ASSESSING THE IMPACT OF CLIMATIC CHANGE IN COLD REGIONS

M.L. Parry and T.R. Carter

(Editors)

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Preface

Over the past few years, IIASA has been involved with the question of climatic change in various ways. Firstly, the Institute's seven-year Energy Systems Program studied the effects that alternative future global energy strategies, based on fossil fuels and nuclear and solar energy, might have on world climate, and treated these possible global warming effects as constraints on feasible energy scenarios. Secondly, the National Agricultural Policies Program is concerned with the influence of climate on global food production, and with the impacts on climate caused by different agricultural policies, such as deforestation. Thirdly, IIASA research projects on the world's natural resources have included studies of the distribution of water supply and demand, which can be significantly affected by changes in climate.

In September 1983 IIASA, together with the Austrian Government, the World Resources Institute, and the United Nations Educational, Scientific, and Cultural Organization, gave support to an International Study Conference on *The Sensitivity of Ecosystems and Society to Climatic Change*, which was cosponsored by the World Meteorological Organization, the United Nations Environment Programme, and the International Council of Scientific Unions. The conference, held at the spa town of Villach in southern Austria, was attended by scientists from 17 countries.

The purpose of the meeting was to evaluate the impact of climatic fluctuations on the sensitive margins of agriculture and of natural terrestrial ecosystems. The emphasis was on climatic changes that might result from increases in the amount of carbon dioxide in the atmosphere, but consideration was also given to past climatic fluctuations, both short- and long-term.

Following a plenary session, which evaluated recent progress in modeling possible climatic changes due to increased atmospheric carbon dioxide levels, the meeting divided into two parallel workshops, which considered climate impacts in cold and dry regions, respectively.

As is evident from the list of participants in the Appendix, IIASA's contribution to the Workshop on Cold Margins was considerable: the workshop discussions were intended as the first component of a two-year

IIASA/UNEP research project. As it turned out, they provided the initial platform upon which subsequent research on climate impact assessment at IIASA has been based. The following report is a summary of deliberations by participants in the workshop, of the observations that emerged, and of the recommendations made. Substantive papers from the workshop are to be published in a special issue of the journal *Climatic Change* in 1984. A summary of the entire meeting (including the plenary session and the Workshop on Dry Margins) is being published by WMO.

Particular thanks are due to UNEP, which was the prime sponsor of the Study Conference and is cosponsor of the Climate Impact Research Project based at IIASA; and to the Austrian Government, which supported IIASA's preliminary research leading up to the Study Conference.

Contents

1 Introduction

For the purposes of this report:
Climatic change describes long-term changes either in the mean values of specific climatic variables or in the variability of these variables.
Climatic variability describes the observed year-to-year differences in climatic variables.
Weather refers to the prevailing state of the atmosphere as measured on a day-to-day basis.

There is a growing body of evidence that suggests that the atmosphere is gradually heating up possibly as a result of the emission of waste gases, in large quantities, from the worldwide combustion of fossil fuels as well as from other sources. Many of these gases, including the most abundant one, carbon dioxide, have the property of being able to absorb and re-emit the long-wave radiation from the Earth's surface, while still allowing the shorter-wave solar radiation through to the surface. The resulting "greenhouse effect," whereby the heat trapped in the atmosphere accumulates, can have important implications for world climate.

Since the first meeting on CO_2 and climate at Villach in 1980 (WMO/ICSU/UNEP 1981), an increasing number of general circulation models have been tested that simulate the effects on equilibrium climate of changes in the atmospheric concentration of carbon dioxide. It is estimated that one effect of a CO_2 doubling would be an increase in the globally averaged temperature of from 1.5 to 4°C. The differences between the estimates are probably due, in part, to the various approaches used to model the ocean–atmosphere coupling.

An earlier Executive Report from IIASA described attempts by Flohn (1981) to determine the likely climatic effects of global warming on different parts of the Earth by drawing analogies with earlier periods of the Earth's history when the global average surface temperature was between 1 and 4°C higher than it is now.

The present report describes an alternative to this paleoclimatic approach, involving the use of models to predict the consequences of global warming in particular (cold) regions. However, it should be made clear from the start that there are two obvious and fundamental weaknesses in any assessment of the impact of possible future climatic changes on ecosystems and society. Firstly, we have inaccurate information on their present-day sensitivity to climatic variability. Secondly, we are uncertain what changes of climate will occur in the future. Thus, on the question of impact from possible CO_2-induced warming there is, typically, some doubt at both ends of the research spectrum. There is doubt about the precision of our scenarios of climatic change that would result from, say, a doubling of the CO_2 level in the atmosphere, and doubt about the precision of our descriptions of the effect of climatic variability on crop yields, livestock-carrying capacity, and fisheries, for example.

1.1 Objectives

The aim of the Workshop on Cold Margins was to explore ground between these two ends of the research spectrum and thus to answer the following questions:

- How far is it possible to make reasonable predictions of the impact on ecosystems and agriculture resulting from possible CO_2-induced climatic changes?
- Can accurate assessments of the long-term impact of climatic change be undertaken using models originally designed to simulate short-term impacts of climatic variability?
- What distance separates the CO_2 models on the one hand and the impact models on the other?
- Can the models be brought closer together, in scientific terms, in order to increase their combined value?
- What other means are there for improving the methodology for assessing the impact of possible long-term climatic changes?

These questions suggest that we focus our attention on two related issues: (a) the current sensitivity of ecosystems and farming systems to climatic variability, and (b) the range of impacts likely for certain changes of climate. Since an understanding of impact presumes a knowledge of sensitivity, it was logical that the former issue be considered first. This report therefore addresses four broad themes:

1. The nature of the research problem
2. Methods of evaluating sensitivity to climatic variability
3. Methods of measuring the impact of climatic change
4. How these methods might be refined.

Although we report some provisional (and previously unpublished) findings on the possible impacts of an increasing amount of atmospheric carbon dioxide on ecosystems and farming systems, the emphasis in this report is less on what these sensitivities or impacts are, than on ***how we can evaluate them more accurately***. The examples are drawn both from terrestrial ecosystems and from agriculture because, at least in terms of biophysics, there are some similarities of response in natural and managed ecosystems. Yet the omission of other areas of possible impact (such as in fisheries, energy, and water resources, etc.) should not imply that the impacts there may be less significant.

1.2 Why Look at Margins?

The focus on marginality in this report derives from the assumption that sensitivity to climatic variability may be more readily observed (a) at the margin between two ecosystems (the *ecotone*), and (b) at the boundaries between different farming systems. It should be noted that there are different kinds of "marginality." For example, we can identify:

1. *Spatial* or *geographical marginality*, which describes the edge of a specified region. The region itself may be defined in biophysical, economic, or other terms.
2. *Economic marginality*, where returns on a given activity barely exceed costs.
3. *Social marginality*, where an underdeveloped population becomes isolated from its indigenous resource base (as a result of socioeconomic change, for instance) and is forced into marginal economies that contain fewer adaptive mechanisms for survival (Baird *et al.* 1975).

These different types of marginality do not necessarily coincide on the ground. For example, a marginal farm is not necessarily located on marginal land, and neither of these is necessarily found at the edge of an agroclimatic region. But it is reasonable to suggest that, whatever the type of marginality, it is characterized by a special sensitivity to changes in resource availability (such as changes in climate, which can be regarded as a resource). The margins can be mapped and their shifts can be used to designate areas of impact from climatic changes or climatic variability.

We can postulate four marginal producer groups at particular risk from climatic variability today and possible climatic change in the future:

1. The first is located in the humid tropics at the mercy of excessive precipitation and, in some areas, of tropical storms. While prone to periodic catastrophe, this group seems in general to experience relatively small year-to-year variability of agricultural yields. The impact here would probably stem as much from changes in the mean values as from changes in the variability of yields. An increase in the frequency of tropical storms, which might occur as a result of increased atmospheric CO_2, could have a severe impact on low-lying coastal regions, for example in the deltaic region of Bengal and Bangladesh.

2. The second group is located in the arid and semiarid areas of the subtropics, particularly in Africa and South Asia, and in the Mediterranean regions of West Asia and North Africa. In general, these exhibit the highest year-to-year variability of yields. Famine has been particularly severe in semiarid Africa for many years. Population pressure and national government policies are exacerbating this problem and reducing traditional devices for risk avoidance, such as nomadism. Any shift of the rainfall distribution in these areas can have a dramatic impact.

3. A third group, accounting for some ten percent of the world's population, includes farmers at high altitudes, such as those in the high Andean basins of Ecuador, Peru, and Bolivia, and in the Himalayas from Kashmir to Assam. These have received relatively little attention until recently: they live in a wide range of conditions at different altitudes and latitudes, and have a similar variety of production systems. In some regions, such as Peru, altitude may favorably modify harsh lowland climates; in others, as in West Asia, it may bring both summer heat and winter cold. It is extremely difficult to predict how such diverse and complex situations would be affected by climatic change.

4. Finally, there is the group at higher latitudes. These farmers are mostly located in developed countries (northern Europe, the USSR, and Canada) and are therefore somewhat less vulnerable to destitution or starvation resulting from climatic change than are other marginal producer groups. However, they are still not immune to economic loss and, because more detailed climatic and economic data are available here than elsewhere, they offer a potentially useful case study for the whole problem.

Figure 1 illustrates the global distribution of semiarid, high-altitude, and high-latitude "marginal" regions. They have been delimited by combining a climatic classification (Köppen 1936) with information on natural vegetation and topography. As with most classifications, the boundaries are arbitrary — they are merely convenient lines serving to mark the location of different agroclimatic regimes.

We have focused on cold areas, where low temperatures resulting either from high latitude or from high elevation (or from a combination of the two) are the major constraint on plant growth. The examples we present in this report are drawn from Iceland, Canada, and northern Europe.

