the poor countries. The level of productivity is high enough for variations not to endanger the farmers' very lives. The risks are therefore not of the same kind.

Moreover, farming in industrialized countries has a certain autonomy, which makes it possible to undertake an analysis in terms of a firm. In contrast, in order to analyze economic behavior in a poor country, it is necessary to consider the family unit and all the monetary flows into it. An analysis of behavior in relation to risk and uncertainty therefore cannot be made solely at the level of farming, but has to take account of probabilities of anticipated income, of whatever origin. Such income probabilities also have to be considered in relation to the calendar of resources and expenditures. The same applies to income in kind. Although some of this income might appear negligible in relation to the annual budget, it is, nevertheless, strategic in nature; at a particular time of the year such income may make it possible to avoid reaching the breaking point. This applies, for example, to resources obtained by gathering in the forest.*

The fact that each family is both part of an economy based on payment in kind and of a monetary economy is of central importance. Failure to take account of this and to give a time dimension to the analysis means that the essential elements of the system will be left out. This, it should be said, is the case for most of the seemingly scientific studies carried out in rural areas of poor countries. The point of departure for a correct analysis consists, on the one hand, of the establishment of a budget in physical terms and a budget in monetary terms and, on the other, of the establishment of a multiple calendar. Such a calendar makes it possible to register changes in stocks and flows, discrepancies between resources and employment, variations in nutrition levels,** the connection between these nutritional

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*This includes gathering of wild fruit, herbs, small animals, wood, and animal fodder. The prohibition of access to forests at the end of the Middle Ages provoked bitter peasant revolts in Europe. Similar measures in India have been a source of great tension.

**Nutritional data in terms of annual averages have very little meaning. It is essential to record variations, particularly declines, in such variables as the quantity and quality of foodstuffs, body weight, and so on.

variations and work distribution (festivals,* ceremonies, pregnancies**), migrations, indebtedness phenomena, discrepancies between the working periods of draught animals and the availability of fodder resources, and so on. While such analysis must be our objective, to date rural inquiries in poor countries have been carried out in a way which hardly permits a departure from the level of simplicity and, at the same time, of abstraction chosen above. As concerns India, for example, reductions in consumption made by different categories of farmers as a result of a drought are very poorly documented.

A LESS SIMPLIFIED MODEL OF DROUGHT IMPACTS

One of the few reliable and more sophisticated pictures of drought has been given by N.S. Jodha (1975). Jodha analyzed the drought in Rajasthan in 1963-1964 which led to a famine situation. Data concerning reductions in consumption are presented not by socioeconomic categories, but as a percentage of households in three consumption groups (see Table 7). Although no distinction is drawn between self-produced and purchased cereals, the table provides valuable information on the impact of a drought on cereal consumption levels.

The figures for April 1964 are particularly striking: almost 70 percent of households are at the 300-450 grams per day consumption level, while the corresponding figure for the year following the drought is a little over 7 percent. The progression of percentages is also noteworthy and bears witness to the progressive decline in consumption levels.

In an agricultural system still oriented towards self-provisioning, such as that characteristic of the poorest parts of India, cultivation of basic cereals is given priority. Our classification of families from A to F on the basis of amount of cereal production therefore corresponds to a mounting scale of poverty. Generally speaking, the

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*For example, the difference between the solar and lunar calendars means that the timing of the main Moslem festivals, which are occasions for animal sacrifices and substantial expenditures, moves from year to year throughout the farming calendar. When these festivals take place immediately before the harvest, during a period of scarcity, they can only be celebrated at the cost of considerable debt. Similarly, when such festivals occur at certain times of the year, the effect on the demographic structure of the herds sacrificed may be very severe. In thousands of Indian villages, Moslem and non-Moslem communities exist together. However, as far as I know, no study has been made of the different influences of the two festival calendars on the family economy or on the nutritional model.

**Unless births are spaced at random, it is important to place pregnancies and nursing periods on the nutritional calendar.

Table 7. Monthly foodgrain consumption by farmers during the drought year 1963-1964, expressed as the percentage of households in each of three categories of daily per capita consumption.[a,b]

Daily per capita foodgrain consumption	Oct 1963	Nov 1963	Dec 1963	Jan 1964	Feb 1964	March 1964	April 1964
300-450 grams	7.7	21.3	34.6	48.1	57.7	60.5	69.2
	(-)	(-)	(1.9)	(5.7)	(3.8)	(5.7)	(7.6)
451-600 grams	21.2	25.0	38.5	34.6	35.5	32.7	25.0
	(67.3)	(73.0)	(69.2)	(74.9)	(76.8)	(78.7)	(78.7)
601-750 grams	71.0	53.8	26.9	17.3	5.8	5.8	5.8
	(32.7)	(27.0)	(28.9)	(19.4)	(20.4)	(15.4)	(13.9)

[a]The figures in parentheses indicate the corresponding details for the year following the drought year.

[b]The foodgrains consumption data, collected partly with the help of the Primary Health Centre in the village, were originally collected for a bigger sample of 80 households in different landholding groups. However, as some households did not reside in the village for the whole period during the drought year, they are not included in the table. Similarly, landless laborers are excluded as this table describes only the cultivators' adjustment mechanism. The consumption details were collected by recording (in some cases by actual weighing) the actual foodgrains consumed during one day each week. Thus the daily per capita consumption, presented in the table, is an average of four (or five) days in a month.

Source: Jodha (1975).

classification also corresponds to levels of food consumption (of which cereals are the major component), from the highest level (family A_1) to the lowest (family F). We can imagine the families sliding at differential rates down Jodha's scale.

The lower the nutritional level at the outset, the more it is reduced by a drought. Families at the lowest levels cannot go below a minimum threshold compatible with their biological survival; and the lower their level of consumption the more rapidly this threshold will be reached. They are thus obliged to resort to substitute foodstuffs at lower prices than their habitual cereals, or even, as has been observed, to go back to such primitive stages of agriculture as the gathering of fruit, plants, and roots.

In bad years, credit possibilities are limited and interest rates increase. The poorer families fall into debt with A families, who take advantage of the opportunity to use their maintained or increased incomes to buy up means of agricultural production (especially draught animals) and land at low prices. Jodha gives examples of average selling prices of animals, fodder, oxcarts, etc., in the drought year 1963-1964, as well as in the "normal" years preceding and following it. The drought year prices represent one-half, one-third, or one-quarter of the prices in "normal" years. For example, the average price of a pair of oxen was 875 rupees (Rs.) in 1962-1963, 431 Rs. in 1963-1964, and 988 Rs. in 1964-1965. Jodha does not identify the purchasers of the oxen; however, he does identify the purchasers of land (see Table 8). This is rarely the case in the numerous studies on drought and famine in India, which only indicate "distress" sales, an indicator which by itself does not show the tendency toward increasing concentration of land holding which accompanies drought.

Similarly, Singh (1975) points out that in the district of Palamau (Bihar), land mortgages rose by 204 percent during the famine year 1967 in relation to those of the reference year 1964, while land sales, in the year following the famine, increased by 33 percent because of the recall of mortgages. He does not, however, designate the purchasers. Ladejinsky (1976) of the World Bank, analyzing the food shortage situation in West Bengal in 1974 (a year marked by both drought and flooding) writes:

> One of the consequences of the rural condition in Bengal in 1974 was the spurt of sales of land by the small and marginal farmers, thereby increasing the size of the landless group. Such sales are mostly "distress" sales. Although land values have been sharply rising in recent years, and more so under the impact of inflation, sales of such land command a very low price; if occasional reports and discussions in the field are to be taken at their face value, a piece of land normally worth Rs.1000

Table 8. Inter-class land transfers in selected village of Rajasthan (1963-1964) by legal procedure.[a,b]

Land holding ownership groups (acres)	Land area lost (acres)				Land area gained (acres)			
	Sub-division gift	Litigation etc.	Outright sale	Sale after mortgage	Sub-divison gift	Litigation etc.	Outright purchase	Purchase after mortgage
1	2	3	4	5	6	7	8	9
No land	-	-	-	-	298.2	17.9	82.3 (10.4)	148.4 (112.1)
Below 10	70.2	132.3	66.0 (3.3)	249.6 (201.2)	-	24.1	11.3	-
10-25	77.1	36.5	78.3 (12.1)	113.2 (87.5)	54.4	41.4	32.7	13.2
Above 25	205.3	47.1	37.1	-	-	132.5	55.1 (5.0)	201.2 (176.6)
Total	352.6	215.9	181.4 (15.4)[c]	362.8 (288.7)[d]	352.6	215.9	181.4 (15.4)[c]	362.8 (288.7)[d]

[a]This table is based on data from records of property transfers and follow-up information from concerned households in three villages (Jodha 1975, Study 5-b). These mainly include (a) households which received land from sub-division of joint family property (actual or on paper) and (b) trader-cum-moneylender households who traditionally did not own land.

[b]The figures in parentheses indicate the land area transferred as a consequence of drought.

[c]This land area constitutes 8% of the total given in column 4 and in column 8.

[d]This land area constitutes 80% of the total given in column 5 and in column 9.

Source: Jodha (1975).

> sells for half the price or less. The badly affected Cooch Behar District (West Bengal) illustrates the situation. June, July, and August, normally dull months for land sales, registered 6000 of them in one sub-division of the district; the total sales for the year will be the largest on record. It also estimated that 80 percent of the sales do not exceed one acre and they fall in the "distress sale" category.

Such distress sales enforced by a drought accentuate social polarization and inequalities and make the position of the poorest families even more marginal; as a result of losing their means of production they have nothing more to offer but their labor.

THE POLITICAL ECONOMY OF DROUGHT

The more complex model described above, which is closer to reality, thus reinforces the conclusions derived from the simplified analysis of a self-provisioning society. The poorest families, caught in the endless cycle of indebtedness, no longer possess even their crop: it is sold in advance, and at the lowest price, i.e., the one in effect at harvest time. They must, in consequence, buy back their means of subsistence on conditions dictated by those who control the economic and social life of the village. They have to sell their labor at prices which they fear to challenge.

The biological need for daily food involves specific requirements which have to be satisfied from uncertain resources. The smaller the amount of resources secured from agriculture, the more severely felt are any fluctuations (resulting from climate, for example) and the more does the social control of reserves become fundamentally at stake. In the case of a fall in the production intended for self-provisioning, and in the absence of any means of exchange for procuring a living, those without reserves are condemmed to emigrate to the towns in the hope of finding casual work there. When all the possibilities have been exhausted, nothing but death awaits them.

Technical, economic, social, and political behavior patterns involve forecasting, and therefore come within the horizons of specific time scales, which are themselves related to the amount of reserves (food, monetary, and social) held against risk: the landless agricultural worker lives from day to day or from season to season. The horizon of the poor peasant is limited to the next harvest. A person who possesses food and monetary reserves, and can rely on the social reserves represented by his share of power, has a horizon of several years, or even, if his reserves are substantial, of a generation.

As Necker wrote in 1775, a little more than a decade before the French Revolution, short-term variations

> ...are a source of anxiety for those who live by their labor. Landlords or their stewards can strike a general balance in their accounts, offsetting the income of one year by that of another; but ordinary people cannot regulate their manner of living in the same way: a man who is haunted by the fear of losing his means of subsistence cannot be expected to think of the present year in terms of the next or of today in terms of tomorrow.

Each peasant family's vision of the future, and the overall vision of the social class to which it belongs, (which in the final analysis determines the family's political behavior) therefore depend on the changing conditions of the present means of livelihood and the memory of a past marked by crises which have imperiled the lives of some and enabled others to strengthen their power. (See Spitz 1978.) In general, a food crisis triggered by drought enables changes to be made in favor of those who wield the economic and social power or, in other words, of those who have the greatest and most diversified reserves. In an agricultural system in which self-provisioning plays a great part, power can be measured in terms of reserves, which are the link between the past and the future. Rural power is thus particularly linked to the capacity to resist the efforts of those not engaged in agricultural production (owners of sharecropped land, cereal merchants, moneylenders *et al.*) to siphon off food surpluses intended to guarantee their own supplies, and/or linked to the capacity to intervene in the surplus extracting mechanisms.

The nature of the surplus (for example, crops), the type (foodstuff or non-foodstuff) the means of extracting it (taxation, credit, market controls, etc.), its destination, the method of its appropriation, and its utilization all greatly depend on the historical periods under consideration. In all historical eras (e.g., pre-colonial, colonial, or post-colonial), drought results in an extension of the tiding-over period, which, even in a "normal" year, is the difficult period during which seasonal hunger occurs—whether for the pastoralist in the absence of adequate exchange entitlements, or for the cultivator in the absence of adequate food reserves. These phenomena are not, however, inherent in nature or the eternal cycle of the seasons. They are always linked to a specific mode of extraction of agricultural surplus by the political power. A drought situation is thus a test of the vulnerability and resilience of the different elements of the economic and social system, and such a drought accelerates the development of vulnerability and resilience like a noise in information theory.

The forces working within society towards increased control of the land by a few and the dispossession of marginal peasants (who are then forced to migrate to cities) find the opportunity to expand themselves fully in a crisis situation such as a drought. The aggravation of inequality prepares the ground for still more acute crises in the future with a growing army of unemployed landless and "factoryless" former peasants. If this feedback effect is considered by the ruling classes to be so serious that it threatens the conditions for perpetuating their domination, a counter-transfer of resources in the form of aid becomes necessary (see also Spitz 1978, pp. 935-936). Or, in some cases, under increased pressure the ruling classes may promise and even adopt reformist measures, in order to avoid the development of counterveiling forces which could break the process of increased polarization through peasant and worker uprisings. Thus, we return to our opening point, that drought cannot be meaningfully considered in isolation from the specific character and state of social systems. In some cases drought can be a key factor in shifting a system from one state to another, while in other cases essentially the original balance will be restored. To try to anticipate which will occur requires much more than arbitrary physical indices of drought.

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CLIMATE AND SOCIETY: THE GREAT PLAIN OF THE DANUBE BASIN

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THE SETTING

One of the regions of the world sometimes mentioned for discussion in a global "climate impact" modeling experiment is Eastern-Central Europe, a relatively new political-geographical unit (Osborne 1967, Enyedi 1978) which encompasses eight countries, with a total area of some 1.3 million square kilometres (Fig. 1).

Contrary to common expectation, this region is very far from being uniform (Enyedi 1967, Sebek 1972, Dobrescu-Blaca 1973, Beck 1975). Apart from the great differences in the natural environmental conditions, there are quite substantial differences among the economic structures of the countries, despite tendencies toward leveling. This means that it is futile to try to draw general conclusions on the possible regional consequences of climatic variability and eventual changes, without closer examination of some more restricted and relatively more homogeneous representative areas within the region.

In the present paper an attempt is made to show that the Great Plain of the Danube Basin could perhaps be one of these representative areas for a closer study. There are at least three good reasons supporting this idea:

(1) The area is a rather exceptional sub-region within Eastern-Central Europe, in that a considerable surplus of substantial food crops may be produced there within a relatively short time (Enyedi 1978).

(2) The area belongs entirely to the semiarid and dry subhumid climatic belts (Szepesiné 1966), which are the types of environment notable for their highest sensitivity to changes and variability of precipitation.

