

WORKING PAPER

ON THE PRACTICAL IMPLICATIONS OF THE CARBON DIOXIDE QUESTION

William C. Clark

August 1985
WP-85-43

Prepared for the United Nations Environmental Programme, in support of the WMO/ICSU/UNEP International Assessment Conference on the Role of Carbon Dioxide, and of Other Radiatively Active Constituents, in Climate Variations and Associated Impacts — held in Villach, Austria, 9-15 October 1985

PUBLICATION NUMBER 26 of the project:
Ecologically Sustainable Development of the Biosphere

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FOREWORD

There is no doubt that atmospheric concentrations of CO₂ and other "greenhouse" gases have been increasing and will continue to do so for the next several decades at least. Climate models predict that this will lead to a significant rise in world temperatures, particularly in polar regions, during the next 50 - 100 years. However, there is uncertainty about the timing and magnitude of the warming, as well as about the strategies that ought to be adopted to try to reverse the trend, or at least to cope with it.

This Working Paper by William Clark is a perceptive contribution to these latter policy questions. It was commissioned as a keynote presentation at the WMO/UNEP/ICSU Assessment Conference on the Role of Carbon Dioxide and of other Radiatively Active Constituents, in Climate Variations and Associated Impacts, to be held in Villach, Austria, 9 - 15 October, 1985.

Dr. W.C. Clark was Editor of the widely acclaimed *Carbon Dioxide Review* (Oxford University Press, 1982). He came to IIASA in the summer of 1984 and is Leader of the Project on Ecologically Sustainable Development of the Biosphere. One of his special interests is the search for better methods of applying incomplete scientific knowledge to environmental policy formulation. In my view, Dr. Clark has been particularly successful in this paper in providing a new perspective concerning the carbon dioxide issue.

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1. Introduction

Questions raised by the increasing atmospheric concentration of carbon dioxide have been intensely studied over the last decade. Several recent reports have summarized the scientific findings of this work. The question remains, So what? What are the practical implications for people?

This paper seeks to develop a useful framework for reflecting on how answers to the "So what?" question might look, and on how we might go about getting them. It does not attempt to provide the answers themselves, nor to summarize the answers that others have given.

Some justification for this approach is warranted. Policy makers and people in general have become increasingly impatient with a scientific community that always seems willing to raise possibilities of terrifying things that might go wrong, but never seems willing to commit itself on how seriously the possibilities should be taken, or on what action they require. Why shouldn't this essay, or ideally some official document, finally attempt a "bottom line" assessment of the practical implications of the carbon dioxide question? Can general frameworks of the sort proposed here really provide a more useful approach?

My own response to this challenge is based on four fundamental characteristics that stand out in recent reviews of the carbon dioxide question (1):

* The carbon dioxide issue is simultaneously local and global. All countries of the earth are potentially affected by carbon dioxide-related environmental changes; no country can do much unilaterally to forestall those changes. The nature, severity and perception of carbon dioxide-related impacts will nonetheless differ greatly among peoples and places. A useful discussion of the practical implications of the carbon dioxide question must serve these differing local and national perceptions of an intrinsically global phenomenon.

* The environmental changes related to carbon dioxide will take place over decades and centuries. The world and its environment can be expected to change dramatically over such periods, significantly altering the context within which carbon dioxide-related changes will be experienced and social responses will be assessed. Also, social values are certain to change. A useful discussion of practical implications of the carbon dioxide question must contend with those long-term background changes.

* Possible causes and effects of carbon dioxide-related changes are intimately linked to other problems of energy, agriculture, population and environment. The linkages are physical, biological, economic and political. Action taken on other problems like acid rain will reshape the carbon dioxide question; actions taken on carbon dioxide will affect those other problems in turn. The practical implications of the carbon dioxide question cannot usefully be addressed without accounting for linkages to related problems and their solutions.