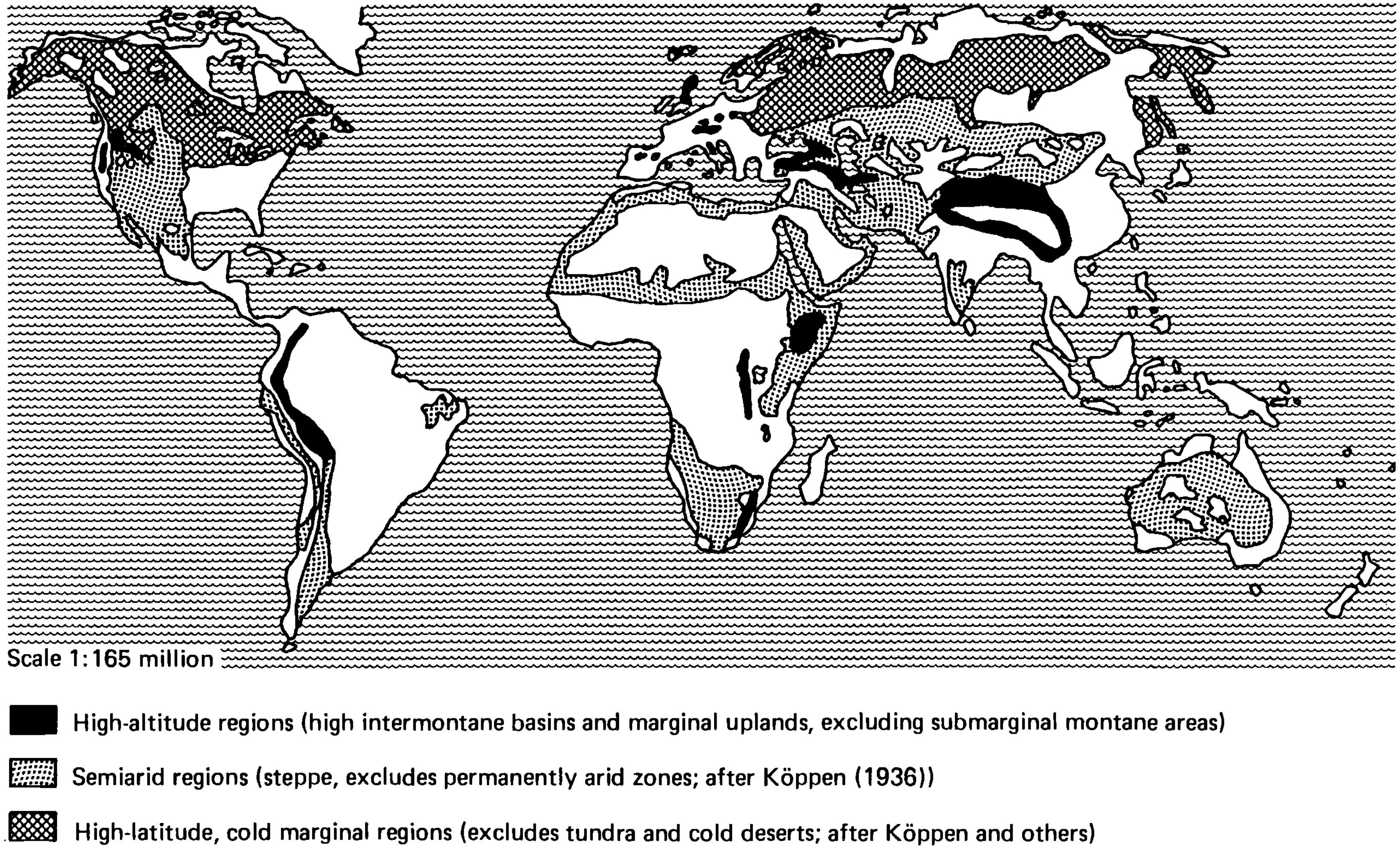

Figure 1 Some climatically marginal regions.

1.3 The Probable Impact of Climatic Change at High Latitudes

Because of the large seasonal variation of climate at middle and high latitudes (i.e. above about 30°) induced by the tilt of the Earth's axis, agriculture in these regions is frequently constrained by low temperatures. Here, the seasonal temperature range is usually much greater than either the year-to-year variation in temperature or the projected temperature change resulting from increasing CO_2 concentration. The important potential climate alteration is therefore not the change in annual mean conditions, but the change in the timing of the seasonal cycle and of the maximum and minimum temperatures reached at various times of the year.

The pattern of precipitation in cold marginal areas usually includes snow at some time during the winter and relatively dry periods during the growing season, thereby often necessitating the thoughtful use of winter precipitation, either through adjustments in the timing of farm operations or through irrigation. Fluctuations in annual precipitation from one year to the next are often quite large, generally larger than the potential change expected to result from increasing CO_2 concentration. However, CO_2-induced changes in the timing of the seasonal pattern of precipitation at a given location are as important to consider as are changes in the absolute amount of precipitation.

Insights gained from climate models and analog analyses can now be used to develop estimates of how the general patterns of temperature and, to a lesser extent, precipitation may change on relatively long time scales. But the model estimates available at present provide little local detail and, furthermore, the various models show considerable differences for the same region. There are, however, certain general patterns of change common to all of these climate models. In the case of CO_2-induced warming, these include the following characteristics:

1. Temperature changes at the cold margins will probably be greater than elsewhere, partly because of feedback processes in these regions. For example, ice sheets might contract as a result of global warming, exposing greater areas of land or ocean, the lower albedo (reflectivity) of which would lead to further warming of the Earth's surface and to further contraction of the ice sheets. Isotherms will generally shift poleward with associated circulation patterns in such a way as to lengthen the warm season and shorten the cold season at a given location.

2. As a result of the changes described above, the *rate of temperature change* at high latitudes will probably be greater than at low latitudes.

3. There may be a tendency (a) to higher precipitation in colder regions, because warmer air can hold more moisture; and (b) to a general poleward shift of winter storm belts in middle latitudes, thereby potentially affecting water resources in these regions.

4. The freezing line and snow limits will tend to rise to higher altitudes, so that in any given area the distribution of changes will also depend on local topography.

2 Formulating the Research Problem

2.1 The Policy Content of Climate Impact Studies

The extent to which climate impact studies should be addressed to the immediate needs of government policy, rather than the longer-term needs of strategic planning, will determine the temporal and spatial scales of the research problem and, in turn, the methodology and research outputs. Since governments are generally concerned more with the short term than the long term, they have a greater interest in sensitivity to climatic variability than in the impact of climatic change. For example, their concern has focused on the impacts of short-term anomalies such as floods, droughts, and cold spells rather than on possible long-term trends such as those that might be produced by increases in atmospheric carbon dioxide. This suggests that a useful form in which long-term climatic change can be expressed for the policy maker is as a change in the *frequency* of such anomalies. One advantage of this approach is that the change can be expressed as a change in the *risk of impact*. Government programs could then be devised to accommodate specified tolerable levels of risk, by adjusting activities as necessary to match the change of risk. This subject is considered further on pp. 11–12.

2.2 Matching the Scale of the Study to the Scale of the Problem

The emphasis on short-term anomalies highlights the problem of an apparent mismatch between the scales of climatic events that claim our attention and the scales of response. Clark *et al.* (1984) have illustrated this with reference to a diagram, similar to those used by Stommel (1963), which represents time on the abscissa and distance on the ordinate, as shown in Figure 2. By plotting hierarchies of systems (e.g. climatic, agricultural, and social systems), we can examine the degree to which they overlap in time and space. Figure 2 shows how the scales of climatic events that we have been able to model and forecast compare with those of agricultural response. Although these are somewhat schematized examples, it is clear that the dominant scales do not coincide. The disruptive climatic events that have the most impact on society (regional, relatively short-term events, such as seasonal extremes, or occasional supraregional and medium-term "El Niño-type"* occurrences) have, until recently, claimed scant attention and are little understood. Therefore, to carry out effective climate impact assessments, we require: (a) a hierarchy of climate models linking the minimum scale now resolved (about 500 km) to microscale events (between 0.1 and 1 km); and (b) a temporal resolution keyed to the spatial scale, ranging from about 10^5 seconds (daily) at the microscale to the order of 10^{10} seconds (centuries) at the macroscale.

Our relatively good understanding of environmental variability at scales of around 1–100 km/10^6–10^9 seconds (i.e. farm to regional scales) should be complemented by work on such aspects as local agricultural planning (farm level), crop insurance schemes (regional level), and grain reserves (national level). Likewise, our understanding of environmental changes (such as the effects of increasing atmospheric CO_2 concentration) at scales of around 10^{3+} km/10^8–10^{10} seconds should be matched by studies of the lifetimes of large civil works projects, of settlement patterns, and of the market penetration of relevant energy and crop strategies.

2.3 Interpreting Climatic Change

2.3.1 A Change in the Range of Options

Since, in agriculture at least, climate can reasonably be construed as a resource, climatic change can produce benefits or disadvantages that may require an adjustment to match altered resource levels. One important path of these impacts is through the range of choice: changes in climate can alter the range of options that may compete for investment of time, money, and other resources. Moreover, the *perception* of these changed options is often important because the timing of investment in relation to weather can significantly influence the return on that investment. For example, the timing of farming operations (ploughing, sowing, harvesting, etc.) frequently explains much of the variation in yields from farm to farm at the local level. Changes in climate might tend to enhance the mismatch between weather and farming operations because of a lag in management response to changes in, most importantly, the

*El Niño, or "the Christ child" (so-called because it generally develops soon after Christmas), is a southward-flowing ocean current that brings warm waters to the normally cool coast of Ecuador and Peru. In exceptional years, a catastrophic version of El Niño is associated with a southerly shift in the tropical rain belt, causing widespread disruption to agriculture. The impact is compounded by the warm waters that may extend along the coast of Peru to 12°S, killing plankton, fish, and guano birds, with devastating consequences for the local economy.