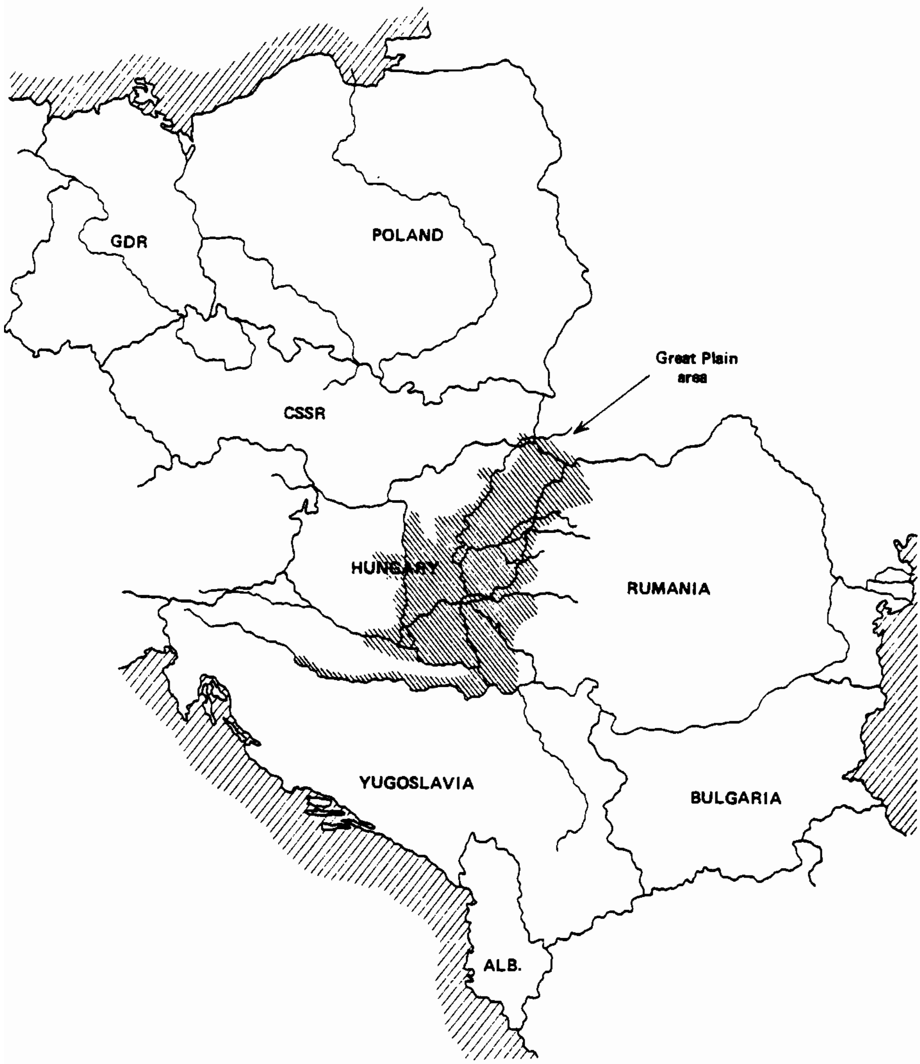

Figure 1 Eastern-Central Europe and the Great Plain of the Danube Basin.

(3) It is an area where during the last 1000 years, and particularly within the last 150 years, extremely marked and well-documented environmental changes have taken place due to human activities (Ihrig 1973).

SOME GENERAL REMARKS ON THE CLIMATE-SOCIETY INTERFACE

Climate impact studies do not yet have a long tradition, but we already do have a set of anticipatory concepts and ideas. We shall review here two problems:

- the separation of short-term and long-term climate variations in the impact studies;
- the meaning of concepts such as adjustment, sensitivity, vulnerability, resilience, etc., of socioeconomic systems.

Impacts of Short-, and Long-term Climatic Variations

There seems to be a tendency towards the view that the impacts of climatic variability (seasonal or inter-annual variations), and the impacts of long-term climate changes, may be investigated more or less independently of each other. This separation may be tempting for two reasons: it reduces the complexity of the problem, and it takes into account the different policy orientations of two main types of user groups (those dealing with short-term decisions and the others interested in long-term planning for society).

A point of caution, however, must be made in the light of the following arguments:

(1) Short-term (inter-annual) variability is usually much larger than the rate of the long-term changes; thus the impact of a slow and gradual climatic change on society and economy usually appears in the shape of difficulties caused by the changing recurrence times of certain extreme values. Any assessment of long-term impacts must therefore be accompanied by a study of the impacts of short-term variability.

(2) A study of the shock-absorbing policies of societies and economies at different levels of development may reveal that, as the economy of a country develops, the nature of the vulnerability of the society to climatic impacts changes. It may happen that some combined effects of short-, and long-term climatic changes become sources of new difficulties.

(3) It would be a depressing perspective if decision makers remained separated in two distinct groups: one group dealing with short-term decisions, and the other group dealing with the long-term ones. The two types of decisions are often conflicting and the short-term problems are usually more pressing. Therefore, some coordination between the two sides seems to be extremely desirable.

	Level of impact	P process	Q quality influencing the extent of the impact	R remedial action by society
0	climatic regime	climatic forcing /hazard, stress, opportunity/	climate variability and/or rate of change	climate modification RO
1	biosphere and economy /agriculture, energy use, etc./	primary response transformation of climatic forcing into changes in economy	sensitivity of biosphere and economy to climate variability and change	reducing sensitivity RI
2	social and political spheres	secondary response transformation of changes in economy into social consequences	vulnerability of society to climate induced changes in biosphere and economy	complex strategy of societal adjustment to climate /including boxes RO and RI/

Figure 2 Stratification of climatic impacts.

These comments are not intended to deny the possibilities and merits of specialized studies on the impacts of short-term variability, or on the slow, pervasive changes of climate. The intention is rather to emphasize the necessity of some additional, combined studies.

Adjustment, Sensitivity, Vulnerability and Resilience

All socioeconomic systems adjust themselves either in a conscious or in an evolutionary way to environmental (climatic, etc.) conditions. The understanding of this process of adjustment is the key to any climate impact study. Economic and societal development generally increases the ability of a nation to control its economy. However, it is probably not the state of development itself, but the kind of adjustment strategy that determines the degree of vulnerability of a socioeconomic system in the face of climate variability and change. Naturally, there may be a close correlation between the development of the economy and the adoption of more advanced adjustment strategies.

There are many possible kinds of adjustment strategies, but all of them may be ranked with one or the other of two basic categories distinguished by the manner of their development. One possible way is evolutionary adjustment, which is a slow process that goes on by trial and error. Another way is scientifically planned adjustment, which is likely to be much faster. It is often thought that planned adjustment is more liable to result in blunders than an evolutionary process. However, the truth may be simply that the mistakes of planned adjustments are more quickly recognized, while the gradual, evolutionary misadjustments (which are desperately common all over the world) may escape recognition, in spite of the fact that they can make some societies extremely vulnerable to climatic impacts.

If we wish to say something more substantive about the various adjustment strategies, we first have to consider the interrelated concepts of sensitivity, vulnerability and resilience of socioeconomic systems. Were this only a question of taxonomy, we could easily dismiss it from our preliminary considerations. However, as the SCOPE workshop on the climate-society interface (SCOPE 1978) has already pointed out, this is really a problem of ordering and stratification of climatic impacts.

The SCOPE workshop has proposed to define five levels of impact: 0, climate; 1, biosphere; 2, human activities; 3, social response; 4, political response. It suggests that the "perception" of the impact by society may occur between level 2 and level 3.

The present work distinguishes only three levels. As seen from Fig. 2, any change in the climatic regime is first regarded as climatic forcing. This may be a climatic hazard (flood, devastating storm, extreme cold, etc.), a climatic stress (lasting drought, cold spell, sequence of high precipitations, etc.), or a climatic opportunity (any climatic event which may present comparative advantages on the market, etc.).

Next, primary responses describe the transformations whereby a climatic forcing is transformed into changes in the biosphere and in the economy (agriculture, energy use, transportation, water management, etc.).

Finally, there is a level of secondary responses, by which we understand transformations of changes in the directly affected economic spheres into consequences in the whole national economy and in the social and political spheres. Such transformations occur if the adverse impact proves to be too large for the directly affected area to overcome its consequences. The disturbance caused by the impact spreads over most of the socioeconomic system. The outcome may range from more or less heavy expenses to be paid for the balancing of the situation up to devastating catastrophes, like famine, increasing heavy unemployment, loss of balance of economy, political instability, etc.

There are factors at all three levels which may influence the extent of the impacts. The first such factor (at level 0) is the spectrum of climatic variations. It ranges from short-term variability to the rate of long-term changes. The latter is characterized by the trend of how the parameters (mean, standard deviation, frequency, etc.) of short-term variations change. In the case of short-term variations one has to distinguish single pulse climatic impacts from multiple pulses, as the successive pulses may follow each other so closely as not to allow enough time for recovery in between.

Two other factors appear at level 1 and level 2, respectively. That appearing at level 1 may be referred to as sensitivity, and that belonging to level 2 as vulnerability. A socioeconomic system will be considered sensitive to climatic impacts to the extent to which the impacts affect the socioeconomically effective biosphere and/or some fundamental economic activities. Influences on the yield of crops or on energy consumption could be examples for such cases. Thus, sensitivity depends on two factors: on the nature and strength of the climatic forcing, and on the tolerance of the affected field. On the other hand, a socioeconomic system will be considered vulnerable to the extent to which it is open and defenseless against harm, losses, and catastrophes arising from the interplay of three components: the adverse climatic event, the rate of sensitivity, and the inability of the socioeconomic system to offset the potential consequences of the former two.

In other words, sensitivity is the measure of direct and automatic responses to climatic impacts, and vulnerability expresses the rate of ultimate defenselessness of the socioeconomic system against these impacts. Sensitivity reflects the natural side of the problem, while vulnerability is a prerogative of the society. Sensitivity always refers to a more or less narrow, specific field, on which the impact is exerted; vulnerability refers to the whole body of the socioeconomic system, and comprises all the primary, secondary, and tertiary damage and deterioration, which actually come into being during the spreading chain reaction launched by the original impact in the sensitive field.

Since climatic circumstances rarely provide optimal conditions for economic activities, it is rather the rule than the exception that harm and loss are attributable to climatic factors. The turning point, however, from where we consider the socioeconomic system vulnerable, is the situation when the stress or burden spreads out into the whole socioeconomic body.

A system that may be qualified as sensitive in the sense described above will not be regarded as vulnerable, if it is able to parry the impacts by controlling the process and by keeping the social consequences within a predetermined and reasonable channel (e.g., if in good crop years reserves are stockpiled, and in bad crop years the reserves cover the losses, so that no one suffers extreme hardship). On the other hand, it will be reckoned as a possibility that some societies, not particularly sensitive to climatic impacts, may eventually prove to be vulnerable.

The relationship between sensitivity and vulnerability, that is, whether low sensitivity is accompanied by high vulnerability, or high sensitivity by low vulnerability (or both are either equally low or high), is remarkably characteristic for a socioeconomic system. We may recognize in this relationship a property which is called resilience. It expresses the rate of ability of the system to take successful specific measures in order to decrease its vulnerability in the face of climatic impacts hitting in sensitive areas. The degree of resilience can thus be determined by a comparison of sensitivity and vulnerability. These notions are, however, modalities and as such can be neither measured nor quantified directly. It is, therefore, their immediate consequence: the total socioeconomic value of the loss occurring through sensitivity on the primary level and evolving through vulnerability on the secondary level. To get a common dimension for the losses on these two levels, we may conceptualize both as a reduction of the performance of the socioeconomic body. To express this reduction there is a wide choice for a common unit of measure and each particular case may suggest its most handy unit by which the best fitting estimates can be made. Once satisfactorily estimated values are associated with sensitivity S and vulnerability V, the effective magnitude of the resilience R can be expressed in the following general form:

$$R = f(S,V) \tag{1}$$

We may call this effective resilience, because a functional relationship between sensitivity and vulnerability is not known. Nevertheless, we may define the nature of this relationship by fixing the following requirements:

(1) In the case of $S = V$, there is no resilience: the system could not cope with the problem, and the potential damage became fully actual.

(2) If $S < V$, the resilience assumed a negative value, and thereby it expressed a tendency towards exacerbation.

(3) If $S > V$, the socioeconomic system proved to be resilient, at least to some extent, as it was able to show an adequate response to an adverse climatic impact.

Perhaps it may be stated that an assessment of the sensitivity is a comparatively simple task, which requires only limited interdisciplinary action. On the other hand, an analysis of vulnerability necessarily implies a complex study of the whole socioeconomic system. This is obviously a much more difficult task, which would require much broader interdisciplinary and multidisciplinary effort, with essential participation of social and behavioral sciences.

Finally, we have to deal with the possible remedial actions. These are indicated in column R of Fig. 2 (note that box R2 contains all possible actions, including those in boxes R0 and R1). This shows that a complex strategy of societal adjustment to climate will include all possible actions by which human societies can protect themselves against the adverse consequences of climate variations and changes, as well as the means of taking advantage of the opportunities presented by climate as a natural resource. Even a preliminary traversing of the options indicates that there is no real strategy to escape from the influences of the climatic factors. There are two basic questions:

(1) Are we prepared to pay in advance, or will we settle the bill later?

(2) Can we find a strategy by which we pay less (or more easily) in advance, as compared to what and how we would be forced to pay in the future?

Beyond these issues, there is a great choice of mechanisms that may serve for absorbing the various climatic impacts falling upon an economy. There are economic routines destined to deal with all kinds of primarily non-climate induced difficulties in national economies. Most of them may be quite effective also in mitigating climatic impacts. Incidentally, this may be the reason why social and behavioral scientists, and particularly economists, rank climate as a minor determinant of socioeconomic activities. In spite of apparent ignorance, most socioeconomic systems have some inherent strategies of adjustment to the climatic regime. Depending on the nature of these strategies, there may be enormous differences in the vulnerability of the societies.

In order to obtain an insight into these processes, it may be useful to review some elemental types of possible socioeconomic responses to a single pulse climatic forcing (for example a single dry summer). Figure 3 presents seven alternative responses.

Strategy 1 is aimed at preventing a climatic impact by modifying the climate. It is unlikely that this solution will spread in the near future, and when its time will come, it will be costly. Nevertheless, this is also a solution one has to reckon with in the long run.

Strategy 2 is directed at lessening the sensitivity of the affected branches of the economy. For example, in cases of plant growing this may be done by irrigation, by selecting hardier plant species, or by increasing mechanization to assure quicker harvests. It is obvious that this strategy does not mean the saving of all climate-induced losses. The real meaning of this strategy is: payment in advance for a relative tranquillity.

Strategy 3 is an adjustment to the climatic regime on a statistical basis. The recurrence times of adverse events are carefully considered, and some risks are taken in such a way that over a longer period the best possible balance should be achieved. It is a strategy whereby the losses of some years are amply compensated by the gains of some other years, and the adverse impacts are spun-out over a longer period.

Strategy 4 means "dissipating" the impact and distributing the load among the various branches of the socioeconomic system. This may be centrally regulated, or may be automatic. For example, in planned economies a loss of exportable wheat may be compensated by a regulated increase of exports or reduction of imports of various other goods. In market economies almost the same effect may be achieved by changing prices.

So far we have looked at examples of real and efficient elemental responses. In contrast further down the list we see the three remaining cases: a natural strategy, a poor strategy, and the case of no strategy.