* Finally, uncertainty dominates every aspect of the carbon dioxide question, from emission rates through environmental consequences to socioeconomic impacts themselves. Assessments that do not address these fundamental uncertainties will be extremely misleading. Useful policy analyses must find ways of characterizing the implications of our incomplete scientific

knowledge. They must highlight the impossible and barely possible as well as the most probable impacts of the increasing concentration of atmospheric carbon dioxide.

"The" carbon dioxide problem has much in common with other grand concerns like "the" population problem or "the" problem of economic development. Such multifaceted, complex problems can be better described as "messes". Experience with messes suggests that any attempt to resolve them will be futile if it presumes the existence of a few key "decisions" or "decision makers" (2). Like the population and development messes, carbon dioxide will have different practical implications for different sectors of the economy, different nations, and different generations. Each of these will make its own interpretation of costs, benefits, uncertainties and suitable responses. Most of whatever social responses do occur will consist of each group's incremental adjustments to its own ongoing activities, taken in the context of its own agenda of other problems and solutions. In such a real world mess of multiple actors and actions, no-one's needs will be served by single "bottom line" assessments that purport to speak for all people and all times.

More useful would be a set of effective tools and approaches that individual nations and interest groups could employ in coping with the practical implications that the carbon dioxide question might hold for them (3). Collaborative use of the tools to shape regional or even global responses would be possible, but independent local responses would be facilitated as well. The tools most needed would help to shape incomplete scientific understanding so that it can be critically applied in the construction of appropriate social responses. They would be useful for expanding the conventional menu of possible social responses and for characterizing their respective strengths and limitations. They would provide means of addressing, if not resolving, each of the fundamental characteristics of the carbon dioxide question listed above. Ideally, the tools could also be used to fashion a commonly accepted, relatively unbiased perspective from which the different interests in the carbon dioxide debate would better comprehend each others' concerns and preferred actions.

Several recent studies have begun to construct important components of the set of tool needed for coping with practical implications of the carbon dioxide question. Much of the most significant recent work is drawn together in a report by the Scientific Committee on Problems of the Environment (SCOPE) on Improving the Science of Climate Impact Assessment (Kates et al., 1985). The SCOPE study reviews the strengths, weaknesses, and accomplishments of a wide range of approaches to understanding the implications of climate variation and change for society. The reader in search of a reasonably comprehensive bibliography of relevant climate work would do well to start with this study. An even fuller computerized bibliography is being prepared by R. Warrick (4). For the non-climatic aspects of the carbon dioxide question, no comparable tool kit exists. A good review of the most useful methods for general environmental impact assessment and management is given by Beanlands and Duinker (1983).

Despite some gratifying progress, however, the tool kit needed for societies to cope effectively with the carbon dioxide question is far from complete. For example, even the best policy analyses and assessments have tended to take their questions from the immediate concerns of natural scientists studying carbon dioxide, and to concentrate on providing answers. But as Thomas Schelling (1983) has shown in the most perceptive treatment yet written on social implications of the carbon dioxide question, this approach leaves many of the most practically relevant questions unformulated and unstudied. Missing

are the broader perspectives that could help to locate the carbon dioxide question within the context of related economic trends, political agendas, and environmental problems. It is these contextual issues that will both shape impacts of carbon dioxide-related environmental changes on societies, and provide societies with their options for dealing with those impacts. This paper attempts to characterize some of the missing perspectives and to provide some of the tools needed for working with them.

We have heard much in recent years of what scientists want to know about the carbon dioxide question. The agenda for basic research seems well in hand. Less clear, however, is what policy makers and publics want to know, and the extent to which their needs will be met by the basic research agenda. In this essay I will attempt to complement existing scientific perspectives with one that starts from a political viewpoint. One of my primary goals will be to characterize changes in present programs of scientific research and policy analysis that will be required if more useful answers to the political questions are to be provided. Section 2 therefore explores how we might come better to understand the relevant political contexts of the carbon dioxide question: How is carbon dioxide linked to other problems and solutions on the political agenda? Section 3 attempts an analogous treatment of the environmental context: How is carbon dioxide linked to other environmental problems, properties, and policies? Section 4 outlines possible social responses that could significantly alter the practical implications of the carbon dioxide question: What are the options for action? Section 5 sketches a framework for assessing the likely effectiveness and limitations of those responses, using knowledge of characteristic time and space scales. Section 6 proposes several areas for future work that might significantly improve societies' abilities to make appropriate responses to the carbon dioxide question.