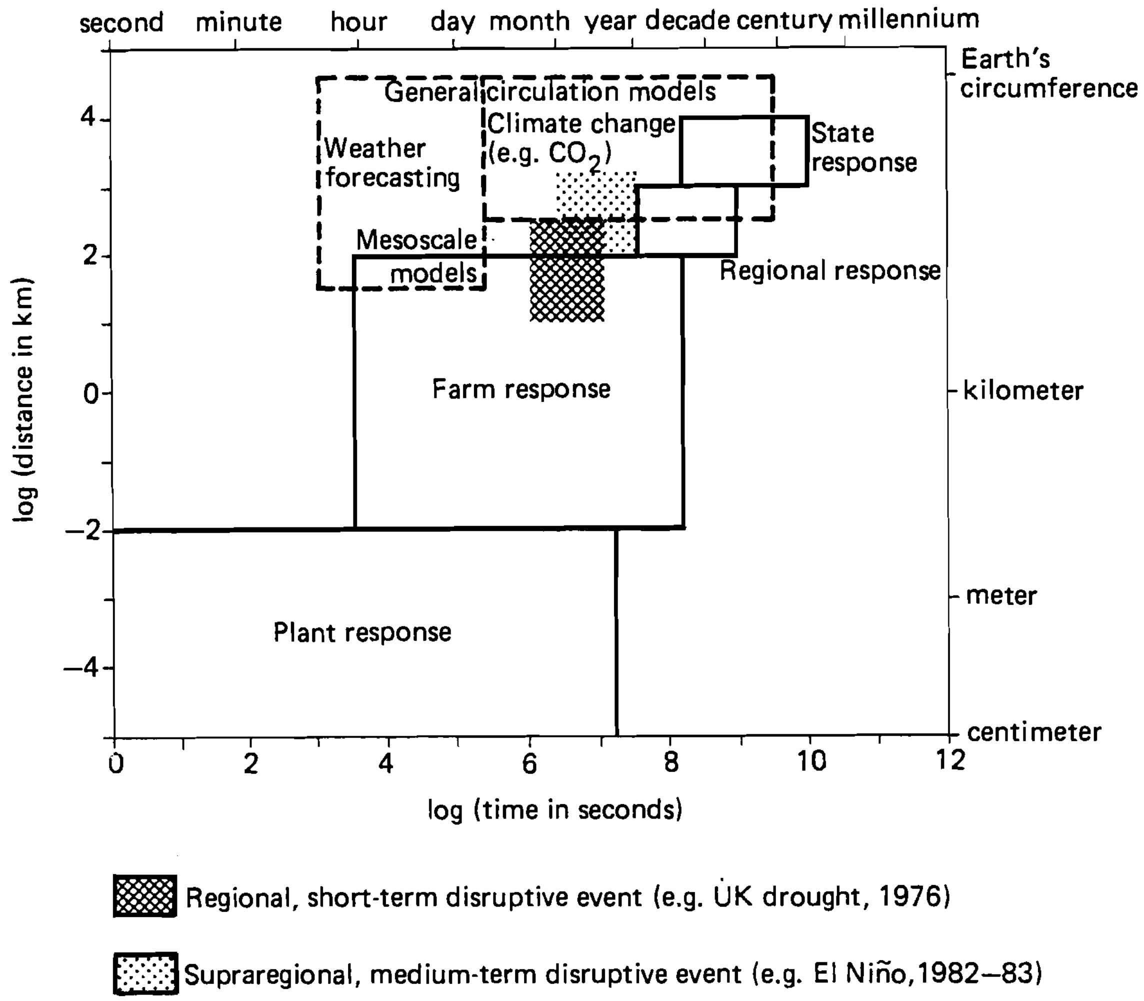

Figure 2 Climate models, events, and responses: a mismatch (after Clark *et al.* 1984).

"time windows" for planting and harvesting. For this reason, crop selection is probably one of the most effective means of response to an adverse climatic change, for the development of new strains or the introduction of new crops can serve to keep open these time windows sufficiently to allow adequate yields to be maintained.

2.3.2 A Change in the Level of Risk

One way of evaluating climatic change in human terms is to consider it as a change in the level of risk, that is, in the *probability* of an adverse or beneficial event, such as shortfall from some critical level of output or excess above the expected yield. In agriculture, for example, we might thus assume that both farmers and, in a sense, individual plants are entrepreneurs whose activities are based upon the expected return from gambling on "good" years (which allow substantial profits, or substantial seedsetting and seed establishment) and "bad" years (substantial losses, or poor seedsetting and seed establishment). In marginal activities (i.e. those in which returns barely exceed costs) the levels of risk are particularly high because the farmer is operating near the limit of profitability for a particular activity or because the ecosystem is functioning near the limit of its viability. Furthermore, spatial changes in temperature or precipitation, which are often broadly linear (e.g. the rate of change of temperature with elevation and latitude), have strongly nonlinear aspects when redefined as the probability of occurrence of a certain anomaly. There may thus be very marked differences over space in the probability of profit or loss, of viability or nonviability. If a change in risk is an important consequence of climatic change, we need to measure the frequencies of occurrence of normal climatic conditions and to use these frequencies as a base upon which to superimpose effects such as CO_2-induced warming, volcanic-dust-induced cooling, etc. to obtain modified frequencies reflecting such events.

2.3.3 A Change in the Frequency of Extreme Events

The notion of risk as an important measure of climate impact derives in part from the view that society adjusts to climatic change by responding to changes in the frequency of extreme events rather than to long-term change of the average conditions. There are, in fact, two somewhat contrasting reasons for focusing our attention on extreme events:

1. In the absence of experience with long-term average change, in terms of data for use in modeling, it is simply one means of understanding how society responds to climate.

2. Anomalies are the very phenomena through which society is affected by, and responds to, long-term climatic change – that is, through changes in the frequency of disruptive (or advantageous) extreme events associated with changes in the mean climate or in its variability (Wigley and Warrick 1984).

If the second explanation is correct, then it is not likely that society would naturally and gradually adapt in pace with slow changes in climate. Rather, the problem for society would be how to perceive and adjust to shifts in the frequency distributions of disruptive climatic events. There may be considerable lags in societal response since, in the absence (or ineffective application) of prior scientific information, the changes in risk can only be perceived through direct experience – a long and potentially costly process. In such circumstances the response to a gradual climatic change would be step-like, being triggered now and then by, for example, a short sequence of extreme years. *Ceteris paribus*, the result would be a poor fit between climatic change and society's response, with concomitant social and economic cost.

An explicit policy of matching adaptation to the rate of climatic change would seek to improve this fit by effectively communicating information about changes in the likelihood of disruptive climatic events. Furthermore, a policy of attempting to match technological change to climatic change should thus focus not only on the rate of change in mean climatic conditions but also on the rate of change in the frequency of climatic extremes.

3 Constructing an Appropriate Methodology

3.1 The Spatial Shift of Isopleths or Boundaries

A method that permits the identification of areas that can be affected by climatic change or variability is one that focuses on the shift of limits or margins representing boundaries between arbitrarily defined classes. The classifications may be of vegetation, land use, yields, and so on. In this sense, the boundaries delimit zones on maps that can undergo a spatial shift for a given change of climate, thus defining impact areas. An example of this method is illustrated in Figure 3, where the impact of climatic change is described in terms of the resulting change in the probability of harvest success or failure. The weather for a number of years, described by a set of meteorological data, can be expressed as a probability of "risk" or "reward" using an appropriate model. When calculated for a number of stations this probability level can be mapped geographically as an isopleth. Scenarios of changing climates can then be used as inputs to the model to produce geographical shifts of the probability isopleth, which are then identified. The areas delimited by these shifts represent areas of specific climate impact. A full description of this method is given by Parry (1984). It is one that has been employed in most of the studies described in Sections 3.5 and 3.6 of this report.

3.2 Combining Different Approaches to the Research Problem

There is some merit in seeking to reconcile and *integrate* what has too often been an unreconciled contrast in approaches between the social and the natural scientist. We should not exaggerate these distinctions but emphasize their complementary roles. In particular, we should exploit the complementarity between direct (or causal) methodologies of the natural scientist and "adjoint"* methodologies of the social scientist. In

*The term "adjoint", which normally refers to the transpose of a square matrix or determinant, is used here to indicate that such methodologies have features in common with direct methodologies, but are opposite in nature.

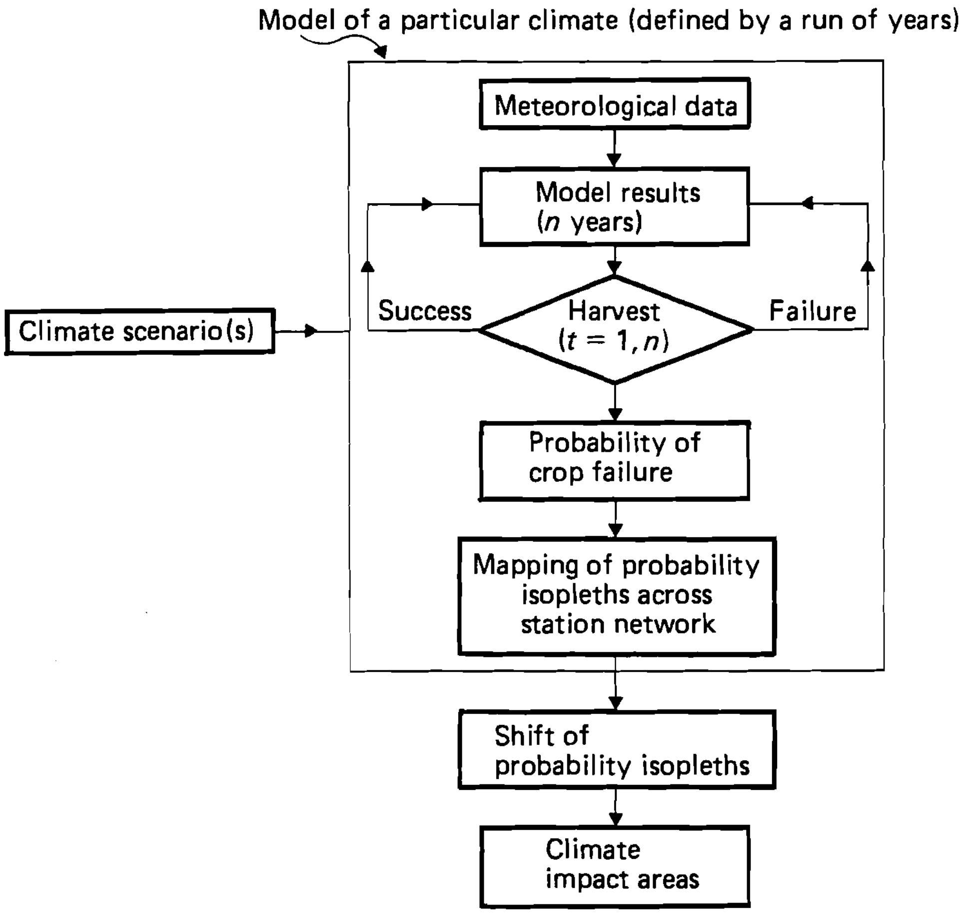

Figure 3 Identifying areas of climate impact, using shifts in the isopleths of the probability of crop failure (after Parry and Carter 1983).

the former, for example, one might perform a sensitivity study by perturbing one input variable (such as CO_2 concentration) and tracing through the effects (climate → agriculture → individual farmer → food prices → society). In the latter, for example, one might consider the perturbations, both climatic and nonclimatic, that influence farmers' decisions and perceptions, and trace those that have a climatic origin to a number of climatic variables and their relationships to the level of atmospheric CO_2 (society → food prices → individual farmer → agriculture → climate). Both approaches may be necessary to understand the full complexity of the interactions, but the adjoint approach has received less attention. Its advantage for those concerned with climate impact is that, by evaluating perturbations caused by climate in relation to perturbations caused by other sources (technology, demand, etc.), the social scientist can produce outputs that can be expressed more readily in terms of policy.