Strategy 5 means gearing up in times of need, or in other words summoning the reserves of the society to fill the gap caused by the impact. This is a natural strategy, not merely because it reflects a natural response to impacts, but because its application is typical of socioeconomic systems at lower levels of development, where the natural use of resources still prevails. It is not really a

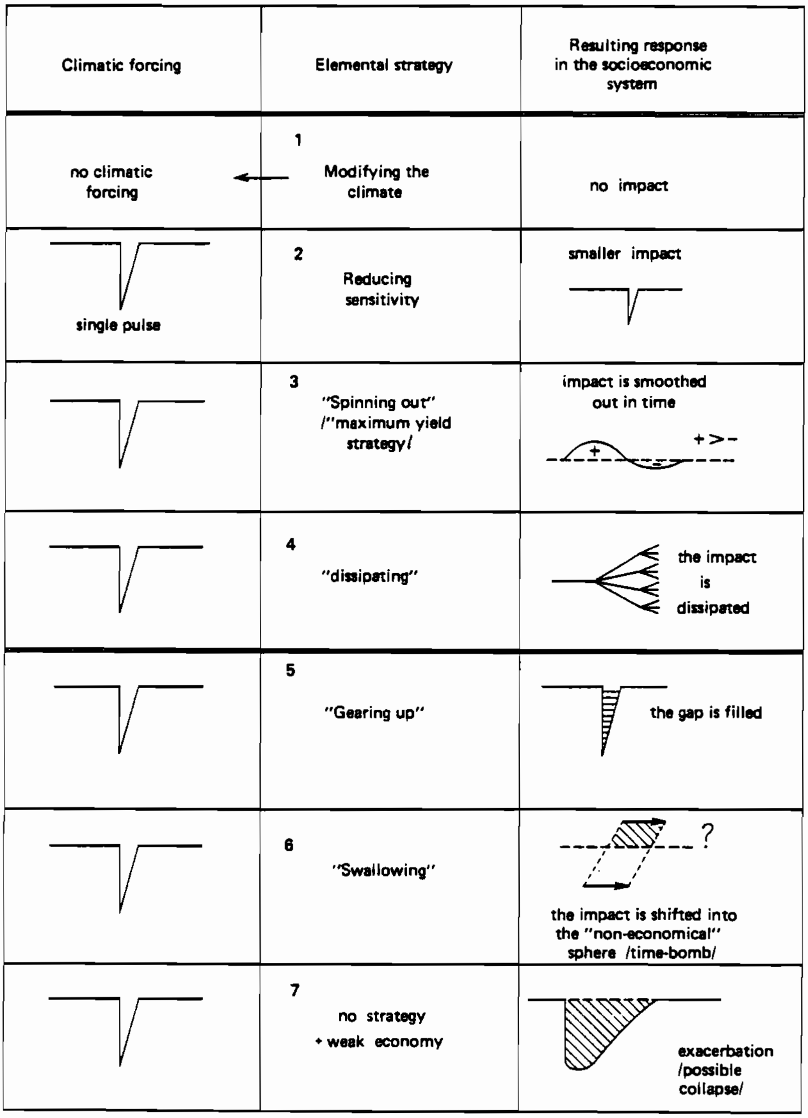

Figure 3 Possible elemental strategies in case of a "single" pulse climatic impact.

strategy, as it is not a planned action, but it still resembles a strategy in the sense that governments count on it. On a higher level of economic development the possibility of applying this course is probably relatively limited.

Strategy 6 is labeled as swallowing, which means that the impact is concealed by shifting it to the non-economic sectors, or to the infrastructure of the socioeconomic system. In this case the impact works as a time-bomb. The slow-downs in the development of infrastructure, education, medical care, etc., or any interim eclipses of environmental issues may become, sooner or later, the sources of more acute problems. Furthermore, the weakness of the infrastructure decreases the resilience of the system to the coming climatic impacts.

Strategy 7 is the case of no strategy. This may occur in countries with very weak and very dependent economies. Such countries may not be able to control the consequences of climatic impacts and, therefore, any impact falling upon them may lead to immediate troubles. There are always some factors, e.g., market speculation, which may easily exacerbate the climate-induced difficulties, and may become the real cause of a disaster — as pointed out by Garcia (1978) in connection with the worst famine in our century, in Bengal in 1943-1944.

In the developed socioeconomic systems, strategies 2, 3, 4 and 5 are probably applied in a mixture. Strategy 2, the reduction of sensitivity, has its role to play in cases of activities that are of vital importance for the society, or concern the protection of life. Strategy 3, the search for the statistical optimum, should be the backbone of the overall adjustment. Case 4, the dissipation of the impacts, is a matter of economic routine. Finally, gearing up should only be a rear-guard of the national economy, as it has its adverse effects (in times of gearing down). The really useful task would be to develop the optimum mix of these strategies.

It should be noted again that this review of elemental responses — as summarized in Fig.3 — refers solely to the case of a single pulse climatic impact. The whole situation and the range of possible societal adjustment strategies would be much more sophisticated in the case of a gradual but pervasive climatic change, or in the case of successive pulses (e.g., successive bad crop years). This may convince us that exploration of the climatic vulnerability of socioeconomic systems should be made stepwise, and it is advisable to start with some smaller-scale pilot studies, in limited and relatively homogeneous representative areas.

ENVIRONMENTAL HISTORY OF THE GREAT PLAIN

The area of the Great Plain of the Danube Basin may be defined as a rather homogeneous territory of some 100,000 square kilometers, spreading over the lands of five countries within the ring of the Carpathians. About half of the area belongs to Hungary, a quarter of it to Yugoslavia, and the rest is shared by Romania, the U.S.S.R. and Czechoslovakia. The altitude above sea level is generally between 80 and 200 meters.

The environmental history of the region is really exciting and no less illuminating. There is an extensive literature on this topic. The Hungarian Meteorological Service has quite recently arranged for the publication of a monograph (Kordos 1979) summarizing the results of Hungarian paleoclimatological researches. This monograph contains more than 300 references and gives a fair description of the paleoclimatic history of the area, with a critical appraisal of the datings, etc. Another important source is the literature on Hungarian water engineering beginning from the 17th century. This gives an account of the water regulations, land reclamations, etc., which have completely changed the face of the land — and its water balance — within the last 150 years. A monograph on this last topic has been published by the Water Authority (Ihrig 1973). Furthermore, there is the well-known book of Réthly (Vol. I 1962, Vol. II 1970) which compiles a wealth of weather- and climate-related records going back to the 11th century, and from 1540 there is some record from each year. It would be an interesting task to prepare a critical summary of all these records and to combine them with information from other sources.

A very brief account of an environmental history of the area may start by noting that in the Lower Pliocene, i.e. 5 to 10 million years ago, almost the whole Carpathian Basin was occupied by an inland sea, and the climate was subtropical in general character. Because of a slow but continuous exchange of water, the original salt content of this Pannonian Sea substantially decreased. Towards the end of the period the sea (or lake) gradually withdrew, but most of the area of the present Great Plain was covered by water till the end of the Upper Pliocene (Ihrig 1973). In the Quaternary the withdrawing waters still occupied much of the area in consideration, and the rivers continuously changed their beds as they spread a thick layer of alluvial deposits all over the basin.

Around the turn of the millennium the entire Great Plain was still a wilderness of virgin gallery forests, steppes on the drier parts, wide meandering rivers, marshes, peat mosses, and trembling bogs in the lower parts. Some historical records indicate that the soil was generally fertile, and a comparatively fast economic development has taken place in the area from the very beginning of the 10th century. On the other hand, the climate-related records from this period (Réthly 1962) suggest frequent droughts and severe winters. This may be an indication of the so-called early medieval warm climatic period (800-1200 AD). The global warming appeared in the higher latitudes (as it should appear, according to theory), whereby the contrast between the poles and the equator decreased and the meridional transport processes became weaker. This meant a decreased activity of mid-latitude disturbances. In addition, as Lamb (1977) has suggested, the track of these disturbances may have been shifted 3-5 degrees northward, to 60-65 $^{\circ}$N, resulting in high pressure conditions and more frequent blocking situations in Europe. Such a change may naturally go along with a drier and more continental climate in the area under consideration.

On the other hand a period of global cooling, as for example the little ice age between 1550 and 1850 AD, may have appeared in the Great Plain area as a more humid, less continental climatic regime. It is certainly true that in the instrumental records of temperature (which are available for the area from 1781) one cannot find the cold tail of the little ice age (Fig. 4).

Furthermore, it appears in the longer time series analyzed by Rudloff (1967) that in Austria and in the neighboring Central European areas the temperature changes on the longer time scale had been more moderate than in other parts of Europe. This may lead to a conjecture that perhaps it is not in the trend of the average temperature, in which global cooling would first and foremost appear in this area, but in, for example, the inter-annual variability of temperature and the hydroclimatic regime.

An evaluation of the hydroclimatic regime is difficult, as this regime depends strongly on the interference of man. In fact, there were many changes in the natural environment (water systems, vegetation, etc.) in the Great Plain area due to human activities. During the 16th and 17th centuries, an apparently drastic environmental degradation took place. In the middle of the 16th century, the central part of contemporary Hungary was occupied by the Osmanli Turks. The ensuing environmental impacts included the following:

(1) The almost continuous wars reduced the population in certain parts to below 1% of the previous level.

(2) The surprisingly sophisticated system of water management, which had been used from early medieval times for catching floods in mortlakes and fishponds, was turned to defense purposes. Thereby, floods were perpetuated, and the lower parts of the Great Plain gradually became extensive morasses.

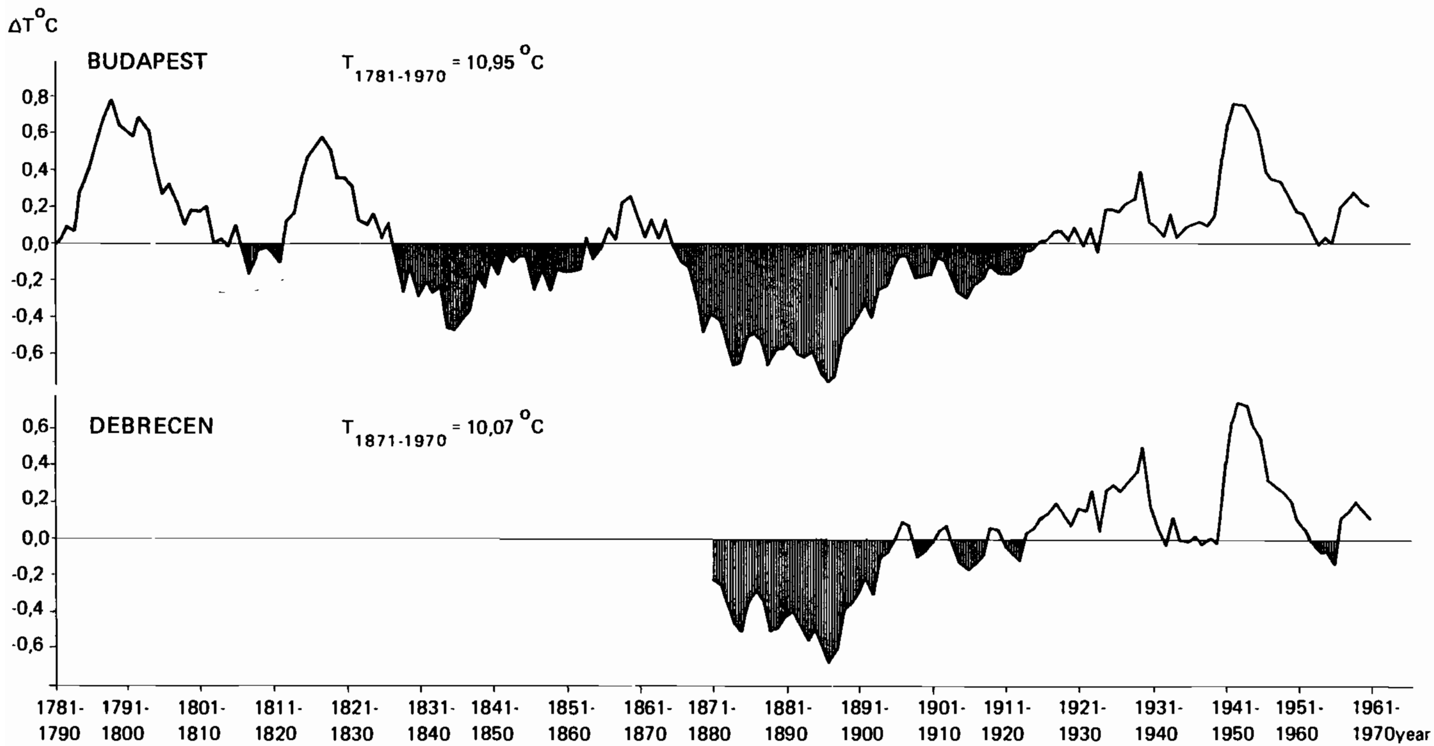

Figure 4 10 years moving averages of annual mean temperatures in the area (after Wagner 1973).

(3) The somewhat higher and drier parts had another fate. As a consequence of an enormous charcoal delivery obligation imposed by the Turkish Empire on the villages, most of the forests disappeared within one and a half centuries. In the deserted land, nomadic herdsmen appeared, and much of what had been left from the natural vegetation cover was destroyed by overgrazing.

This example is intended to demonstrate that some traditional activities may be just as effective in damaging the environment as modern ones.

It is interesting to note that the so-called puszta (meaning something like waste), which is often believed to be the typical environment in Hungary, was not typical at all before the 17th century. The greatest still existing puszta area, the Hortobágy, was covered by birch and oak forests in the late Middle Ages. The disappearance of the forests decreased the water retaining capacity of the drier areas and thereby the overall water balance became more negative. This resulted in a strange situation. While by the end of the 18th century about half of the area of the Great Plain was covered by shallow waters and marshes (Fig. 5) (Ihrig 1973), and the floods of the rivers (particularly of the River Tisza) caused regular disasters, the rest of the land suffered from droughts. As a contemporary saying put it, "This land needs two Gods, one for rain, and one for taking the water away."

Such had been the situation at the end of the 18th century, when the large scale regulation of the waters started. The results of the ensuing regulations and land reclamations were striking. The meanders of the rivers were cut, waterways opened, floods put under control. Vast areas have been recovered from marshes and mortlakes and turned into arable land or meadow. This — in principle — has opened the way to agricultural development, which was however, rather slow at the beginning. The soil conditions were miserable in many parts as a consequence of leaching caused by the unregulated water conditions. There were extensive alkali flats in some areas. The overall water balance of the area remained negative, or rather became more negative than it had been before the regulation, as the water-holding capacity of the soil — which had been earlier deprived of its natural ground cover — was further reduced. With this the incidence and severity of droughts increased.

Partly to remedy this problem, and partly for the development of the forest economy, a large-scale reforestation program was launched some 30 years ago, based on the assumption that where forests had been able to survive in the past, a new forest might be able to throw roots again. This assumption seems to be justified by experience. In these days we are witnesses of new environmental changes in the area, but this time the changes are made for the better.

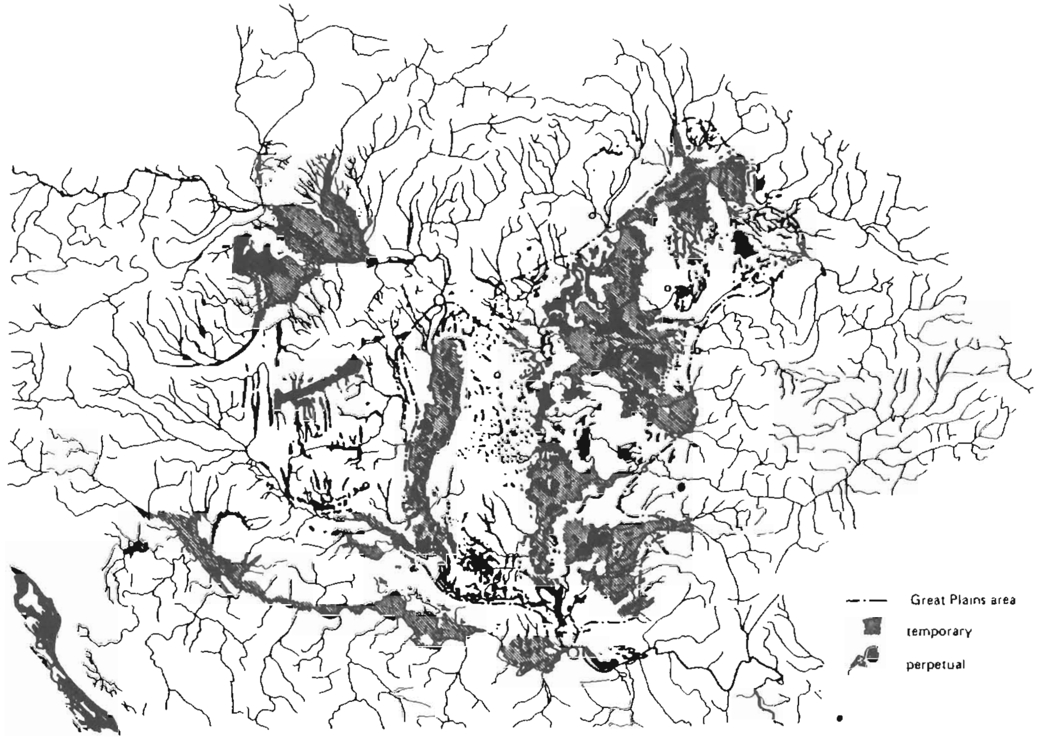

Figure 5 Perpetual and temporary waters and marshes over the Great Plain area by the end of the 18th century (Ihrig 1973).