2. The Carbon Dioxide Question in its Political Contexts

Scientific investigations of the carbon dioxide question have raised an ever increasing number of possible implications for society. Since few if any of those implications entail unambiguous direct impacts on today's life, societies' concerns have largely reflected those of the scientists. But as the debate over carbon dioxide and its implications has evolved, publics and their politicians have increasingly come to view their concerns about carbon dioxide within a broader context that incorporates political as well as scientific perspectives. The scholarly research agenda has not, in general, kept pace with these changing and varied perceptions of the carbon dioxide question. As a result, a gap has widened between the questions that the experts most want to address, and the questions that everyone else most wants to have answered.

Clearly, scholarly inquiry on a matter as complex and wide ranging as that posed by the carbon dioxide question should not be channeled entirely along lines defined by present political perceptions. Changes in our scientific understanding of the carbon dioxide question should continue to shape public perceptions as they have in the past. But societies' actions or inaction will ultimately take place within a context of other political problems and solutions. Scholarship that ignores or misperceives that context will become increasingly irrelevant to what is actually done with respect to carbon dioxide. An overdue step in efforts to address the practical implications of carbon dioxide is therefore to document the questions that most concern the politicians, businessmen, financiers, and private citizens who will be the real actors in any social response.

Even a casual survey of societies' concerns about carbon dioxide-related issues indicates that they span an extraordinary range of perspectives. Some nations with Arctic territories, for example, have paid great attention to possible benefits of carbon dioxide-induced environmental changes (eg. Hare 1981). Several nations of the tropics, on the other hand, have objected to what they feel is the misplaced emphasis of international organizations on long term climate changes as opposed to short term variability (1). From yet another perspective, a former Indian foreign service officer has argued that a long term focus on climate change is appropriate, but that the emphasis should be on policies that would cool the tropics, not ones that would prevent warming of the temperate zones (Bandyopadhyaya 1983).

The presence of scientists in senior policy positions of the Soviet Union has produced an active and sophisticated high level discussion relevant to the practical implications of the carbon dioxide question. For example, responding to a question of whether modern societies had not become reasonably independent of climate conditions, a member of the Presidium of the Supreme Soviet commented:

In fact... present human society needs much more precise assessment of climatic conditions in order to create a more rational strategy of development. Many of the activities we engage in, including irrigation and others, are projected for a long term period in the future. Errors in assessment of climatic resources and their possible changes will lead to increasing losses (Federov 1979).

The same senior policy maker noted that

From the social and political point of view it is necessary to consider whether it is possible to produce climate changes in some region of the earth as a result of actions in some other region. Is it possible that one country, on account of actions on its own territory, could have an impact on the climate of other countries? (Federov 1979).

He added that though such events seemed to him to have a low probability, they nonetheless had to be considered as a possible source of international tensions (2). Other Soviet policy makers have consistently emphasized the practical benefits of improved understanding of climate change. The Vice Chairman of the Council of Ministers has written:

The complex investigation of... global atmospheric and oceanic circulation processes will make closer the time when science will be able to forecast climatic variations and long term weather changes thus improving the life of people on earth (Marchuk 1979).

And the Chairman of the State Committee for Hydrometeorology and Control of the Natural Environment has repeatedly argued that because of the importance of detecting possible global climate changes, an

urgent measure [is] the organization of an international system of complex monitoring of the atmosphere, ocean, and biosphere (Izreal 1984).

A more systematic and critical survey would doubtless identify additional and comparably diverse perspectives. But such a survey would also probably reveal a number of more subtle political contexts for the carbon dioxide question. I base this statement on my own review of what members of the United States Congress want to know when they think about carbon dioxide. (I focuss on US policy makers only because extensive documentation reflecting their concerns was most readily accessible to me). My analysis covered questions asked by Congressmen of scientists and other expert witnesses during formal hearings held over the last decade on carbon dioxide, climate, and related issues (3). Several of the more significant concerns running through their questions are summarized below.