Assessment of the impact of possible long-term climatic change could be substantially improved by increasing the compatibility between models of impact (i.e. *transfer functions*) and models of change (e.g. *climate scenarios*). Much of the following attends to this task, firstly by considering alternative methods of modeling climate impact and climatic change, and secondly by discussing how these methods can be brought closer together.

3.3 Constructing the Transfer Function

3.3.1 Crop–Weather Models

Crop–weather models are a means by which quantitative predictions can be made about crop yield in response to weather or climate. The two main types are empirical–statistical models (regression models) and simulation models (physiological models).

- *Empirical–statistical models*

In the empirical–statistical approach, one or several measured variables (such as meteorological observations and soil and technology time trends) are related statistically to crop responses such as yield. The virtue of these models is in their potentially high practical value for yield prediction, often over large areas, although they require only modest quantities of data and little computer time. However, the statistical approach does not easily lead to an explanation of cause-and-effect relationships, and only identifies those variables that show a strong association with crop yield on short time scales. This can be a shortcoming where the climatic variable that is the main limit to a crop (e.g. temperature for wheat on the Canadian prairies) is not the one that causes the main year-to-year variability (e.g. precipitation). Not all such models have been properly tested by independent verification. Furthermore, the relative contributions to crop yield of technology, weather, and other factors such as disease are frequently poorly distinguished and the models do not usually allow for sporadic events such as hailstorms, floods, late or early frosts, etc. In addition, most models are specific to the locations that provided the data from which the regression equations were developed. In spite of numerous deficiencies this approach is, however, widely used. It is probably most valuable for climate impact assessment in areas where crop yields are highly sensitive to a single variable and where that variable is of particular interest in impact analyses (e.g. temperature in Iceland).

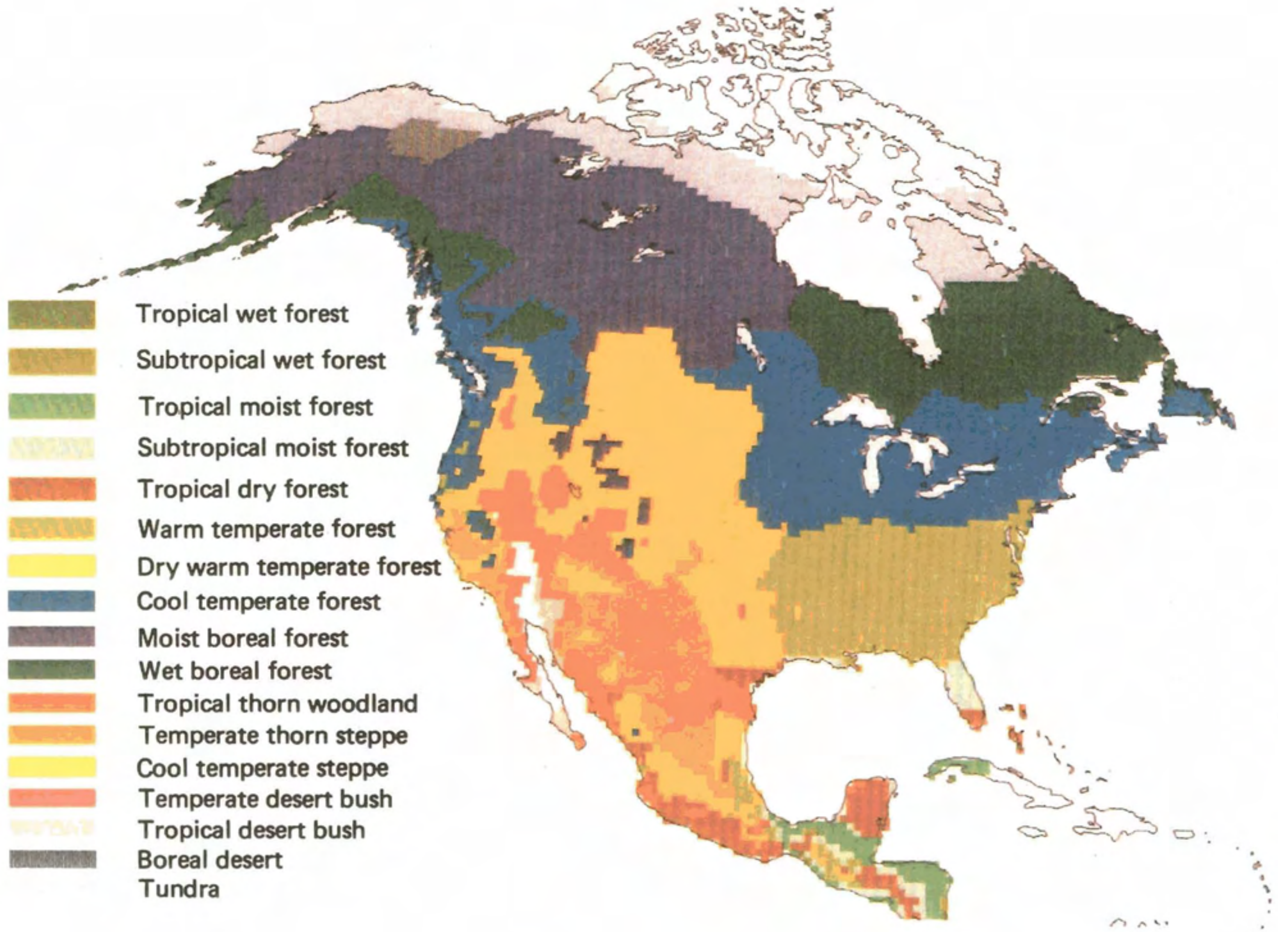

Figure 4(a) Holdridge Life-Zone Classification for present conditions of mean annual biotemperature and precipitation (Emanuel and Shugart 1984) (see p. 24).

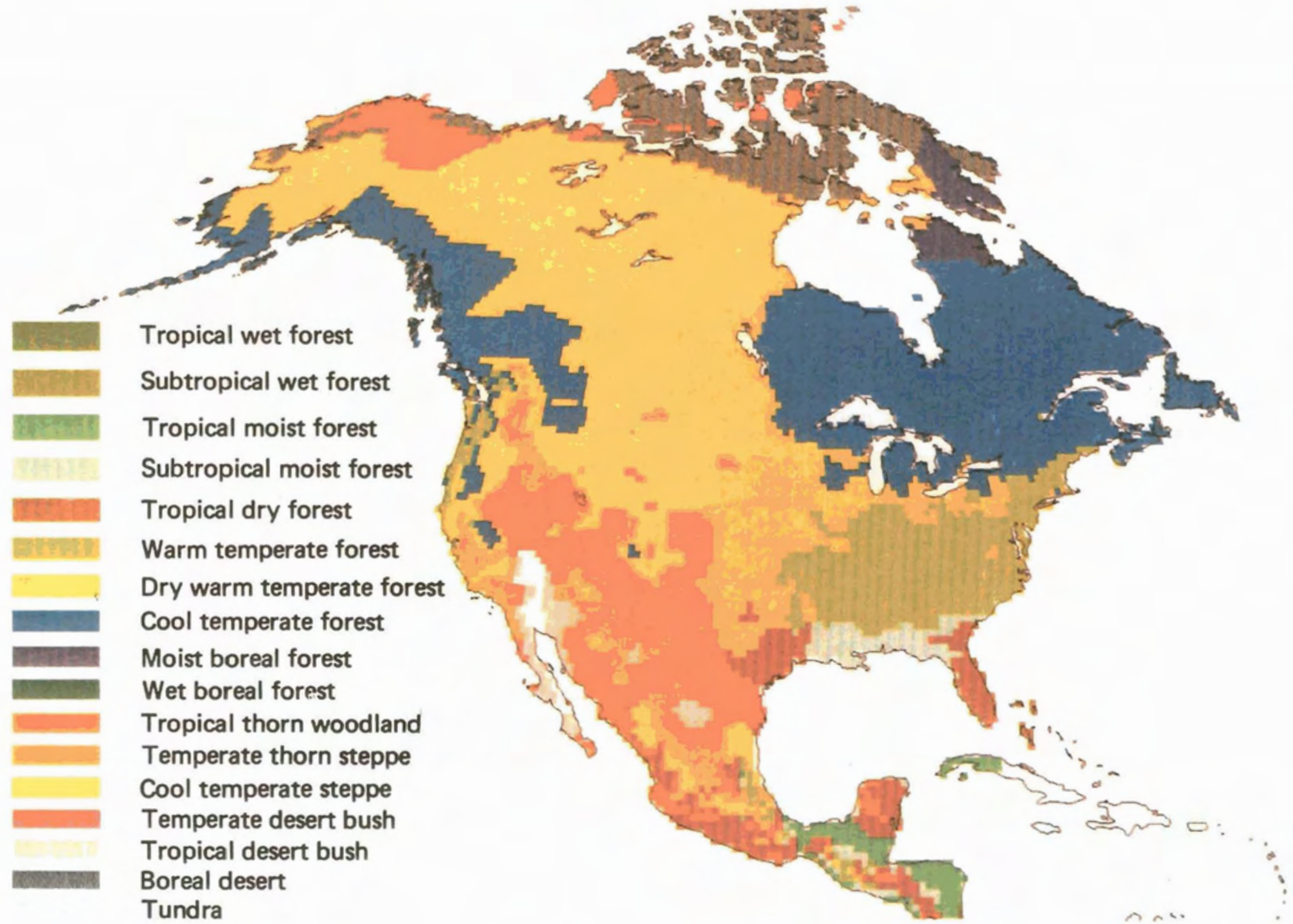

Figure 4(b) Holdridge Life-Zone Classification for 2 × CO_2 conditions of biotemperature (assuming unchanged precipitation) (Emanuel and Shugart 1984) (see p. 24).