CLIMATE AND ECONOMY IN THE GREAT PLAIN AREA, WITH SPECIAL REGARD TO AGRICULTURE

With respect to climatic impacts, agriculture occupies a special place in the economic systems in the Great Plain area. The leading branch of the economy is clearly industry, as its GNP (Gross National Product) contribution is more than twice as large as that of agriculture. However, if one takes into account the sensitivity to climatic forcing, agriculture advances to the first place (Czelnai, Dési and Szepesi 1970). This may be shown by a simple analysis. Table 1 contains three rankings of the most important economic activities. Figures in column *a* express a ranking by contributions to the GNP. Column *b* gives the climate sensitivity rank. Finally, column *c* is a combination of the two previous rankings. Percentage climate sensitivity estimates are multiplied by GNP contribution figures. As a result, contributions of the economic activities to the overall climatic sensitivity of the socioeconomic systems of the area are obtained.

Table 1 Climate sensitivity rank.

Economic activity	*a*	*b*	*c* (%)
Agriculture and forestry	2	1	60
Construction, urban development	5	2	13
Energy use	3	4	13
Transport	6	5	4
Recreation, tourism	7	6	3
Water supply	8	3	3
Commerce	4	7	2
Industry	1	8	2
			100

a = GNP rank; *b* = climate sensitivity rank; *c* = estimated contribution to the overall climate sensitivity (%).

This tabulation suggests that in a first approximation we may limit our attention to agriculture, which alone contributes 60% to the estimated overall climatic sensitivity of the economic systems within the area. It should be noted however, that these relationships may lose their validity in the case of climatic changes entailing substantial restructuring of the economy. In such a case construction and urban development may proceed to the top of the ranking. Alternatively, if energy systems will have to be changed, the field of energy use may become decisive.

As was mentioned in the opening section of the paper, the area of the Great Plain has a very considerable potential for food production. Its climate is particularly favorable for variegated plant cultivation. Because the area is located in a transitional zone of the continental, Atlantic, and Mediterranean climates, it offers a remarkable opportunity for maneuvering agricultural product patterns. (This possibility may be endangered by future climatic change.)

Presently the main-field crops in the area are wheat and maize, but alfalfa, sunflower, sugar beet, spring and winter barley, rye, fodder peas, red clover, rape, rice, soy-beans, tobacco, and potatoes are also grown. Furthermore, fruits, grapes, and a broad range of vegetables are produced in commercial quantities. Based on the production of various fodder crops (alfalfa, maize, etc.), there is highly developed animal husbandry, with outstanding production of pork, beef, broiler chicken and duck, eggs, fish, etc.

The most weather sensitive plant cultures (and the most demanding in respect of climate) are alfalfa, maize, grapes, some fruits (particularly drupes), culinary plants, soy-beans, tobacco, the various tuber- and root crops, and rice, for which the climate of the area is nearly marginal. The climate sensitivity of the various plant cultures is — at least approximately — a quantifiable characteristic. It can be approached through so-called agroclimatic potential (*ACP*), which is a complex value depending mainly on three climatic factors: water balance, temperature, and solar radiation.

$$ACP = f(WPP,\ TPP,\ SPP) \tag{2}$$

where WPP = water balance part-potential, TPP = temperature part-potential, SPP = solar radiation part-potential. The most important of these part-potentials is always that one which is furthest away from the optimum. In the case of the Great Plain area this is clearly the water balance. The situation has been thoroughly analyzed by Szepesiné (1966), on the basis of the Thornthwaite method. The results of the analysis are shown in Fig. 6.

As we see, approximately 30% of the area in the central part of the Great Plain belongs to the semiarid belt, and most of the remaining part to the dry subhumid belt. The delineation of the climatic belts is based upon the so-called moisture index I_m, which is defined as a combination of two indices:

$$\text{moisture surplus index } I_s = \frac{100 \text{ surplus}}{\text{need}} \tag{3}$$

$$\text{moisture deficiency index } I_d = \frac{100 \text{ deficiency}}{\text{need}} \tag{4}$$

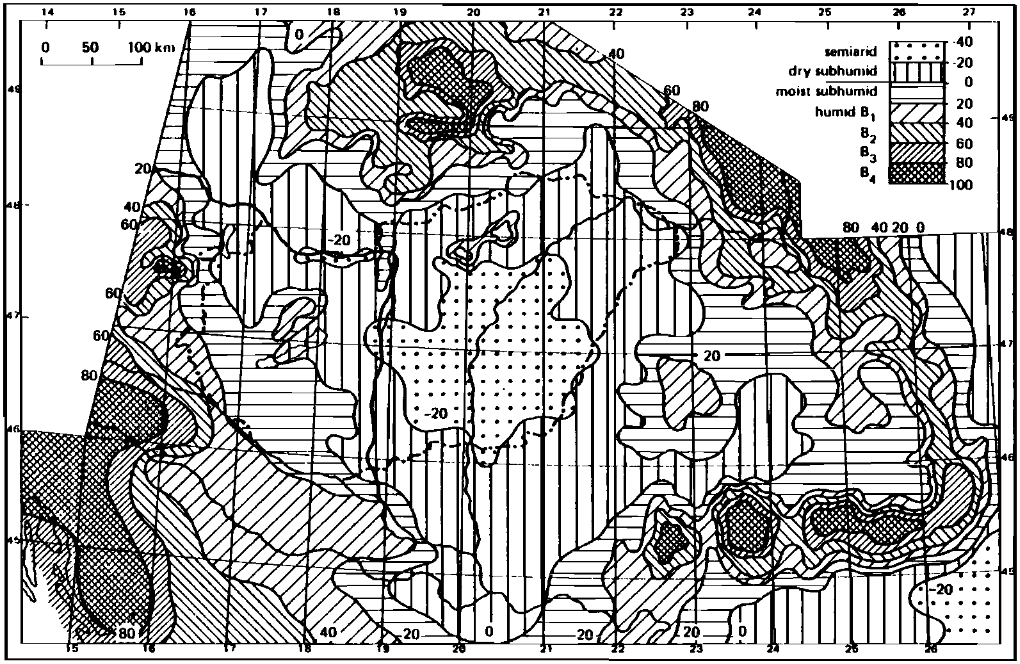

Figure 6 Climatic belts, based on Thornthwaite's moisture index in the Carpathian Basin (after Szepesiné 1966):

$$\text{moisture index} = \frac{\text{surplus} - 0.6\ (\text{deficiency})}{\text{need}}$$

On empirical grounds,

$$I_m = I_s - 0.6I_d \tag{5}$$

The need is defined as the potential evapotranspiration *POT*, while the surplus (as well as the deficiency) is defined as the difference between precipitation *R* and effective evapotranspiration *ET* (Thornthwaite and Mather 1955).

The annual behavior of the characteristics influencing this index is roughly described by Fig. 7 for a semiarid location (Kecskemét). In addition, the data from two stations outside the area are also given for comparison. These are a humid type (Mönichkirchen), and a wet subhumid type (Vienna). Kecskemét is located almost in the geometric center of the Great Plain, where water deficit starts in April and develops through seven months, i.e. throughout the entire growing season.

The relative dryness of the Great Plain area is explained by its location. It occupies the deepest part of the Carpathian Basin, and there is a slight orographically induced subsidence of the air over the whole area, which subtracts a certain fraction from the lifting motions. A very important feature of the climate is a relative concentration of the limited amount of rain in the growing season (Fig. 8). Although the rain is not enough to fill the gap of the water balance, its good timing substantially improves the situation.

In Fig. 8, however, it is also shown, that the variability of precipitation is rather high in the area. We may add that, for example at Kecskemét, 151 mm, and 528 mm are the minimum and maximum precipitation amounts for the whole growing season (April-September), which is a marked difference. This variability means in terms of crop conditions that the recurrence of unfavorable years has a fairly high probability (Antal 1978). Figure 9 presents the probability distributions of water deficiencies for alfalfa and maize in the area of Debrecen. (Water deficiency for a given crop is defined as the difference between the need of that crop and the water available. A positive difference means deficiency.) It may be seen in Fig. 9 that in the case of alfalfa the climatic water deficiency surpasses 200 mm in 50% of the years and — as an average — there are only 10 years in a century when alfalfa receives the required amount of water from natural sources (i.e., without irrigation). For maize the situation is somewhat more favorable, but basically similar (Posza 1978).

We have already mentioned that in the Great Plain area the water balance is the most important climatic factor. Nevertheless, we should not neglect the influence of temperature and sunshine. Figures 10 and 11 give some indication about the climatic variability of these elements.

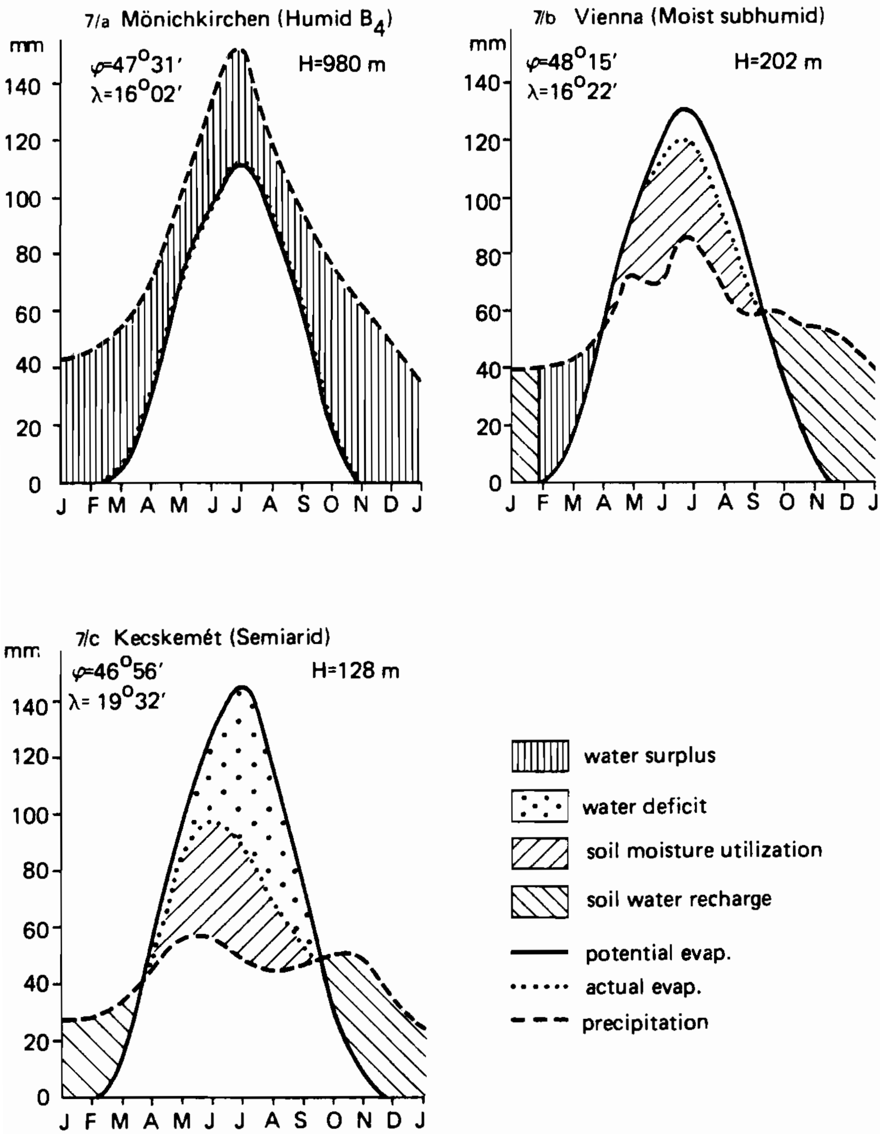

Figure 7 Average path of potential evapotranspiration, actual evapotranspiration and precipitation through the year at three stations of different climatic types (after Szepesiné 1966).

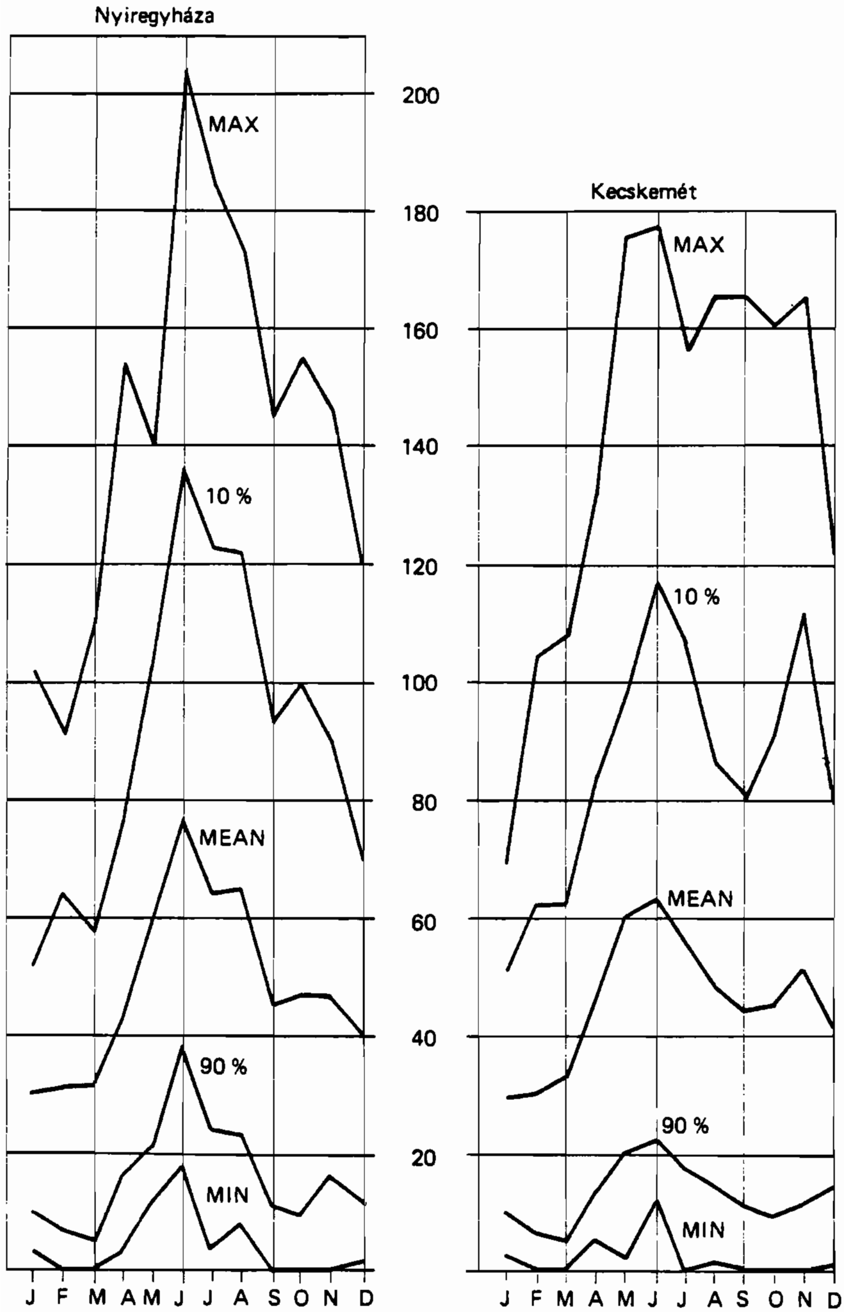

Figure 8 Monthly precipitations, Nyiregyháza and Kecskemét, 1897-1976 (after Koflanovits).