Winners and losers: Congressmen emphasize the geopolitical significance of an environmental change that could be felt worldwide, with some nations benefiting and others suffering. Their interest is not in global averages, or "bottom line" assessments, but rather in who -- especially who among the superpowers -- could win and lose what:

"[I]n assessing the importance and severity of the problems for us... I think it is not particularly useful to average in the good effects with the bad effects and conclude that everything comes out in the wash." (Gore 1980: 74)(4).

"I want to focus ... in a more narrow way for the policy makers on this committee: What happens to the United States...? [H]ow likely is it that our grain belt will shift northward to Canada?" (Gore 1981: 33,74).

"How would [carbon dioxide] affect China?" (Scheuer 1981: 116).

"[A Soviet article says that effects will be] beneficial to them. How would you respond to that?" (Bumpers 1980: 110).

Responses, not impacts: Virtually without exception, the Congressmen assume that societies will respond to any carbon dioxide-induced environmental changes that do occur. They are less concerned with asking what are the environmental (or economic or social) impacts, than with identifying and evaluating actions that could modify those impacts. This interest in the options for effective social response is wide-ranging:

"Obviously in periods of past climate change the human race has been able to make adjustments that allowed it to survive. In your opinion, is human society today, with its greater population and greater technical resources and complexity, more or less adaptable than in earlier historical periods? ... I am interested in the kinds of flexibility that you think could be built into our social and economic structure... What kinds of systems can we develop to help us counteract the climatic variations?" (Brown 1976: 185, 216).

"Can society adapt to increasing levels of carbon dioxide?" (Ribicoff 1979: 29).

Not surprisingly, however, policy makers' specific questions about societies' response capabilities focus on the agricultural impacts and rises in sealevel emphasized in scientific assessments of the carbon dioxide question:

"[S]uppose that weather conditions were to change, and we were faced with a worldwide shortage that extended over a considerable period of time... Have we contemplated the appropriate policies to deal with that kind of situation?" (Brown 1976: 148).

"Would it not be a prudent approach at this time to produce those types of hybrid plants that would be adaptable?" (Myers 1976: 154).

"There are many places in the world, particularly in the developing countries, where the cost of relocating populations that are located near oceans would be painful, cruel, and nearly impossible. Those kinds of dislocations ... can't be faced and they have potentially devastating economic and social and political implications... [T]he loss is not just crop loss, but vast human destabilization, and that goes far beyond the cost of crops or forest lands or grazing lands." (Scheuer 1981: 85).

Energy responses: The implications of carbon dioxide for energy policy attract more Congressional questions than any other topic. Many of those questions are straightforward attempts to understand how alternative fuels or use rates differ in terms of their carbon dioxide releases:

"We've been told that decreasing oil use may help. But you tell us that coal produces 1.7 times as much carbon dioxide as oil." (Gore 1982: 3).

"Can you comment on the relative impact of biomass fuel sources, as opposed to fossil fuel and alternatives to those systems?" (Emery 1976: 141).

"If we were to ... begin an aggressive reforestation program [and] use the net annual growth as fuel... we could make at least a minor effect on

reversing the present trend lines. Now the only thing that bothers me is, I haven't the vaguest idea what kind of numbers we are talking about... I do not know what the overall capability in terms of equivalent amounts of coal, for example, are from increasing the net biomass resource." (Brown 1981: 77-8).

"If we [the U.S.] were to double coal production... what do you feel would happen to the atmosphere? Is it anything we have to be concerned about?" (Percy 1979: 32).

"[I]f we were able to stabilize the use of fossil fuel at our current level internationally, would you anticipate any difficulty by the year 2000?" (Bumpers 1980: 132).