- *Agroclimatic indices*

An alternative but related method of agroclimatic resource analysis is based on an agroclimatic index, such as the ratio of natural precipitation to the water requirement of cereal crops (e.g. Sly 1970). Use of such indices is aimed at the identification of areas suited for various crops and thus overcomes the crop limit problem faced by empirical–statistical models. But they were not intended for, nor can they readily be used in, quantitatively evaluating the likely impact of climatic changes. A solution involves relating the agroclimatic indices to yield data, as was done for the agroclimatic resource index (ACRI) produced for Canada by G.D.V. Williams (Science Council of Canada 1976) and for the climatic index of agricultural potential (CA) developed by Turc in France (Turc and Lecerf 1972). The Turc method involves the computation of a heliothermic index and a moisture index, which are multiplied together for each month and accumulated over one year to obtain CA, and may provide a useful alternative to the ACRI method. However, neither method has yet been fully evaluated for use in climate impact assessments. This work is in progress.

- *Simulation models*

Simulation models are simplified representations of the physical, chemical, and physiological mechanisms underlying plant and crop growth. Attempts are made to understand and model the basic plant processes, such as photosynthesis and transpiration, and their relationships with water supply, temperature, solar radiation, and other factors, so that growth rates, productivity, and other responses of the plant to these environmental conditions can be simulated.

Such models are suitable for detailed field studies (although they usually assume ideal conditions of no disease, adequate nutrient supply, etc.) and are capable of modeling crop response to episodic events. A general disadvantage for climate impact assessment is their requirement for very detailed meteorological and physiological data, first to validate the model and then to apply it for specific locations. As a result, few have been properly tested by independent verification. An advantage is the ability of some models to consider the direct effects on plant growth of enhanced levels of atmospheric carbon dioxide.

3.3.2 Probabilistic Models of Climate Impact

If the response of society to climatic change is such that an important path of climate impact is through rare, extreme events, then the frequency of such events and, in addition, the cumulative effects of consecutive or clustered extremes are an important dimension of climatic change. Simple probabilistic models can be used to demonstrate these effects – in particular, that the probability of two extremes in consecutive years is far more sensitive to climatic change than is the probability of a single extreme (Parry 1978). To illustrate this, we can suppose that extremely cold winters or dry summers occur with a probability p of 0.1. The return period for the occurrence of a single extreme is, therefore, 10 years, while the return period for the occurrence of two consecutive extremes is 100 years (assuming a normal distribution of such events).

Climatic change would lead to a change in p through a change in climatic variability, which will change p directly, and/or through a change in the mean conditions, which must also change p if the extremes are judged relative to an absolute threshold. Alternatively, p may change through changes in some critical impact threshold as a result of land-use changes, new crops or crop mixes, increasing population pressure, etc. If p becomes 0.2 then the return period for a single severe season is halved to five years. The return period for consecutive severe seasons, however, is reduced by a factor of four to only 25 years.

The value of probabilistic models is that they can be linked with risk analysis models that seek to analyze the probability distributions of potential economic losses or returns resulting from certain strategies. For example, agricultural decision models (including game-theoretical models) have been developed to consider strategies to reduce entrepreneurial risk and increase profitability. Changes in risk frequency due to change in climatic variability or in mean climatic conditions can be built into such models to provide information in a form appropriate for agricultural planners.

3.3.3 Integrating Climatic and Economic Models

A serious flaw in much analysis of climate impact is the omission of economic feedback mechanisms. There is considerable scope for integrating microeconomic models and climate impact models at the level of the individual farm, for example in a decision-analytical framework. At the regional level, we should seek to integrate climatic and economic scenarios in assessing likely changes in geographical distributions of crops. The economic aspects might be dealt with by methods such as those employed by Lozano (1968), who used income–population potential* for the economic side of his analysis and determined how margins for various crops in 48 states of the USA depended on either economics or climate or both.

*The income–population potential of a particular piece of land is related to the distance of the market population, weighted according to income, from that land. For example, the potential of an agricultural state such as Iowa would depend, among other things, upon the distance to the major food markets in the eastern USA, the markets being expressed in terms of population and income.

3.4 Constructing the CO_2 Scenario

Three data sources have been used to develop high-CO_2 climate scenarios:

- Results from general circulation models of the atmosphere and ocean
- Instrumental data (e.g. the contrasting of warm and cold years or periods)
- Paleoclimatic data.

In this report consideration is given, firstly, to the use, in climate impact assessment, of scenarios derived from general circulation models and, secondly, to those scenarios derived from instrumental data. Those based on paleoclimatic data were not considered at the workshop. A discussion of these can be found in Kellogg and Schware (1981) and elsewhere.

3.4.1 Scenarios from General Circulation Models

With growing confidence in the estimates of atmospheric CO_2 concentrations from preindustrial times to the present, modelers have made preliminary attempts to validate some aspects of general circulation models (GCMs) by comparing instrumental temperature data with model estimates (for example, estimation of the CO_2 effect by attributing all of the recorded rise in mean annual temperatures in the Northern Hemisphere over the past century to increased CO_2 levels). By extrapolation, the predicted global temperature increase for a CO_2 doubling would, *ceteris paribus*, be between 1 and 2°C. However, this method ignores the possible contribution of other exogenous effects on the climate, such as volcanic activity or fluctuations in the solar constant.*

While the global-scale temperature and precipitation patterns for the $1 \times CO_2$ equilibrium climate in GCM control runs are broadly similar to real conditions, errors at any one grid point may be large (up to perhaps 5°C or a factor of two for temperature and precipitation estimates, respectively). Whether the change between the $1 \times CO_2$ and $2 \times CO_2$ equilibrium conditions adequately reflects the real changes that would occur as a result of a CO_2 doubling is not known.

No general circulation model at present provides outputs of sufficient detail and reliability to be used with any confidence as inputs to models employed by climate impact analysts (e.g. crop–weather models). At the present stage of GCM development, instrumentally based scenarios provide

*The flux of solar radiation received normal to the Earth's surface (after correction for absorption in the atmosphere) – about 1,340 watts per square meter.

a valid (and equally realistic) alternative to GCM scenarios. We can, however, promote a greater compatibility between GCM outputs and the input requirements for impact models by, firstly, seeking to increase the detail and reliability of the former and, secondly, by reducing the detail and quantity required by the latter. In this respect it is useful to identify the present requirements of impact studies relating to the CO_2 question – requirements that can be viewed as a list of ideal GCM outputs for climate impact assessment.

In general, there is a need for "control" values of climatic variables (for comparison with the real world and as controls in impact studies) and for "perturbed" values of the variables (e.g. for a $2 \times CO_2$ simulation). Information on the detailed geographical distribution of the variables (temperature, precipitation, sunshine duration, and windspeed) is needed, ideally, on a daily time scale although daily data can be derived from monthly means, assuming no change in frequency distributions around the perturbed means. This would provide: sets of representative daily sequences of the variables mentioned above, in addition to days each month with maximum temperature above 30 °C or minimum temperature below 0 °C; dates of onset and close of the growing season (defined in terms of specific meteorological parameters); and growing season degree-days* above a specified temperature threshold. All these data need to be accompanied by some measure of their uncertainty.

While existing methods, both empirical and model-based, produce climate scenarios that are unlikely to be realistic, this should not mean that such scenarios cannot at present be used as input data for impact studies. Indeed, it can be argued that such work should proceed now, so that the methods of assessing impacts of possible long-term climatic changes can be refined. In this manner, we can hope for simultaneous progress in the application of both climate models and impact models to the carbon dioxide question.

One means of improving the compatibility of climate models and impact models is to experiment with combinations of them:

1. Using *the same scenario* for a particular region, consider the outputs (changes in biomass production, crop yield, etc.) produced by *different empirical and simulation impact models and agroclimatic indices*. This would indicate some of the uncertainty in long-term climate impact assessments that can be ascribed to uncertainties in impact models.

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*Degree-days are the units used in measuring accumulated temperature – a variable frequently adopted to predict the timing of crop development stages. Accumulated temperature is calculated as the integrated excess of temperature above a fixed datum (base temperature) over a period required for a specific phase of development. Commonly, the datum selected for a particular crop is the critical temperature above which plant growth commences and is maintained.

2. Using *different scenarios* for, say, a 2 × CO_2 atmospheric concentration for a particular region, consider the outputs produced by *the same impact model* (empirical, simulation, or agroclimatic index model). This would indicate some of the uncertainty in long-term climate impact assessments that can be ascribed to uncertainties in climate models.

3.5 Impact Assessments for GCM-Derived Scenarios

In the Workshop on Cold Margins at Villach, participants were requested to report on experiments relating to the assessment of impacts on agriculture and natural ecosystems by use of different empirical and simulation approaches for the same scenario (in this instance, participants were asked to use results from the Manabe and Stouffer (1980) experiments). A summary of the impact assessments is given below, but it should be emphasized that these are preliminary results that, for the most part, participants had not had the opportunity to verify. The summary should therefore be considered an interim report of work still in progress.

3.5.1 Changes in Natural Ecosystems

Emanuel and Shugart (1984) reported the development of a world life-zone map based upon the Holdridge Life-Zone Classification (Holdridge 1947). This classification attempts to represent the broad distribution of terrestrial ecosystem complexes as a function of annual temperature and precipitation. The world Holdridge Life-Zone Map was created by interpolating climate data from approximately 9,000 meteorological stations to a uniform grid of 0.5° latitude by 0.5° longitude on the Earth's land surface. If the map (Figure 4(a), p. 18) is used as a surrogate for natural vegetation zones, it is possible to consider the influence of climatic change on the distribution of terrestrial ecosystems. In a preliminary exercise a Holdridge Life-Zone Map has been derived for a 2 × CO_2 climate using the GCM results of Manabe and Stouffer (1980), who state that the climatic effects of a CO_2 doubling may be estimated by simply *halving* the results of their 4 × CO_2 scenarios. The simulated values of temperature change were interpolated to the 0.5° grid and added to values of the annual average biotemperature (average temperature, discounting unit-period temperatures below 0 °C) derived from meteorological data.

The changes in the distribution of life zones, and therefore of terrestrial ecosystems, indicated by this exercise are quite substantial (Figure 4(b), p. 19). However, the work is preliminary. Simulated changes in precipitation and the direct effects on vegetation of enhanced CO_2 levels are not considered. The surrogate vegetation zones themselves (i.e. the Holdridge classification system) have yet to be verified on the ground. Since this is strictly a climatic classification, other factors, such as soil properties, fire risk, and species competition, need to be overlaid on the basic classification in order to assess accurately the impact of climatic change on vegetation zones. Some of this further work is now proceeding.