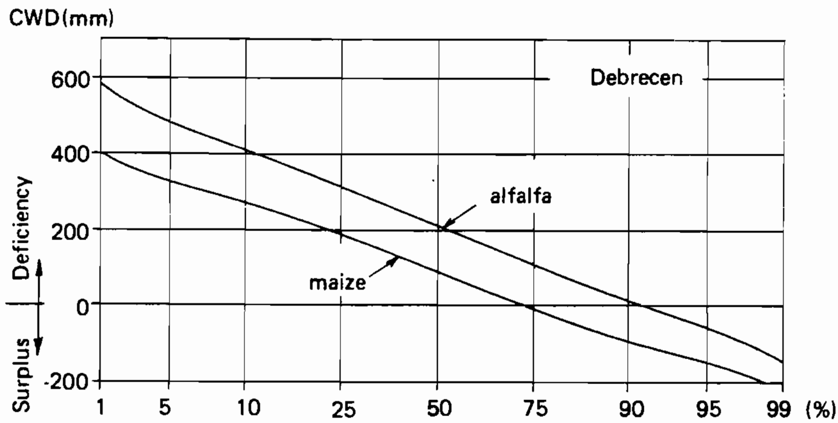

Figure 9 Empirical probability distributions of water deficiences (*CWD*) in the growing season (April-Sept.) for alfalfa and maize, Debrecen, 1901-1970 (after Antal 1978).

Some of the main crops in the Great Plain area are particularly sensitive to temperature variability within the actual range. An example is given (after Posza 1978) in Fig. 12, which contains synchronous paths of the grain yield of maize, the mean temperatures in May, and in the period from May to September, and precipitation sums in June, July and from May to September. The grain yield data are taken from an experimental farm at Szarvas, where the agrotechnical factors, the plant species and the use of chemical fertilizers had been kept on a constant level, so that the changes express the climate sensitivity of a certain species of maize.

It can be seen from these data that the climatic factors define the possibility of a good crop, while the other factors only help to exploit this possibility. Outstanding yields were obtained only in those years when the monthly precipitation sum surpassed 80 mm in June as well as in July, the mean temperature for the growing season was at least at the average level, and the mean temperature in May was high. The case of 1973 shows that the beneficial effect of sufficient rain in June and July can be spoiled if the rest of the growing season is dry.

By using these data, and other results of a similar kind, an analysis was made in order to determine the relative frequency of good crop years, such as 1975. It was found that within the period from 1901 to 1975 there were only 14 years when the precipitation sum in the bimonthly period of June and July surpassed 160 mm. From among these 14 years two years were eliminated because of the low rainfall amounts during the rest of the growing season. Additionally, six other years had to be deleted for low temperatures in May. All in all, only six years were found in a

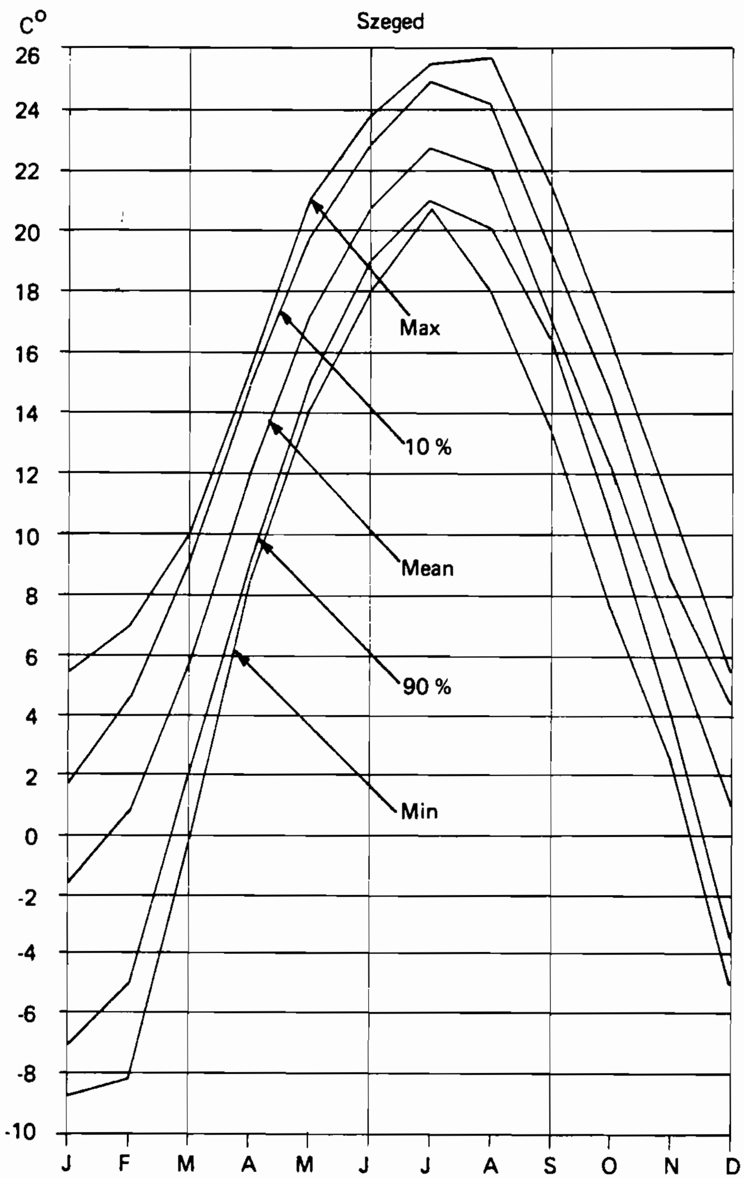

Figure 10 Monthly mean temperature, Szeged, 1931-1970 (after Wagner).

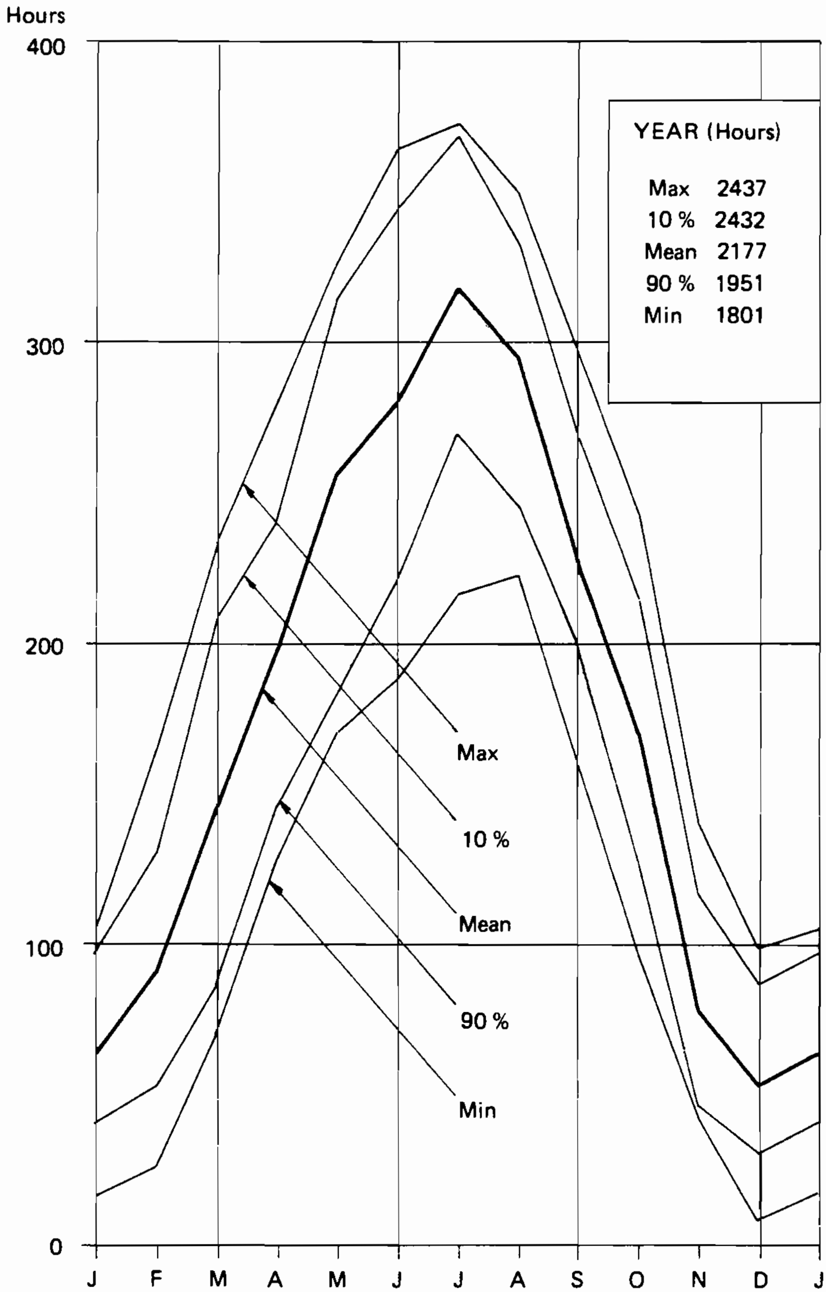

Figure 11 Monthly amounts of sunshine hours, Szeged, 1931–1970 (after Zemplényi).

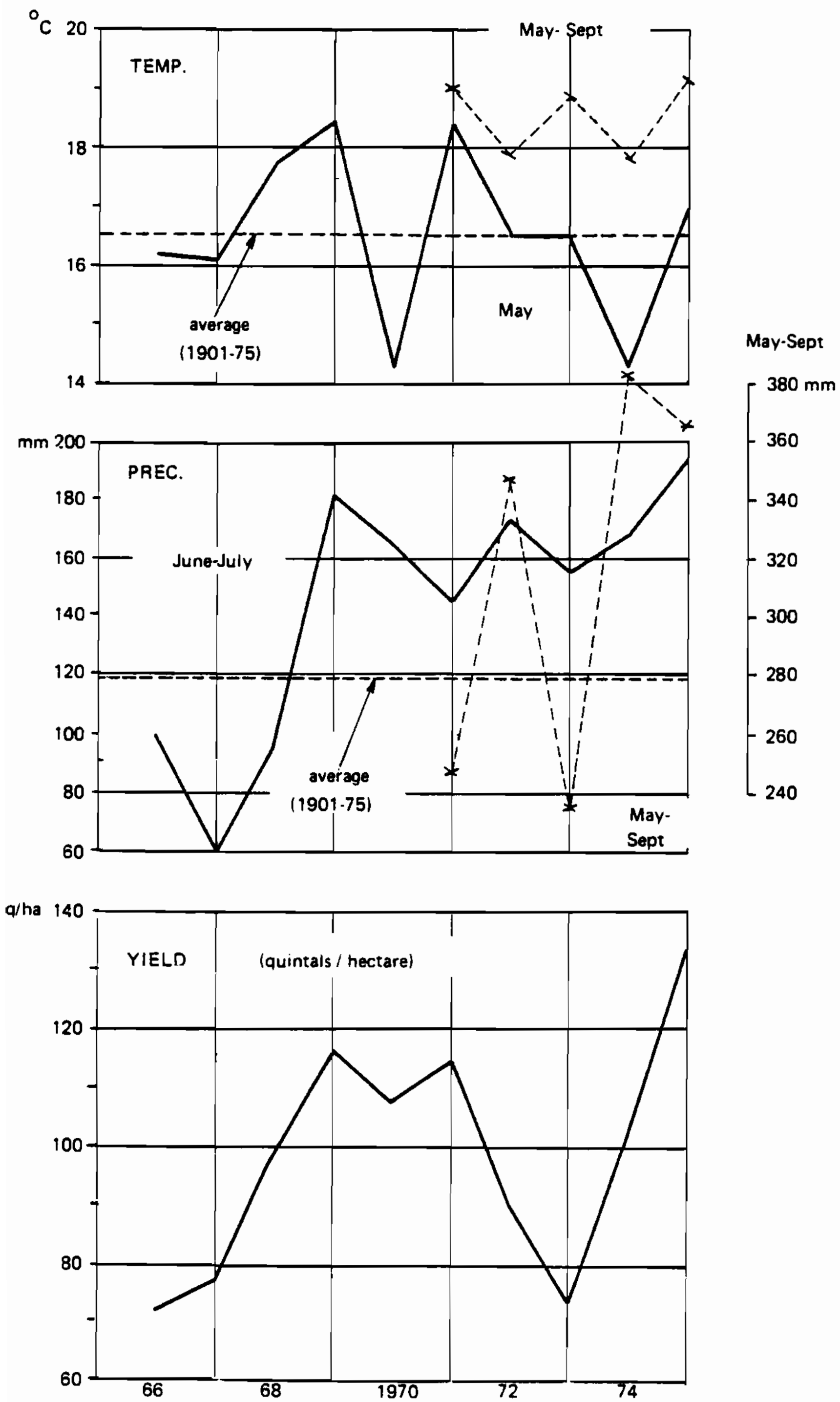

Figure 12 Grain yields of maize, mean temperature, and precipitation sums, Szarvas (after Posza 1978).

period of 75 years, when all climatic factors could be regarded as really favorable. This represents only 8% of the cases!

On the other hand, it should be stressed that under the present climatic regime temperature conditions which hamper the realization of good grain crop yields of maize occur in only 25% of the years.

From this, two possible conclusions can be drawn:

(1) The application of an intensive maize production technology with costly machines and high rates of chemical fertilizers must include irrigation.

(2) The high costs of such systems may necessitate protective prices, without which the whole strategy of production may have to be changed, i.e., it may have to be directed towards the highest cost efficiency instead of maximum yields.

The same conclusion has a bearing upon almost the entire plant growing sector in the Great Plain area. Thus, one may count on irrigation as a means of increasing the agroclimatic potential, or alternatively one may seek various water sparing, environment protective, and cost-efficient technologies. According to Antal (1978) the overall natural agroecological potential of the area reaches only 44-54% of the theoretical potential that would be realizable with irrigation. Thus, the presently realized potentials could be roughly doubled by irrigation, at least theoretically.

However, there are substantial possibilities for improving the utilization of the available water. One possibility is to increase the water-holding capacity (i.e., the so-called field capacity) of the soils. Another possibility may be the selection of new plant species, which require less water. Last, but not least, the whole agricultural water management may be attuned to keeping as much rainwater on the territory as is possible without detriment to the soil. This last solution would mean reducing the evapotranspiration by various means (covering, etc.), and/or minimizing the runoff (increasing the water-retaining capacity of the fields, building flat-land water reservoirs, etc.).

These premised considerations give some grounds for speculation about the possible consequences of future climatic change and variability. In this we will limit our attention to changes in temperature and rainfall. Both may change in both directions, or both may remain unchanged. For the sake of simplicity we assume that temperature (or rainfall) separately has three options: increase (+), no change (x), or decrease (-); and the two together have nine options. From among the nine types of possibilities the most desirable (and fortunately the most probable) one is the case of no change (xx). The two extreme cases, when both elements change in the same direction (case ++, or case --), have rather low probabilities, as the underlying climatological-physical processes are not favorable for such combinations. It should be added that while case ++ could be (within certain limits) beneficial to the socio-economic systems concerned, case -- is clearly not only undesirable but the worst of all possibilities.

In a preliminary study like the present one, it will suffice to consider the possible consequences of the variations in temperature, and precipitation separately. Let us take the hydroclimatic regime first. It may be assumed that a moderate increase in precipitation would be beneficial. Nevertheless, if recurrences of heavy rainfall peaks increase, it may render the existing urban sewage systems, as well as the flood control systems, obsolete. The financial implications of such a situation would be very large.

Less precipitation would create even more serious problems. Presently the river Danube is the only river of any substantial size which still carries consumable excess waters in this area. To direct its waters to rather distant places for irrigational purposes — especially since irrigation is extremely water consuming — would be enormously expensive. This would, on the one hand, substantially increase the production costs and thereby the prices of products, and on the other hand induce a strong tendency to change the whole present product pattern for crops demanding the least water. This would first of all diminish the share of fodder crops (maize and alfalfa), which would, in turn, affect animal husbandry, one of the most important sectors of agriculture in the area at present.

A substantially drier climatic period would bring about serious environmental problems as well. A striking example in this field could be the problem of sewage water disposal. Presently, the bulk of sewage waters — whether cleaned or not — is disposed in water courses, and these water courses are already on the edge of being overloaded in most cases. A dry period, with its immediate consequence of lessening discharges in the rivers would instantly turn over the already shaking balance of the sewage water — fresh water ratio. To go a step further, a lasting dry era would certainly lead to a successive sinking of the groundwater table. Most communities meet their freshwater demand from groundwater. The drying-off of tens of thousands of wells, the need to deepen them, and the costs of producing water from deeper layers would not be a negligible task for the socioeconomic system.

A possible change in the temperature regime is yet another problem. High temperatures, if they are combined with a drier climate, would increase the deficiency of the water balance and this, beyond certain levels, would raise difficulties similar to those mentioned above. But the greatest problem could be caused by lower temperatures. The present agricultural product pattern of the area is adjusted to the temperature conditions in such a way that a broad range of field crops and other plants is grown, for which the northern borderline is very close to the area. Such crops include grapes, rice, maize, tobacco and soy-beans.

In the case of global cooling, the climate scenario of the Great Plain area would probably show an increased variability of temperature, without — maybe — a change in the average. However, the recurrences of unfavorable years would become more frequent, and this could be a serious blow, e.g., on maize production.

CONCLUSION

In light of the previous discussion, it seems justified to conclude that climate has such an overall effect on the whole body of socioeconomic activities in the area that even a slight but lasting change in climate determinants would entail large scale, and in some aspects unpredictable, consequences. But economic measures, such as introducing protective food prices, may be effective remedies, within certain limits.

This brings us to the question of the vulnerability of the socioeconomic systems having a share in the area. This question would clearly require extensive study. Nevertheless, it can be stated with some assurance that the present climate sensitivity of the area is still rather far from a critical level, beyond which one could seriously speak about vulnerability. But it may be emphasized that a substantial increase of the productivity of the agriculture of the area would bring it closer to the limiting agroecological potentials. This could then result in a greatly increased sensitivity to climatic variability and change, and thereby the danger of a sizeable vulnerability would also appear.

At present, under the auspices of the Hungarian Academy of Sciences, an extensive study is in progress, aimed at the estimation of the agroecological potential of Hungary (and of the central part of the Great Plain area). In this work, five supreme authorities, and more than 15 research institutes, universities, and computer centers are taking part, marshalling the contributions of some 500 scientists (Harnos and Györffy 1979). In spite of the size of this project, it is still considered as a preliminary effort. The present aim is only to determine the maximum yields that natural environment (precipitation, temperature, solar radiation, soil, topography, water supply, etc.) and genetic potentials would allow by the end of the millennium, with the assumption that there will be no fundamental changes in the environmental conditions. With all its limitations, however, this extensive project will lay down a very sound basis for later climate impact studies as well. This may be an additional argument supporting the idea of a closer study of the climate-society interface in the Great Plain of the Danube Basin.

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A METHOD FOR ESTIMATING CLIMATIC FIELDS BASED ON THE SIMILARITY OF SEASONAL AND LONGER CLIMATIC VARIATIONS

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INTRODUCTION TO THE SIMILARITY METHOD

The growing effects of human activities on the environment engender a real possibility of climatic change. As a result, estimates of climatic changes which might occur within the upcoming decades or century have begun to appear in the meteorological literature. Most of the estimates are related to temperature fields, and considerably fewer deal with pressure and wind fields. Despite the exceptional importance of the hydrological cycle for agriculture, the state of water resources, and hydroelectric power production, prognostic estimates of variations in moisture circulation or precipitation intensities are still rare and unreliable. This is due to the fact that the simplified climatic models used for making estimates generally do not contain a description of the hydrological cycle adequate for this purpose. In truth, simulation of moisture transfer remains an unresolved problem in more complex models, too. Even in the more complete and detailed global circulation models, cloudiness and precipitation fields are calculated in a highly simplified way and, at best, correspond only qualitatively to reality.

The present work suggests a method for estimating climatic fields. The method is based on the similarity between seasonal changes and longer climatic changes of physical fields in the atmosphere. I have outlined a theory of the similarity of the states of global atmospheric circulation in the course of seasonal and longer climatic changes in previous papers (Sergin 1974, 1976, 1978). This theory does not offer ways of forecasting climatic changes under the effect of different factors. However, if one were to assume that certain factors had caused a climatic change, the theory of similarity would provide a method for estimating the average annual fields of the meteorological elements of the new climatic state.

Cooling of the climate in each of the hemispheres is known to result in expansion of the polar zones, and in contraction and shifting of the temperate, subtropical, and tropical zones towards the equator; concomitantly, this cooling produces an increasing difference between the temperatures at the equator and the poles and a decline in the average hemispheric temperature. Seasonal cooling during the transition from summer to winter represents a similar process. With warming, whether seasonal or climatic, the changes are reversed. The temperature difference between the equator and the pole decreases, and the average hemispheric temperature increases. The possible similarity of changes in the heat fields between such seasonal variations and longer-term climatic changes is thus apparent. Since the circulation of the atmosphere, averaged over a decade or more, may be considered quasi-stationary, similarity in the changes of heat fields would mean that the states of general atmospheric circulation would be similar in the course of climatic and seasonal changes. Seasonal variations in the general atmospheric circulation are assumed to be averaged over a period of about 10 years or more. Climatic variations in the general atmospheric circulation are regarded as changes in average annual fields.

A study of the similarity problem through analysis of a system of hydrodynamic and thermodynamic equations for the atmosphere and ocean (described below) shows that the seasonal variations in the fields of meteorological elements can be taken as a physical model of longer-term climatic variations in average annual fields. (For the convenience of the reader, the mathematical notation used in the analysis is summarized in a table at the conclusion of the paper.) Seasonal variations in general atmospheric circulation are monitored by an entire modern instrumentation network and, in contrast to climatic changes, abundant relevant experimental data have already been accumulated. If an atmosphere with a given seasonal course of boundary conditions is regarded as an experimental unit, then by applying the common rules of the theory of similarity, one can obtain basic quantitative estimates characterizing the average annual fields of various climatic states. The equality of thermal Kibel numbers* was shown (Sergin 1974, 1976, 1978) to be a necessary condition for the similarity of the states of the atmosphere in the course of seasonal and climatic changes.

$$Ki_{\mathrm{T}} = (gH/a^2 l^2)\Gamma/\Theta \tag{1}$$

where Θ is the average atmospheric temperature in the hemisphere, Γ is the temperature difference between the equator and the pole, g is the acceleration of the force of gravity, a is the Earth's radius, H is the height of the troposphere,

*Outside the USSR, the thermal Rossby number Ro_{T} is a more customary term.

and l is the characteristic value of the Coriolis parameter. Furthermore, let us estimate Γ as the difference between the temperatures T in the centers of zones located at 0-20 and 60-90° lat, i.e., $\Gamma = T|_{\phi=10°} - T|_{\phi=70°}$. All the temperatures will be assigned to the underlying surface. Table 1 shows the seasonal variations in Θ, Γ, and Ki_T as calculated by empirical data (Sergin 1978).

Table 1. Seasonal variations in Θ, Γ, and Ki_T in the northern hemisphere for the underlying surface.

Month	Θ K	Γ K	Ki_T
January	280.4	49.0	0.0175
February	280.9	48.8	0.0174
March	283.1	46.0	0.0162
April	286.5	39.4	0.0138
May	289.6	30.8	0.0106
June	292.4	23.8	0.0081
July	293.8	20.3	0.0069
August	293.6	21.2	0.0072
September	291.8	26.1	0.0089
October	288.6	33.6	0.0116
November	284.7	42.6	0.0149
December	281.6	47.0	0.0167
Annual average	287.2	35.7	0.0124

If we are interested in a certain new state of the climate, this new state should be characterized by only one pair of numbers, namely, the average annual values of Θ and Γ; this permits evaluation of the quantity Ki_T. Then for the seasonal variation (Table 1) we should select a time interval lasting a month or more, which would be characterized by the same value of Ki_T as the new climatic state under analysis. The averaged fields of meteorological elements determined empirically for this interval of seasonal variation are then used as estimates of the average annual fields of the new climatic state under study. Thus, the average annual climatic fields are evaluated by sampling from experimental data on the seasonal variation in the fields of meteorological elements of a certain set corresponding to a given time interval (to a given value of Ki_T).

Sample Applications of the Similarity Method

Let us now examine some possible practical applications of the theory of similarity for estimating climatic fields.

The meteorological literature contains calculations indicating the possibility of global warming of the climate under the influence of given amounts of carbon dioxide, man-generated heat, and other factors. Digressing from the question as to whether or not these factors can actually cause considerable warming in the foreseeable future, it would be interesting to clarify to what extent such warming would be dangerous, and what the structure of precipitation, cloudiness, wind, and other fields would be in a warmer climatic epoch.

Suppose we are interested in a warming characterized by elevation of the average annual surface temperature in the northern hemisphere by 2 ^{o}C. Warming on such a scale occurred in the past, i.e., during the Pleistocene climatic optimum. Such a warming is characterized by an elevation of the average temperature by about 1.5-2 ^{o}C and a 4-6 ^{o}C decline in the temperature differential between the equator and the pole (Sergin 1978). Let us then take for examination the climatic state characterized by Θ = 289 K, Γ = 31 K, and Ki_T = 0.0107. (For reference, the following values characterize the recent climate: Θ = 287.2 K, Γ = 35.7 K, and Ki_T = 0.0124.) An evaluation of the average annual fields of this warm climatic state is useful, not only because it characterizes a climate possible in the future, but also because it is a reconstruction of one of the most interesting climates of the past. The latter circumstance also permits possible verification of the results by means of independent data from paleoclimatic reconstructions.

It can readily be calculated that in terms of the seasonal variation the March-November time interval (characterized by Θ = 289.3 K, Γ = 31.5 K, and Ki_T = 0.0109) satisfactorily corresponds to the state of the climate we wish to study. Empirical data on the fields of meteorological elements from March to November, averaged over a period of many years, provide estimates of the average annual fields of the climatic state under consideration. Table 2 shows estimates of some zonally averaged fields calculated on the basis of empirical data presented in the works of other authors (Guterman 1965, Musaelyan 1968, Sokhrina *et al.* 1959, Oort and Rasmusson 1971). An analysis of their estimates shows that in a warm climatic epoch wind velocities are lower than in recent times over all latitudes except at 50-60 ^{o}. Furthermore, in the 30-50 ^{o} zone, the amounts of precipitation and cloudiness are lower. This suggests that many arid regions would become drier in a warmer climatic epoch. However, in the 20-30 ^{o} band, the amount of precipitation increases. In the tropical zone and in northern regions characterized by sufficient or excessive moisture, the amount of precipitation also increases. The average climate in the hemisphere is characterized by greater humidity, cloudiness, and precipitation in the warm period, as compared with the recent climate.

Table 2. Estimates of average annual zonal fields of some meteorological elements in the northern hemisphere for a warm climatic epoch ($\Theta = 289$ K, $\Gamma = 31.5$ K, $Ki_T = 0.0109$).

Zone of latitude	Scalar wind velocity at 850 mbar (m/s)		Specific air moisture at 850 mbar (g/kg)		Cloudiness		Intensity of precipitation (cm/yr)	
	Recent climate	Warm climate	Recent climate	Warm climate	Recent climate	Warm climate	Recent climate	Warm climate
90-80 °N					6.2	6.8		
80-70 °N	7.9	7.7	1.6	1.9	6.9	7.4	24.2	25.0
70-60 °N	8.6	8.4	2.3	2.7	6.8	6.8	46.4	48.1
60-50 °N	11.9	12.0	3.1	3.6	6.3	6.3	72.0	74.8
50-40 °N	9.5	9.0	4.1	4.7	5.5	5.2	81.4	80.9
40-30 °N	8.2	7.7	5.5	6.1	4.8	4.6	81.1	80.6
30-20 °N	7.3	7.1	7.2	7.9	4.8	4.8	81.8	87.0
20-10 °N	7.0	6.9	9.3	9.8	5.1	5.4	119.0	132.3
10- 0 °N	5.8	5.6	10.8	11.0	6.4	6.7	174.6	185.8
Hemispheric average	7.8	7.6			5.6	5.7	96.3	101.6

Figure 1 shows an estimate of geographical areas in which the average annual precipitation fields would differ in the warmer climatic epoch in comparison with recent times [the empirical data are taken from Rand reports (Schutz and Gates 1971, 1972, 1973, 1974)]. The estimate presents only three general gradations (more, less, or no change in precipitation), in view of the relatively low accuracy of the empirical data. One can see from Figure 1 that a warmer climate is characterized by a tendency for the amount of precipitation to decrease in the arid regions of the Mediterranean area, the Near East, and the Middle East. At the same time, in some dry areas, as the southern Sahara, the amount of precipitation increases. The same is observed in most of the regions with sufficient or excessive moisture.

It is also of interest to estimate the change in precipitation fields in the case of a cooling of the climate of roughly the same extent. For this purpose we shall examine the climatic state characterized by the values Θ = 285.2 K, Γ = 40.3 K, and Ki_T = 0.0141. Since temperature fields averaged over the time interval from September to May are characterized by these values of the parameters Θ, Γ, and Ki_T, the fields of meteorological elements averaged from September to May are the estimates of the average annual fields of the cooler climate. Figure 2 shows the estimate of the geographical areas in which the average annual precipitation fields would differ in the cooler climatic epoch in comparison with recent times [the empirical data are again taken from Rand reports (Schutz and Gates 1971, 1972, 1973, 1974)]. One can see that during the cooler climatic epoch the amount of precipitation increases in most of the arid regions. However, in the southern Sahara the amount of precipitation decreases.

These estimates may contain considerable errors because they are based on somewhat outdated empirical data. However, since the estimates are made mostly with a view to illustrating the possibilities for practical application of the theory of similarity, the errors are not of great importance for our purposes.

The similarity method permits estimation of the average annual fields of meteorological elements for various climatic states, each of which is set only by one pair of Θ and Γ values. However, one cannot set both values arbitrarily. Zonally averaged temperature fields in the atmosphere form quite definite and stable latitudinal functions and restrict the ratios of the values of Θ and Γ. The simplest rule would be that any given pair of values should be contained in the table of seasonal variations (e.g., in Table 1) or be obtained by averaging the values in the table for the time interval τ < 1 year.