A more specific case of linking an ecosystem zone to climate was explored by Kauppi and Posch (1984). They use a measure of accumulated temperature, the *effective temperature sum* (ETS) above a base of 5 °C, as an indicator of tree growth in the boreal forests of Finland. The ecological response to possible changes in temperature (in both its mean and its variability) has also been investigated (on the assumption that temperature is the main factor limiting growth) by plotting the predicted ETS (the "growth" surrogate) on nomograms. The index is simple to apply, although the same reservations apply as for the Holdridge example. Further validation of the index is necessary, not only in Finland but also in other taiga regions, such as northern Canada, before it can be usefully applied to climate impact studies of the boreal zone.

3.5.2 Changes in Crop Potential

G.D.V. Williams (1984) reported an application of Turc's climatic index of agricultural potential (CA) to estimate the effect of a CO_2-induced warming in the Canadian prairies. The index was applied with climatic data that had been derived (from averages for the period 1931–60) for the 110 intersections of whole-number latitudes and longitudes in the province of Alberta (Williams and Masterton 1983). Grid values of CA were compared with CA recalculated to simulate the effects of the Manabe and Stouffer (1980) climatic scenario of a quadrupled atmospheric concentration of carbon dioxide. Results indicated that in northern areas warming would be quite beneficial, while in dry, southeastern parts of the province it would depress production because of the greater moisture stress associated with warming. For the province as a whole the net result would be a rather small gain in biomass production if the climate warmed according to the $4 \times CO_2$ scenario.

An indication of the likely movements of boundaries that would be computed on the basis of the scenario was given by examining one component of Turc's CA, the heliothermic index (HT). Under $4 \times CO_2$ conditions, the thermal climate of Alberta (as expressed by HT) would be comparable to that of Nebraska today, 2,000 km to the southeast.

Further validation of Turc's index is still required, and the index does not consider winter survival of perennial and autumn-sown crops (important in the colder regions), or the probable fertilization effects of enhanced CO_2 levels, or the effects of more CO_2 on the efficiency of water use. However, the technique, if properly validated and extended to other regions, could offer valuable insights into climate impact on biomass productivity at the macroscale.

3.5.3 Changes in Empirically Modeled Crop Yields

Santer (1984) reported the use of outputs from two GCMs to model impacts on wheat yields and grass biomass potential in the European Economic Community. The GCMs – a model from the United Kingdom Meteorological Office (UKMO) (Mitchell 1983) and a model developed at the Goddard Institute for Space Studies (GISS) by Hansen *et al.* (1983) – both give climate scenarios for a doubling of atmospheric CO_2 and both produce results that differ from those obtained by Manabe and Stouffer. An unverified multiple-regression model (Hanus 1978) that predicts wheat yield as a function of monthly means of five climatic variables was used to estimate, for a number of sites, changes in wheat yield that might result from the climatic changes accompanying a doubling of atmospheric CO_2 concentration.

Considering the EEC as a whole (Greece and the United Kingdom were excluded from the analysis), both the UKMO and the GISS scenario lead to average decreases in wheat yields. On a country-by-country basis, both positive and negative effects occurred. The magnitude of even the largest of these changes (relative to current average wheat yields) was no greater than ±3%. Although interesting from the modeling point of view, the weaknesses of the empirical–statistical modeling approach should be borne in mind. This is particularly pertinent because, there being no major climatic factors limiting wheat growth in much of Europe, the statistical relationships between climate and yield are not always as well defined here as they are elsewhere. It is plainly inappropriate to use the Hanus model to estimate anything other than the broadest-scale impacts, and then only with the utmost caution.

3.5.4 Changes in Simulated Crop Yields

An alternative approach is to use simulation models. Santer (1984) reported experiments made with a model that uses meteorological data to calculate effective evapotranspiration and potential biomass production of grass (Santer *et al.* 1983). The model may be considered as analogous to some refinement of the Turc index, employing a month-by-month simulation approach, but also including a number of empirical relationships. An index of biomass potential has been mapped (again for the EEC) for the UKMO and GISS scenarios ($1 \times CO_2$ and $2 \times CO_2$). The $2 \times CO_2$ scenarios produce quite different effects on biomass potential. The UKMO scenario yields both negative and positive changes in biomass potential, ranging from $-3.5\,t\,ha^{-1}\,yr^{-1}$ in Sicily to $+2.6\,t\,ha^{-1}\,yr^{-1}$ in southwestern France. In contrast, the GISS scenario produces only positive changes in biomass potential, with the lowest increases in Greece and Italy (ca. $0.7\,t\,ha^{-1}\,yr^{-1}$) and the highest increases in eastern central areas (ca. $2\,t\,ha^{-1}\,yr^{-1}$). The different results are illustrated for the Federal Republic of Germany in Figure 5. They are due, in part, to the fact that there are quite substantial differences in the temperature and precipitation values of the two

GCMs for the 1 × CO_2 "baseline" case. Since neither GCM accurately represents the measured data set used to calibrate the impact model, the validity of the modeled impacts of the 2 × CO_2 scenarios is open to question.

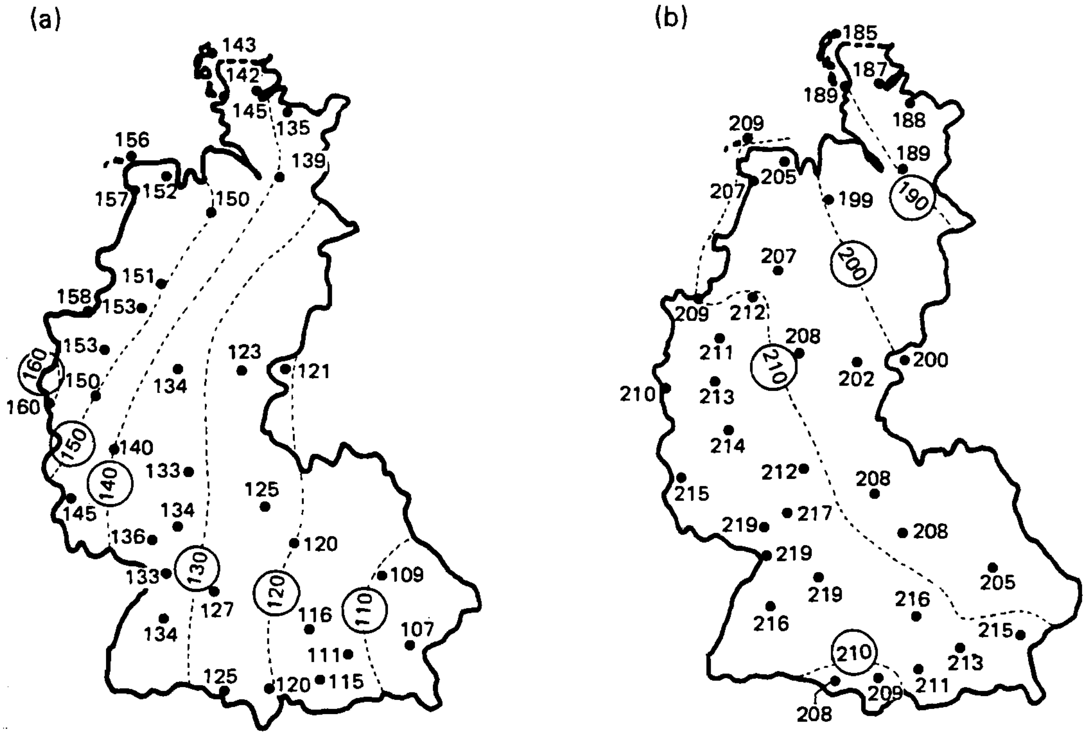

Figure 5 Changes in "biomass potential" ($g\ cm^{-2}\ yr^{-1}$) in the Federal Republic of Germany resulting from 2 × CO_2 experiments (relative to 1 × CO_2 "baseline" case) with (a) UKMO and (b) GISS general circulation models (Santer 1984).

Carter reported experiments with a cereal growth simulation model developed for winter wheat in England (Parry and Carter 1983). The model, which has been verified for lowland conditions, predicts the weekly amount of total dry-matter accumulation of winter wheat. Carter has employed it for upland areas, selecting meteorological stations at different elevations in northern England in order to assess the climatic potential for growth of winter wheat. GCM anomalies can be input to the model as monthly adjustments, either to values averaged over a period of years or to data for an individual year, and the model rerun for the scenario conditions. An advantage of using a simulation model of this kind is the ability to consider the direct effects on crop growth of enhanced CO_2, in addition to the indirect effects of CO_2-induced climatic changes.

Provisional results suggest that, for a fully irrigated crop, temperature increases predicted by all the 2 × CO_2 GCMs would reduce wheat productivity (total biomass) in lowland England, although the direct effects of a doubled CO_2 concentration could well offset this decrease. However, moving up the altitudinal gradient, positive temperature anomalies (within the range of current GCM predictions) would increase productivity by shortening the required growing time and by reducing the risks of frost and waterlogging. The increase would be augmented by the direct effect of increased CO_2 on rates of photosynthesis.

3.6 Impact Assessments for Instrumentally Based Scenarios

3.6.1 Changes in Empirically Modeled Crop Yields

Several studies have used composites of recent instrumental data to construct climate scenarios of a high-CO_2 world, employing natural (non-CO_2-induced) changes as analogs for the CO_2-induced case on the grounds that the character of the climatic change is apparently similar for the different types of forcing (Wigley *et al.* 1980, J. Williams 1980). More recently, attention has focused on the use of data corresponding to longer time scales (e.g. 20-year periods), rather than to individual years, as analogs because the processes that cause year-to-year climate variations may differ from those involved in the CO_2 case. Lough *et al.* (1983) have compared data from the warmest and coldest 20-year periods (namely, 1934–53 and 1901–20) and, by means of a regression model based on meteorological and yield data for several types of crop in England and Wales over 1885–1966, have estimated the changes in crop yields for the different scenarios.