The principal condition for effectively applying the theory of similarity for estimating climatic fields is the

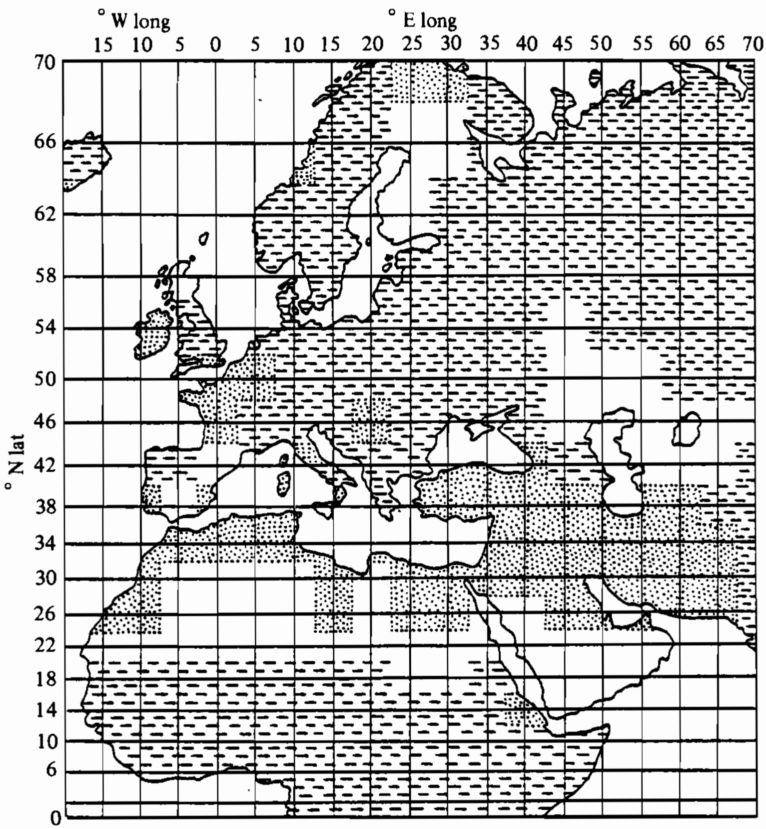

Figure 1. Estimate of the average annual precipitation field for a warm climatic period (Θ = 289.3 K, Γ = 31.5 K, Ki_T = 0.0109), in comparison with recent times. In areas marked with broken lines, the amount of precipitation increases; in areas marked with dots, the amount of precipitation decreases; and in areas which are blank, the amount of precipitation is unchanged.

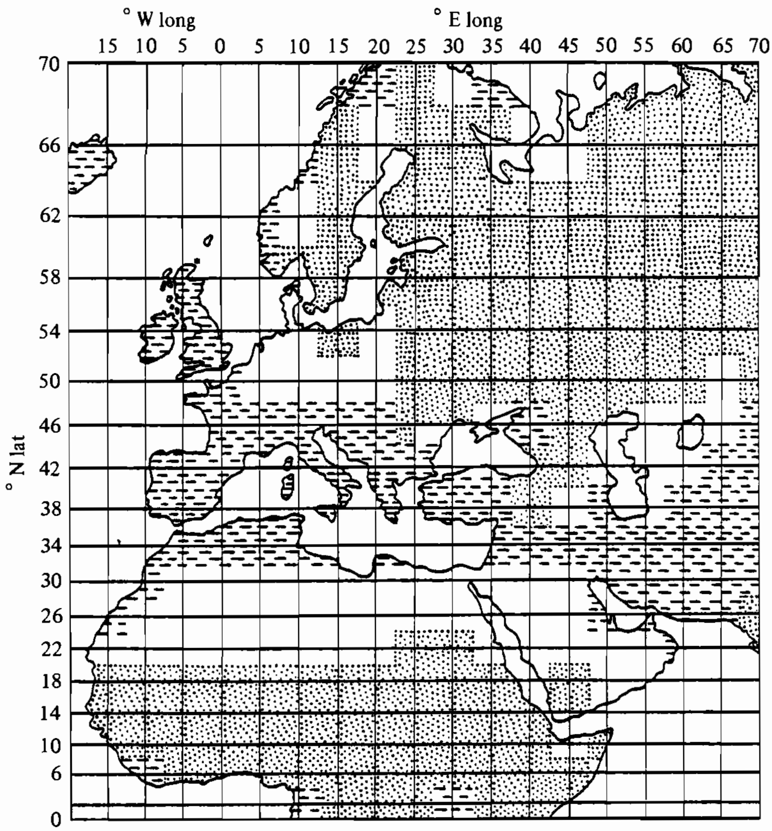

Figure 2. Estimate of the average annual precipitation field for a cold climatic period (Θ = 285.2 K, Γ = 40.3 K, Ki_T = 0.0141), in comparison with recent times. In areas marked with broken lines, the amount of precipitation increases; in areas marked with dots, the amount of precipitation decreases; and in areas which are blank, the amount of precipitation is unchanged.

existence of a pool of meteorological information in data banks set up especially for this purpose. Then one could develop a relatively simple operational system and a set of software programs which would permit automatic estimation of climatic fields and produce results in a form most suitable for users.

THE THEORY OF SIMILARITY OF THE STATES OF GENERAL ATMOSPHERIC CIRCULATION IN THE COURSE OF SEASONAL AND LONGER CLIMATIC VARIATIONS

Let us see to what extent and in terms of which criteria the states of the general atmospheric circulation are similar in the course of seasonal and longer climatic variations. The problem before us is to determine whether or not the seasonal variations in the general atmospheric circulation offer a good physical model of longer-term climatic changes. To address this problem, we must analyze the problem of similarity to a sufficiently detailed degree, i.e., the analysis requires scrutiny of a system of hydrodynamic and thermodynamic equations for the atmosphere and ocean. In order to somewhat simplify the problem, let us start by examining zonally averaged equations for the atmosphere.

Analysis of Zonal Circulation of the Atmosphere

Ignoring small terms, the averaged equations describing zonal dynamics may be presented in the following form (Kochin 1935):

$$\rho \frac{\partial \upsilon_\theta}{\partial t} - \rho l \upsilon_\psi = - \frac{1}{r}\frac{\partial p}{\partial \theta} + \frac{\partial}{\partial r}\, \mu\left(\frac{\partial \upsilon_\theta}{\partial r}\right) \tag{2}$$

$$\rho \frac{\partial \upsilon_\psi}{\partial t} + \rho l \upsilon_\theta = \frac{\partial}{\partial r}\left(\mu \frac{\partial \upsilon_\psi}{\partial r}\right) \tag{3}$$

$$\frac{\partial p}{\partial r} + g\rho = 0 \tag{4}$$

$$\frac{\partial(\rho r^2 \sin\theta)}{\partial t} + \frac{\partial(\rho \omega r^2 \sin\theta)}{\partial r} + \frac{\partial(\rho \upsilon_\theta r \sin\theta)}{\partial\theta} = 0 \tag{5}$$

The equation for heat influx has the following form:

$$c_p\rho \frac{\partial T}{\partial t} + c_p\rho \frac{\upsilon_\theta}{r}\frac{\partial T}{\partial \theta} = \frac{\partial}{\partial r}\, \lambda' \frac{\partial T}{\partial r} + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\, \lambda'' \sin\theta \frac{\partial T}{\partial\theta} + \frac{\partial F}{\partial r} + L\beta \tag{6}$$

$$p = R\rho T \tag{7}$$

where μ is the dynamic coefficient of turbulent viscosity, λ' and λ'' are coefficients of vertical and horizontal turbulent heat conduction, ρ is the density, l is the Coriolis parameter, r is the vertical coordinate, θ is the latitude supplement, υ_θ, υ_ψ, and ω are the meridional, zonal, and vertical velocity components, respectively, p is the pressure, c_p is the specific heat capacity at constant pressure, T is the temperature, F is the total radiation flow in reference to unit surface, β is the condensation rate of water vapor in reference to unit volume, and L is the latent heat of evaporation.

If equations (2)-(7) are to be written in dimensionless form, all the similarity numbers of the system are contained in equations (2) and (6); hence, let us examine only these equations.

$$Sh\rho \frac{\partial \upsilon_\theta}{\partial t} - \frac{1}{Ki} \rho l \upsilon_\psi = - \frac{1}{Eu} \frac{1}{r} \frac{\partial p}{\partial \theta} + \frac{1}{Re}\left(\frac{a}{H}\right)^2 \frac{\partial}{\partial r}\left(\mu \frac{\partial \upsilon_\theta}{\partial r}\right) \qquad (2')$$

where the primes denoting dimensionless variables are omitted. Hence, the similarity numbers are

$$Sh = a/u\tau, \quad Ki = u/al, \quad Eu = \rho u^2/\pi, \quad \text{and } Re = au/\nu$$

where $\nu = \mu/\rho$ is the kinematic coefficient of turbulent viscosity, π is the characteristic pressure difference, τ is the characteristic time, and u the characteristic wind velocity.

Since the seasonal and longer climatic variations occur in the same physical system, the geometric similarity numbers $(a/H)^2$ are equal. For seasonal oscillations averaged over a period of many years, and for climatic oscillations, $Sh < 10^{-2}$, from which follows a quasi-stationary state of the general atmospheric circulation. An analysis of similarity in respect to the other numbers requires certain preliminary evaluations. Let us assume that Ki_T is the estimate of Ki, and that the velocity of thermal wind

$$u_T = (gH/al)\Gamma/\Theta$$

is the estimate of the characteristic wind velocity. In addition, let us consider the largest deviations of the average monthly values as the maximum seasonal changes, and the largest climatic deviations in the course of glacial oscillations which have occurred during the past million years as the maximum climatic changes. Corresponding estimates of the seasonal and climatic parameters are shown in Table 3. It is obvious that in the seasonal variation one can always select a time interval (month, season, or other portion of the year), for which the value of Ki_T is equal to the value characteristic of the climatic epoch that interests us. For instance, the month of January and the period of maximum glaciation of the northern hemisphere are characterized by virtually the

Table 3. Estimates of Θ, Γ, Ki_T, and u_T for seasonal oscillations in recent time and for glacial oscillations in the Pleistocene epoch.

	Seasonal oscillations		Glacial oscillations	
Hemisphere	January	July	Epoch of maximum glaciation	Interglacial epoch
Northern				
Γ K	49	20	53	30
Θ K	280	294	280	289
Ki_T	0.018	0.007	0.019	0.01
u_T(m/s)	18	7	19	10
Southern				
Γ K	34	50	49	39
Θ K	289	283	282	286
Ki_T	0.012	0.018	0.017	0.014
u_T(m/s)	12	18	17	14

SOURCE: Sergin (1978).

same values of Ki_T. Similarly, the time interval from March to November corresponds to the interglacial epoch (climatic optimum) in terms of Ki_T. The estimates shown in Table 3 relate to temperatures at the Earth's surface, although estimates of temperatures for the entire troposphere are in fact essential. However, the temperature of the underlying surface is known to characterize rather well the temperature of the entire troposphere. Figure 3 shows the zonal temperature profiles at various altitudes (Khanevskaya 1967). As is apparent from Figure 3, marked temperature changes with latitude correspond to weak changes in the vertical temperature difference in the troposphere. Hence, the vertical temperature difference in the troposphere, averaged over a long period, is a conservative characteristic. We can therefore conclude that estimates of the underlying surface temperature adequately characterize the entire troposphere.

Atmospheric states similar for Ki_T should also be similar for Eu, because the typical values of velocity u_T and Ki_T vary equally (see Table 3) and $\pi = \rho l a u$ follows from the geostrophic relation. Besides, the atmospheric states similar for Ki_T are also similar for Re. Yet, in the turbulent

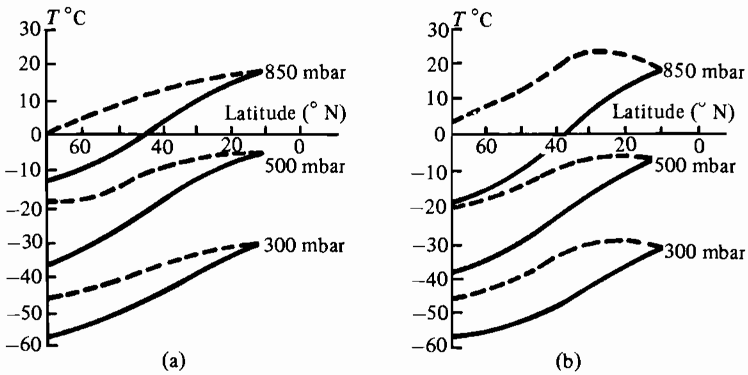

Figure 3. Zonal temperature profiles over (a) oceans and (b) continents in the northern hemisphere for January (continuous lines) and July (dotted lines); after Khanevskaya (1967).

atmosphere *Re* exceeds critical values, and similarity for *Re* probably always exists.

Let us represent the equation for heat transfer in the following dimensionless form:

$$\frac{a}{u\tau}\,\rho\,\frac{\partial T}{\partial t} + \rho\,\frac{\upsilon_\theta}{r}\,\frac{\partial T}{\partial \theta} = \frac{k''}{ua}\left(\frac{\lambda'}{\lambda''}\right)\left(\frac{a}{H}\right)^2 \frac{\partial}{\partial r}\,\lambda'\,\frac{\partial T}{\partial r}$$

$$+ \frac{k''}{ua}\,\frac{1}{r^2 \sin\theta}\,\frac{\partial}{\partial \theta}\,\lambda'' \sin\theta\,\frac{\partial T}{\partial \theta} + \frac{Fa}{c_p \rho T u H}\,\frac{\partial F}{\partial r}$$

$$+ \frac{L\,\beta a}{c_p \rho T u}\,\beta$$

where $k'' = \lambda'/c_p\rho$ is the typical value of the coefficient of horizontal turbulent heat diffusivity. The primes denoting dimensionless variables are omitted here. One can take the amplitude of the temperature oscillations as its characteristic value T. Applying the known ratio $a/u = H/\omega$ and noting that the characteristic value of the vertical turbulent heat flow $c_p\rho\overline{u'T'}$ may be recorded as $P = c_p\rho uT$, we have $Fa/c_p\rho uHT = F/P$. Similarly, $L\beta a/c_p\rho Tu = L\beta Ha/c_p\rho THu = B/P$, where B is the heat influx into the atmosphere from condensation of water vapor by unit surface. Now the heat influx equation may be written in the following form:

$$Sh\rho \frac{\partial T}{\partial t} + \rho \frac{\upsilon_\theta}{r} \frac{\partial T}{\partial \theta} = \frac{1}{Pe}\left(\frac{\lambda'}{\lambda''}\right)\left(\frac{a}{H}\right)^2 \frac{\partial}{\partial r} \lambda' \frac{\partial T}{\partial r}$$

$$+ \frac{1}{Pe} \frac{1}{r^2 \sin\theta} \frac{\partial}{\partial \theta} \lambda'' \sin\theta \frac{\partial T}{\partial \theta} + \frac{F}{P}\frac{\partial F}{\partial r} + \frac{B}{P}\beta \qquad (6')$$

In contemporary studies of general atmospheric circulation, the coefficient of horizontal macroturbulent transfer is usually regarded as constant or dependent on the horizontal gradient of the temperature $k'' \sim \Gamma$. Hence, the seasonal and longer climatic variations are similar for $Pe = ua/k''$ if they are similar for Ki_T. A macroturbulent transfer in the atmosphere is produced by cyclones and anticyclones, in which the vertical and horizontal velocity components are related in accordance with the continuity equation. Consequently, the intensities of the horizontal and vertical macroturbulent transfer are also related. From this follows the constancy of $\xi = \lambda'/\lambda''$ for the general atmospheric circulation. For long-term changes, the rate of steam condensation for the whole atmosphere is determined by the evaporation rate. Vertical turbulent flows of heat and moisture are related by the well-known Bowen ratio. Hence, turbulent heat flows and the condensation rate are also related, and the states of general atmospheric circulation are similar for Ki_T.

Seasonal variations in the general atmospheric circulation are caused by seasonal variations in the radiation influx over the external boundary of the atmosphere. Changes in the radiation influx in the course of climatic variations are unknown. At worst (for fulfilling similarity conditions), the radiation influx should be regarded as constant. The amount of solar radiation absorbed directly by the atmosphere constitutes 20-30% of the total solar radiation absorbed. This can serve as an estimate of the maximum error in fulfilling the similarity conditions for F/P. The effect of this error may be in fact insignificant. Rakipova (1966) calculated the vertical profile of the average annual temperature for an ice-free Arctic and the vertical temperature profile for the warm half-year in recent times (see Table 4). The temperature profiles virtually coincide, despite the fact that in recent times the heat influx during the warm six months is caused by changes in insolation at the upper boundary of the atmosphere, whereas in the epoch of an ice-free Arctic it was caused by albedo changes, heat advection, and other factors.

The vertical profiles of the meridional temperature gradients plotted with empirical data (Guterman 1965) are

Table 4. Vertical profiles of average annual air temperatures for an ice-free Arctic and for the warm six months in recent times, at 70 °N lat, 80 °N lat, and 90 °N lat (°C).

km above Earth's surface	Ice-free Arctic			Warm half-year: Calculated			Warm half-year: Actual		
Z	70°	80°	90°	70°	80°	90°	70°	80°	90°
0	2.0	0.5	- 0.5	2	0	- 2	3	- 2	- 5
1	- 0.5	- 1.5	- 2.0	- 1	- 3	- 4	- 1	- 6	- 7
2	- 4.5	- 6.0	- 7.0	- 4	- 7	- 8	- 5	- 7	-10
4	-12.5	-13.0	-13.5	-14	-16	-17	-15	-17	-18
6	-31.5	-34.0	-34.5	-27	-30	-31	-28	-31	-32

SOURCE: Rakipova (1966).

roughly similar for different levels of solar irradiation (see Figure 4). One's overall impression is that the heat budget at the underlying surface is chiefly important for the heat state of the stationary turbulent atmosphere. The influence of individual heat budget components is not substantial in a first approximation. Equality of temperatures at the underlying surface in the course of seasonal and climatic changes is indicative of equal heat budgets, in which

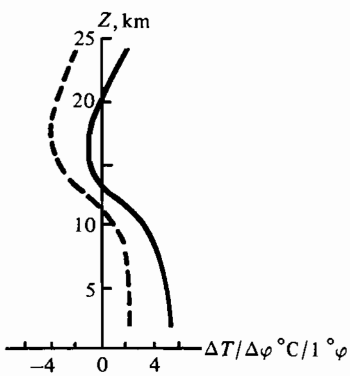

Figure 4. Vertical profiles of meridional temperature gradients for January (continuous line) and July (dotted line), averaged for the northern hemisphere (Guterman 1965).

the component of solar radiation absorbed directly by the atmosphere has already been taken into account. Thus, by virtue of the specific properties of the atmosphere, changes in insolation over its external boundary are taken into account by conditions prevailing over the lower boundary, and these conditions determine the heat state of the atmosphere.

An estimate of the similarity numbers resulting from the system of equations (2)-(7) permits us to regard as established the similarity of zonal atmospheric circulation states in the course of seasonal and climatic variations. The atmospheric states similar for Ki_T are also similar for all the other numbers.

Empirical Data on Similarity of Zonal Circulation

Let us examine some features of seasonal variations in zonal atmospheric circulation, for which one can find comparable empirical data on climatic variations. During seasonal variations in the northern hemisphere, the kinetic energy of atmospheric circulation about doubles from summer to winter, and the zone of the most intensive westerly winds shifts to the south by 10-15 $^{\circ}$. The principal trajectories of cyclones and the moistening zones of humidity shift southward. In summer, when the temperature difference between the equator and the pole decreases, the intensity of atmospheric circulation also decreases, and the trajectories of cyclones and the zone of humidity shift northward (Gruza 1965).

Based on an analysis of paleoclimatic data enabling reconstruction of past climates, Willet (1958) arrived at the conclusion that in glacial times the zone of cyclonic precipitation in temperate latitudes shifted by 15 $^{\circ}$ southward, i.e., to the current subtropical low-pressure zone with its relatively dry and stable weather; this low-pressure zone in turn shifted towards the equator during the glacial period. In general, glacial periods in both hemispheres are characterized by intensification of the principal wind zonal systems at increasing wind velocities, by greater amounts of precipitation over all the principal convergence zones, and by zonal shifts towards the equator. Interglacial periods are characterized by shifting of western zonal flows and cyclone paths from middle latitudes to high latitudes, with considerable warming of the latter as well as an increase in precipitation. At the same time, the subtropical high-pressure region spreads to temperate latitudes, creating stable, mild, and windless conditions over a rather extensive region with insufficient moisture. With such shifting of the zonal system of general circulation towards the poles, the intensity of total circulation becomes weaker, and the zonal patterns of the climate become less distinct.

Flohn (1969) found that during glacial times the principal frontal zone, the paths of cyclones, and the zone of subtropical high pressure shift southward, while during interglacials they shift northward. Lamb (1974), whose work contains a detailed analysis of atmospheric circulation states during the last glaciation cycle, arrives at similar conclusions.

Using climatic data for the last millennium, Lamb (1964) established that the principal pathways of cyclones shift southward with cooling and northward with warming. In another work (1966) based on an analysis of average five-day maps of sea-level pressure plotted for the period from 1890 to 1938 for a large part of the northern hemisphere, as well as an analysis of many maps of the average monthly (January and July) values of pressure at sea level beginning from 1750, Lamb concludes that both seasonal and longer climatic variations normally follow shifts in the middle boundaries of the snow and ice cover in latitudes where western flows are dominant. Both in seasonal and longer climatic variations, more intense atmospheric circulation and shifting of the zone of highest wind intensity southward are noted as temperature gradients become higher. Changes in the opposite direction take place with warming. Analyzing data on climatic variations with characteristic time scales of one-hundred and one-thousand years, Willet (1958) obtained a similar picture of changes in general atmospheric circulation. As a result, he arrived at the conclusion that all climatic fluctuations, both long- and short-term, are characterized by the same geographic variation pattern, differing solely in period and amplitude. Thus, empirical data confirm that zonal atmospheric circulation states in the course of seasonal and longer climatic variations are similar.

The Problem of Similarity for Non-Zonal Atmospheric Circulation

Smoothed seasonal variation in general atmospheric circulation constitutes, in our view, a physical model of the climatic variation of average annual fields of meteorological elements. It is common knowledge that two physical systems are similar if they are (1) described by the same system of equations, (2) geometrically similar, and if (3) the common physical parameters in the equations are similar, (4) the processes are stationary or initial conditions are similar, (5) the determining similarity numbers are equal, and (6) the boundary conditions are similar. In addition, deviations of model variables must be equal to or greater than deviations of variables of an empirically studied physical system. Table 3 shows that the seasonal oscillations of the temperature fields in recent times answer this requirement.

The first of the above-mentioned similarity conditions is fulfilled, since we examine variations solely in terms of smoothed values of variables, i.e., seasonal variations in the fields of meteorological elements averaged over approximately one or several decades and climatic variations in average annual fields. The second and third conditions are fulfilled by virtue of the physical identity of the systems. In the case of both phenomena, the processes are approximately stationary. As was established above for the case of zonal circulation, the similarity numbers are roughly equal. It is easy to see that in the more general case of non-zonal circulation no new questions arise regarding the equality of similarity numbers.

It was shown above that variations in insolation over the external boundary of the atmosphere are roughly given by conditions at the lower boundary, which actually determine the thermal state of the atmosphere. Precisely for that reason, the equalities of Kibel's thermal numbers proved sufficient for determining the similarity of zonal atmospheric circulation states. Hence, in the more general case of non-zonal circulation, the determining similarity condition is also the similarity of thermal fields over the lower boundary of the atmosphere.

It is well-known that the differences in the thermal properties of continents and oceans engender heterogeneities among the thermal fields along the parallels of latitude. Due to the low coefficient of land heat conduction, the temperature of the land surface becomes established during several hours or days. As a result, the land surface reacts approximately equally to variations in heat influxes over various time periods. The coefficient of the turbulent heat conduction of the ocean is a few orders of magnitude greater; hence one can expect substantially varying changes in the temperature of its surface with variations in heat influx over different characteristic time scales. This may be the reason for violations in the similarity of changes in the non-zonal component of thermal fields in the course of seasonal and longer climatic variations.

Let us examine in more detail the reaction of the ocean to seasonal and long-term variations in external conditions. Since horizontal transfer by currents of heat and salts exceeds turbulent transfer by one to two orders of magnitude (Kozlov 1969 and Sarkisyan 1966), we ignore the latter. The geostrophic ratio for large-scale motions in the ocean exceeds that for large-scale motions in the atmosphere by two to three orders of magnitude (Sarkisyan 1966); therefore, let us restrict ourselves to the approximation for the ocean. The hydrodynamic and thermodynamic equations for the ocean can be expressed in dimensionless form as follows:

$$l\upsilon_{\psi} = -\frac{Ki}{Eu}\frac{\partial p}{\partial \theta}, \qquad l\upsilon_{\theta} = \frac{Ki}{Eu}\frac{\partial p}{\partial \psi} \tag{8}$$

$$\frac{\partial p}{\partial r} = -\frac{Eu}{Fr}\rho \tag{9}$$

$$\frac{1}{\sin\theta}\left[\frac{\partial \upsilon_{\psi}}{\partial \psi} + \frac{\partial}{\partial \theta}(\upsilon_{\theta}\sin\theta)\right] + \left(\frac{a}{u}\frac{\omega}{H}\right)\frac{\partial \omega}{\partial r} = 0 \tag{10}$$

$$\frac{\partial T}{\partial t} + \frac{1}{Sh}\left(\frac{\upsilon_\psi}{\sin\theta}\frac{\partial T}{\partial \psi} + \upsilon_\theta \frac{\partial T}{\partial \theta} + \omega \frac{\partial T}{\partial r}\right) = Fo \frac{\partial^2 T}{\partial r^2} \tag{11}$$

$$\frac{\partial S}{\partial t} + \frac{1}{Sh}\left(\frac{\upsilon_\psi}{\sin\theta}\frac{\partial S}{\partial \psi} + \upsilon_\theta \frac{\partial S}{\partial \theta} + \omega \frac{\partial S}{\partial r}\right) = Fo \frac{\partial^2 S}{\partial r^2} \tag{12}$$

$$\rho = \rho(T,S) \tag{13}$$

The primes denoting dimensionless variables are omitted here. It follows from equation (8) that $Ki/Eu = 1$, whence $\pi = \rho lau$. This equality is fulfilled well in the process of seasonal changes of current fields and apparently cannot be noticeably violated in a slower climatic evolution of currents. The requirement that $Eu/Fr = 1$, which follows from equation (9), is trivially and always fulfilled for large-scale motions. As usual, $a\omega/uH = 1$. $Fo = k\tau/H^2$ characterizes the time homogeneity of the processes of ocean heat adaptation. The 1-2 x 10^4 cm thick upper layer of the ocean takes part in seasonal oscillations. Taking $k = 10$ cm^2 s^{-1} for $\tau = 3 \times 10^7$ s, we find $Fo \approx 0.8$-3.0. The entire ocean layer ($H = 4 \times 10^5$ cm) takes part in the long-term (glacial) climatic oscillations ($\tau = 3 \times 10^{11}$ s). The heat conduction coefficient for the entire ocean is apparently lower by one order of magnitude than that for the upper layer [in Bryan and Cox (1967), for instance, the authors advise taking $k = 1$ cm^2 s^{-1} for the whole ocean, although for the upper layer it is about 10 cm^2 s^{-1}]; then $Fo = 2$. Despite their approximate values, the estimates which have been made reveal a curious thing: the ocean's reaction to oscillations with characteristic times of 1 and 10^4 years is similar in terms of Fo. Together with the discussion above regarding the reaction of land, this signifies that variations in temperature fields along the parallels of latitude in the course of seasonal and longer climatic oscillations may be similar.

The values of $Sh = a/u\tau$ for seasonal and climatic oscillations differ by at least one order of magnitude. This means that the processes of adaptation of current fields in the course of seasonal and climatic variations do not possess time homogeneity. Thus, as a result of the analysis, one may consider as an established fact only the similarity of the area-averaged reaction of the ocean to variations in external conditions with characteristic times of 1 and 10^4 years.*

*For seasonal oscillations, Sh equals about 10^{-1}, and for climatic oscillations $Sh \ll 10^{-1}$; in this case the processes are quasi-stationary and the similarity conditions are fulfilled more accurately.

The relationship between the ocean temperature and the baric field over it is so great that, as was shown by Sherkhach (1967), the contour lines in average maps AT 500 (i.e., representing the pressure distribution corresponding to the altitude at which the air pressure is supposed to be 500 mbar) of the northern hemisphere virtually coincide with the lines of equal deviations of water temperature from zonal values. Similar associations can also be observed in the southern hemisphere. This circumstance and the analysis presented above permit the conclusion that changes in non-zonal components of general atmospheric circulation are approximately similar in the course of seasonal and longer-term climatic oscillations.

CONCLUSIONS

The conclusions formulated in the present paper indicate that, with sufficient averaging and sufficiently small variation rates, the average states of the atmosphere follow the boundary conditions. Moreover, the conditions at the lower boundary of the atmosphere are determinative, so that the variations in the influx of radiant energy at the external boundary of the atmosphere are also taken into account. Seasonal variations in the fields of meteorological elements may be regarded as a physical model of longer-term climatic variations. In this case, one may obtain answers to many questions relating to climatic changes, which can be formulated when one has a physical model with definite possibilities. The following are some of the possibilities:

(1) Experimental data on seasonal variations in the general circulation of the atmosphere can be applied to find numerical values of parameters in equations representing mathematical models of the climate. The same experimental data can serve as a foundation for constructing all kinds of empirical ratios and semiempirical functions designed for application in climatic models or for climatological calculations.

(2) Experimental data on seasonal variations in the fields of meteorological elements can be applied to estimate the average annual fields of different climatic states. In this case, it would be sufficient to have minimum information on the selected climatic epoch, enough to estimate Ki_T, i.e., information on the average annual values of Θ and Γ.

(3) At least from the Cretaceous period (about 100 million years ago) the latitudinal profiles of the average annual zonal temperature for different climatic states (see Figure 1 in Fairbridge 1964) are similar to the seasonally (or monthly) averaged zonal temperature profiles of the recent climate. The deviations of average annual values Θ and Γ for this time are within the range of seasonal oscillations of monthly averaged values for these parameters. Hence, applying the method described above, one can estimate the integral characteristics of zonal atmospheric circulation and of

zonal averaged fields of meteorological elements for different climatic epochs starting from the Cretaceous period.

The concept of the similarity of states of general atmospheric circulation, as developed in the present paper, underlines the importance of research programs aimed at monitoring global atmospheric processes and their seasonal variations. Reliable experimental data on seasonal variations in the fields of meteorological elements, averaged for a period of many years, can serve as the empirical foundation for constructing mathematical models of climate and make possible reliable estimations of average annual fields for different climatic epochs.

Nomenclature

a	Earth's radius
β	condensation rate of water vapor in reference to unit volume
B	heat influx into the atmosphere from condensation of water vapor by unit surface
C_p	specific heat capacity at constant pressure
Γ	temperature difference between the equator and the pole
F	total radiation flow in reference to unit surface
g	acceleration of the force of gravity
H	height of the troposphere
Θ	average atmospheric temperature in the hemisphere
θ	latitude supplement
Ki_{T}	thermal Kibel number
k	constant
k''	typical value of the coefficient of horizontal turbulent heat diffusivity
l	characteristic value of the Coriolis parameter
λ'	coefficient of vertical turbulent heat conduction
λ''	coefficient of horizontal turbulent heat conduction
L	latent heat of evaporation
μ	dynamic coefficient of turbulent viscosity
ν	kinematic coefficient of turbulent viscosity
π	characteristic pressure difference
p	pressure
P	characteristic value of the vertical turbulent heat flow

(cont.)

Nomenclature (cont.)

ρ	density
r	vertical coordinate
T	temperature
τ	characteristic time
u	characteristic wind velocity
u_T	velocity of thermal wind
υ_θ	meridional velocity component
υ_ψ	zonal velocity component
ω	vertical velocity component
Eu, *Fo*, *Fr*, *Ki*, *Pe*, *Re*, *Sh*	similarity numbers

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