Bergthorsson (1984) reported a study that relates hay yield to annual temperature (October–September) at Stykkisholmur (western Iceland) for the period 1901–75. The sensitivity of yield to temperature is illustrated by comparing the mean yield retrodicted for a cool period (1873–1922) with the mean yield for a "normal" period (1931–60). The estimated mean yield in the former period is 16% lower than that in the latter. Cool periods also make winter grazing more difficult, so the requirement for alternative foodstuffs increases hay consumption. Thus, as supply (yield) falls, so demand (consumption) rises – one consequence of which is to reduce the livestock-carrying capacity of the land (tested historically by Bergthorsson). Bergthorsson also makes similar estimates for a period indicative of a possible CO_2 warming. He assumes that the period is equally warmer than 1931–60 as that normal period was warmer than 1873–1922. Results indicate that in a warmer Iceland hay yields would increase by about 11% and livestock-carrying capacity by up to 27% relative to the normal.

3.6.2 Changes in Simulated Crop Yields

The limited variety and resolution of early instrumental data limit their applicability as inputs to simulation models. It is possible to obtain some indication of the response of crops to the conditions reflected by these data, although this usually involves a number of simplifying assumptions about those variables for which data are not available. For instance, Carter has adjusted monthly temperatures at five sites in northern England for an average year (1968–69) to values indicative of those in the late seventeenth century, by bridging across to Manley's (1974) central England record. He assumes a preindustrial atmospheric CO_2 concentration of 280 ppm, but retains all other values at their 1968–69 levels since no data are available for the earlier period. Nonetheless, after inputting to the cereal growth simulation model, the temperature and CO_2 variables give some indication of the climatic potential for wheat growth in conditions analogous to those of the so-called Little Ice Age. The slightly beneficial effect of cooler conditions on crop biomass at lowland stations is more than offset by the low CO_2 concentration. At upland stations, lower temperatures alone are sufficient to depress yields by extending the required growing time later into the year, when solar radiation receipt is lower.

3.6.3 Simple Probability Models

The concept of a change of climate producing a change in level of risk was discussed on pp. 11–12. Parry (1978) made use of this concept when mapping the probability of (oats) crop failure in southern Scotland. This analysis has now been extended back to the seventeenth century using central England monthly mean temperatures (Manley 1974, updated). Growing degree-days have been calculated (adjusted to relate to southern Scotland) for the period 1659–1981. The rate of temperature decrease with increasing elevation being known, it is possible to plot, for each year, the altitude at which the minimum number of growing degree-days required for oats ripening is achieved. This minimum was estimated for a particular variety of oats to be 970 GDD. Below this figure the crop can be presumed to have "failed." The result is a record of the altitudinal shift of hypothetical crop failure (Figure 6; Parry and Carter 1984).

Close inspection of this long record reveals marked contrasts between conditions in different periods. We can illustrate this by comparing the cool 50-year period, 1661–1710, with the warm 50-year period, 1931–80. The difference between frequencies of crop failure is substantial: for example, the frequency of single harvest failures in the cool period is three times that in the warm period, and the frequency of consecutive failures is eight times greater.

If we assume marginal areas for cropping to be those with failure frequencies of between 1 in 5 and 1 in 30 years, the marginal zone for the full record (1659–1981) lies between about 295 m and 350 m (lines B and C

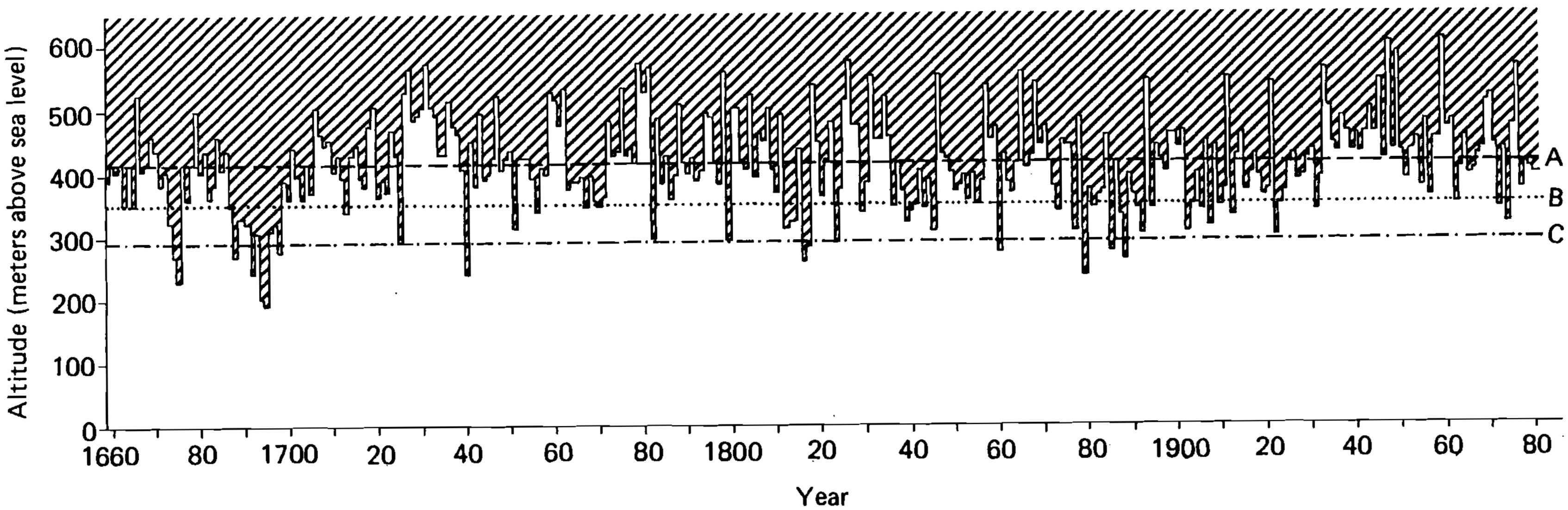

Figure 6 Hypothetical shift of oats crop failure with altitude, 1659–1981 (Parry and Carter 1984). A, mean altitude of crop failure; B, 1-in-5 failure frequency; C, 1-in-30 failure frequency.

in Figure 6). Comparison of the two 50-year periods mentioned above shows that the marginal zone moves from 240–310 m in the cool period to 325–395 m in the warm period, a shift of about 85 meters. In spatial terms, this can involve very large areas of change (over 1 million hectares, or one-sixth of Britain's unimproved moorland). When considered in terms of changes in the frequency of extreme events, the impact from apparently small changes in mean temperature can thus be substantial, especially in marginal areas.

Wigley has demonstrated that technological or other nonclimatic factors may, of course, also bring changes in risk. He has computed the frequency of harvest failure for winter wheat (expressed in terms of yield shortfall relative to expectation) for crop reporting districts in Kansas. Two periods are compared: 1932–59 and 1960–75. In both periods the frequency of harvest failure increases from east to west, but harvest failures are more frequent in the earlier period. This indicates a greater variability of harvest yields in the earlier period, which could be interpreted as reflecting greater climatic variability. However, analysis of climate data from southwest Kansas and south-central Kansas reveals no significant change of variability in those climatic variables correlated to wheat yield. Other factors (e.g. technology) are likely to be the prime cause of the later decrease in yield variability.

4 Conclusions

From the preliminary results presented and evaluated at the workshop, and from the workshop discussions of concepts and methods in climate impact assessment, it is possible to report a number of observations.

4.1 Observations

1. Present inadequacies of general circulation models should not discourage the assessment of impacts of possible CO_2-induced climatic changes. Preliminary studies should concentrate on refining the methods of impact assessment, the present emphasis being less on what the impacts are than on how we can assess them more precisely.

2. At the present stage of GCM development, instrumentally based scenarios are valid and realistic alternatives as inputs for impact analysis. They may also be used to supplement large-scale aspects of GCM output in order to produce more detailed scenarios of a high-CO_2 world.

3. A greater compatibility between GCMs and impact models can be promoted by increasing the reliability and detail of GCM outputs and by reducing the quantity and detail required of input data for impact models.

4. Further experiments are required that combine climate models and impact models. Two means of pursuing this objective are (a) to experiment with *different types of impact model* for *the same scenario* of CO_2-induced climatic change, and (b) to experiment with *different scenarios* using *the same impact model.*

5. Preliminary and, for the most part, unverified experiments of the type 4(a) indicate substantial changes in northern ecosystems and farming systems as a result of a doubling in the atmospheric CO_2 concentration.

6. The major policy preoccupation with respect to climatic change is the short-term impact, not the possible long-term trend. There are, therefore, advantages in expressing changes in climate as changes in the return period of specified extremes (instead of changes in the mean values of climatic variables), particularly because changes in mean values have strongly nonlinear effects when re-expressed in terms of the return period of extreme events.

7. There are advantages in evaluating climatic changes as changes in risk. Probability models of climate impact can be useful here, enabling policies of response to be matched to changes in the likelihood of occurrence of climatic events. We need, therefore, to measure frequencies of such events for natural climatic conditions and use these frequencies as a base upon which to superimpose effects such as those of CO_2-induced warming to obtain modified frequencies reflecting such conditions. A policy of attempting to match technological change to climatic change should focus as much on rates of change in these frequencies as on rates of change in mean climatic functions.

8. The important and overriding issues described frequently by the climatologist as "noise" (technology, social factors, etc.) must somehow be included in, not excluded from, any conclusions concerning climate impact. This could be facilitated by making efforts to combine direct and adjoint methodologies.

9. While marginal areas can be appropriate "laboratories" for initial assessments of climate impact and for refining our research methods, the net major impact may come in areas of food production that are not currently marginal, and which could lose some of their viability as a result of adverse changes in climate. Parallel progress should be made in impact studies in both marginal and non-marginal areas.

10. The spatial shift of isopleths or boundaries can be used to define areas affected by climatic change.

11. The workshop addressed only terrestrial ecosystems and agriculture. Increased attention should be given to potential impacts of climatic change on water resources and fisheries.

4.2 Recommended Case Studies

There have so far been insufficient case studies and few substantive results from assessments of the impact of climatic change. More case studies should be undertaken, selected according to the hypothesized extent of the impact or according to their global significance (e.g. in food production). For cold margins, the following are recommended:

1. Tundra areas, where rising temperatures may lead to permafrost melting (e.g. northern Canada and Alaska).
2. The tundra–taiga interface or northern timberline (e.g. Finland), where temperature changes can have a pronounced effect on forest ecosystems, while water is not a limiting factor.
3. The tundra–agriculture interface, where temperature changes (and little constraint from lack of precipitation) have a dominant effect on yields. Iceland, which has a long and detailed set of meteorological and crop yield data, could provide a particularly suitable case study.
4. Mountainous areas where changes in the snow line could affect water supply for irrigation, e.g. the Sierra Nevada Mountains and water supply in the Central Valley of California, USA.
5. Mountainous areas where the frequency and timing of frosts may greatly influence the risk of damage to crops (e.g. the Peruvian Andes).
6. Comparative case studies of areas with analogous climates and similar degrees of climate-induced variability in crop yields, but with contrasting technological responses, e.g. Turkish Anatolia and the US Pacific Northwest.

Postscript

Several of the observations and recommendations reported here have been incorporated into a research project at the International Institute for Applied Systems Analysis. This project, entitled *Integrated Approaches to Climate Impacts: The Vulnerability of Food Production in Marginal Areas*, is being sponsored by IIASA and the United Nations Environment Programme as part of the World Climate Impact Programme.

In line with recommendations from the Villach meeting, the research focus is on the shifts of limits or boundaries of agricultural potential that can occur as a consequence of given changes or variations of climate. Furthermore, the emphasis is on analyzing climate impacts in terms of changes in the range of farming options and changes in the risk of disruptive climatic extremes. Case studies are under way in areas recommended at the Villach meeting: at the tundra–agriculture interface in Iceland, at the northern timberline in Finland, and in mountainous areas: in the UK uplands, European Alps, and high Andean basins. With reference to observation (4), different forms of analysis are being employed to assess impacts on agriculture for a number of climate scenarios. The focus of this work is Saskatchewan, Canada. A similar approach is being taken in case studies in semiarid areas, for example in central India, northeast Brazil, and the southern USSR.

References

Baird, A., O'Keefe, P., Westgate, K., and Wisner, B. (1975) Towards an explanation and reduction of disaster proneness. *Occasional Paper* 11, Disaster Research Unit, University of Bradford, UK.

Bergthorsson, P. (1984) Sensitivity of Icelandic agriculture to climatic variations – Some case studies. In: *Climatic Change*, special issue: Measuring Sensitivity to Climatic Change (in the press).

Clark, W.C., Holling, C.S., and Parry, M.L. (1984) The responses of societies to climatic change. In: *Climatic Change*, special issue: Measuring Sensitivity to Climatic Change (in the press).

Emanuel, W.R., and Shugart, H.H. (1984) The Holdridge Life-Zone Classification: Climatic change and the distribution of terrestrial ecosystems. In: *Climatic Change*, special issue: Measuring Sensitivity to Climatic Change (in the press).

Flohn, H. (1981) Life on a warmer Earth: Possible climatic consequences of man-made global warming. *Executive Report* ER-81-3. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Hansen, J., Russell, E., Rind, D., Stone, P., Lacis, A., Lebedeff, S., Ruedy, R., and Travis, L. (1983) Efficient three-dimensional global models for climate studies: Models I and II. *Monthly Weather Review* 3: 609.

Hanus, H. (1978) Vorhersage von Ernteerträgen aus Witterungsdaten in den Ländern der EG (Forecasting of crop yields from meteorological data in the EC countries). *Agrarstatistische Studien* (Agricultural Statistical Studies) No. 21. EUROSTAT, Luxemburg.

Holdridge, L.R. (1947) Determination of world plant formations from simple climatic data. *Science, NY* 105: 367–368.

Kauppi, P., and Posch, M. (1984) Sensitivity of boreal forests to climatic change. In: *Climatic Change*, special issue: Measuring Sensitivity to Climatic Change (in the press).

Kellogg, W.W., and Schware, R. (1981) *Climate Change and Society: Consequences of Increasing Atmospheric Carbon Dioxide*. Boulder, Colorado, USA: Westview.

Köppen, W. (1936) Das geographische System der Klimate. *Handbuch der Klimatologie*, ed. W. Köppen and R. Geiger, vol. 1, part C. Berlin: Bornträger.

Lough, J.M., Wigley, T.M.L., and Pallutikof, J.P. (1983) Climate and climatic impact scenarios for a warmer world: Part I, Europe. *Journal of Climate and Applied Meteorology* 22: 1673–1684.

Lozano, E.E. (1968) Location and region: Agricultural land use in an integrated economy. *Harvard Papers in Theoretical Geography*, Geography and the

Properties of Surfaces Series, No. 12. Harvard University, Cambridge, Massachusetts, USA.

Manabe, S., and Stouffer, R.J. (1980) Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere. *Journal of Geophysical Research* 85: 5529–5554.

Manley, G. (1974) Central England temperatures: Monthly means, 1659 to 1973. *Quarterly Journal of the Royal Meteorological Society* 100: 389–405.

Mitchell, J.F.B. (1983) The seasonal response of a general circulation model to changes in CO_2 and sea temperature. *Quarterly Journal of the Royal Meteorological Society* 109: 113–152.

Parry, M.L. (1978) *Climatic Change, Agriculture and Settlement*. Folkstone, UK: Dawson.

Parry, M.L. (1984) The impact of climatic variations on agricultural margins. In: R.W. Kates (ed.), *Improving the Science of Climate Impact Assessment*. New York, USA: Wiley (in the press).

Parry, M.L., and Carter, T.R. (1983) Assessing impacts of climatic change in marginal areas: The search for an appropriate methodology. *Working Paper* WP-83-77. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Parry, M.L., and Carter, T.R. (1984) The effect of climatic fluctuations on the probability of impact from extreme events in marginal upland areas. In: *Climatic Change*, special issue: Measuring Sensitivity to Climatic Change (in the press).

Santer, B. (1984) The impacts of a CO_2-induced climatic change on the European agricultural sector. In: *Climatic Change*, special issue: Measuring Sensitivity to Climatic Change (in the press).

Santer, B., Schwieren, G., Schnell, C., Meinl, H., Bach, W., Juerg, H.J., and Knottenberg, H. (1983) Socioeconomic impacts of climatic change. *Project Status Report*, April. Dornier System GmbH, Friedrichshafen, FRG.

Science Council of Canada (1976) Population, technology and resources. Report No. 25. Science Council of Canada, Ottawa.

Sly, W.K. (1970) A climatic moisture index for land and soil classification in Canada. *Canadian Journal of Soil Science* 50: 291–301.

Stommel, H. (1963) Varieties of oceanographic experience. *Science, NY* 139: 572–576.

Turc, L., and Lecerf, H. (1972) Indice climatique de potentialité agricole. *Science du Sol* 2: 81–102.

Wigley, T.M.L., Jones, P.D., and Kelly, P.M. (1980) Scenario for a warm, high-CO_2 world. *Nature* 283: 17–21.

Wigley, T.M.L., and Warrick, R. (1984) Climate impact assessment. *Nature* (in the press).

Williams, G.D.V. (1984) Estimated bioresource sensitivity to climatic change in Alberta, Canada, a dry cold-margin area. In: *Climatic Change*, special issue: Measuring Sensitivity to Climatic Change (in the press).

Williams, G.D.V., and Masterton, J.M. (1983) An application of principal component analysis and an agroclimatic resource index to ecological land classification for Alberta. *Climatological Bulletin* 17: 3–28.

Williams, J. (1980) Anomalies in temperature and rainfall during warm Arctic seasons as a guide to the formulation of climate scenarios. *Climatic Change* 2: 249–266.

WMO/ICSU/UNEP (1981) *On the Assessment of the Role of CO_2 on Climate Variations and their Impact*. Meeting of experts, Villach, Austria, November 1980. Geneva: WMO.

Appendix

Participants of the Workshop on Cold Margins

Dr. M.L. Parry (Chairman), International Institute for Applied Systems Analysis, Laxenburg, Austria
Mr. T.R. Carter (Rapporteur), International Institute for Applied Systems Analysis, Laxenburg, Austria
Mr. P. Bergthorsson, Icelandic Meteorological Office, Reykjavik, Iceland
Dr. W.R. Emanuel, Oak Ridge National Laboratory, Tennessee, USA (reporting on joint work with H.H. Shugart)
Dr. P. Kauppi, International Institute for Applied Systems Analysis, Laxenburg, Austria (reporting on joint work with M. Posch)
Dr. P. Oram, International Survey for National Agricultural Research (ISNAR), The Hague, The Netherlands
Dr. W. Sanchez, Universidad Nacional Agraria, Lima, Peru
Mr. B. Santer, Dornier System GmbH, Friedrichshafen, Federal Republic of Germany
Professor W.C. Thomas, University of Alaska, Fairbanks, USA
Dr. G.D.V. Williams, Atmospheric Environment Service, Downsview, Ontario, Canada

Observers

Dr. Antonovski, c/o USSR State Committee for Hydrology and Control of the Natural Environment, Moscow, USSR
Mr. E. Bobek (Austrian Government), Ministry of Health and Environment, Vienna, Austria
Professor B. Bolin, International Meteorological Institute, University of Stockholm, Sweden
Dr. W.C. Clark, Institute for Energy Analysis, Oak Ridge, Tennessee, USA
Dr. B. Döös, International Meteorological Institute, University of Stockholm, Sweden
Professor L. Gates, Oregon State University, Corvallis, USA
Dr. G.N. Golubev, United Nations Environment Programme, Nairobi, Kenya
Mr. H. Haider (Austrian Government), Ministry of Health and Environment, Vienna, Austria
Dr. C.P. Hekstra, Ministry of Environment, The Hague, The Netherlands
Professor C.S. Holling, International Institute for Applied Systems Analysis, Laxenburg, Austria

Dr. J. Maini, International Institute for Applied Systems Analysis, Laxenburg, Austria

Professor T.F. Malone (ICSU), Butler University, Indianapolis, Indiana, USA

Dr. M.C. McCracken, University of California, Livermore, USA

Dr. G. McKay (WMO), Atmospheric Environment Service, Downsview, Ontario, Canada

Mr. T. Potter, World Meteorological Organization, Geneva, Switzerland

Mr. P.E.O. Usher, United Nations Environment Programme, Nairobi, Kenya

Mr. C.C. Wallen (UNEP), c/o World Meteorological Organization, Geneva, Switzerland

Dr. R. Warrick, International Meteorological Institute, University of Stockholm, Sweden

Professor R. Watts, International Institute for Applied Systems Analysis, Laxenburg, Austria

Dr. T.M.L. Wigley, Climatic Research Unit, University of East Anglia, Norwich, UK