Energy strategy: More often than not, however, the Congressional questions are looking for more general guidance on how alternative energy strategies differ in their overall environmental impacts:

"How long do you think it would take to ... quantify the effect of long-term energy use programs on the environment, both here and in the Soviet Union and Western Europe?" (Scheuer 1976: 33).

"What form of energy production would have the least amount of effect on climate?" (Winn 1976: 129).

"If you had to choose ... between a coal-fired power plant and a nuclear power plant, which one would you select?" (Tsongas 1980: 40).

"If we support and develop energy programs with prospective dangers, what should we be doing in the interim to lessen those dangers?" (Ribicoff 1979: 18).

Energy advocacy: Finally, concerns about carbon dioxide have been invoked by Congressmen to advocate nonfossil energy sources running the spectrum from nuclear breeder reactors to conservation:

"[W]hat safeguards would any of you recommend be put into that synthetic fuel legislation to insure that we develop alternate sources; to promote diversity, and not commit ourselves to one energy source to the exclusion of other, more environmentally satisfactory sources?" (Ribicoff 1979: 34).

"[I]sn't the political response to all these scientific findings ... to make use of every bit of energy as efficiently as possible, to conserve as much as possible, and to convert to nonfossil energies as quickly as possible, and add reforestation?" (Bumpers 1980: 132).

"We are faced with potentially catastrophic consequences, requiring balanced, informed energy policy. It seems to me there is good evidence for advancing the nuclear option, like Europe, as well as a strong liquid fuels [from biomass] program." (Walker 1982: 6).

"I believe we ought to discard all of the smaller options of trying to adapt to it like maybe giving some travel tax credit to those people in Florida who have to move their homes or adapting agricultural policy in Nebraska to come up with sand flea farms... [Should we not] concentrate instead on boxing the large problem straight in the eye, recognizing its global cause and selecting the one obvious solution for the problem...

which is a rather dramatic change in the energy consumption patterns world wide ... ie. accelerating a moving away from fossil fuel?" (Gore 1981: 75).

Questions of timing: Before leaving the Congressmen's focus on policy actions and other responses it is worthwhile to emphasize their pervasive interest in related questions of timing. When impacts might occur, when sufficient information will be available to predict them, and when remedial actions would have to be initiated are all treated as questions of the utmost practical significance:

"[T]he problem of coastal flooding ... is a matter of grave importance. When would that come into effect?" (Ribicoff 1979: 36).

"When can you make public policy recommendations? When will the data base be sufficient?" (Scheuer 1982: 15).

"How soon do we have to act?" (Scheuer 1982: 10).

"[H]ow long would it take to move to the solar sources you recommend? Can we beat the problem that way, or do we need to go with a current technology such as nuclear?" (Carney 1982: 5).

Uncertainty: An examination of Congressional questions about carbon dioxide also shows that some aspects of basic scientific understanding are of great concern to policy makers. Foremost among these is the question of technical uncertainties and disagreements among scientists. Congressmen seemed less concerned with learning about the specific character or magnitude of these uncertainties, than with knowing how long it would take to resolve them. Their implicit assumption that sufficient time and research will resolve the politically significant uncertainties of the carbon dioxide debate was not contested by any of the scientists testifying at the hearings:

"What areas of uncertainty remain?" (Gore 1982: 3).

"How soon are you going to have a data base sufficiently reliable to put some of these factors into our public policy making machinery on development of new sources of energy?" (Scheuer 1981: 90).

"You said we can afford to wait for impacts studies until you have a core of basic knowledge. But it is this central core that's going to trigger action. Its holding up the decision making process... When can you make public policy recommendations? When will the data base be sufficient?" (Scheuer 1982: 14-15).

"Don't we know enough? Can't we begin taking corrective efforts...? Now is the time to begin reaching out for political will, to go to the next stage." (Walker 1982: 1).

Thresholds and surprises: A second area of basic science of great concern to the Congressmen is the matter of thresholds. They want to know whether the increasing carbon dioxide concentration might one day push the natural system across a threshold and confront policy makers with a situation that is suddenly deteriorating so rapidly that it swamps societies' adaptive capabilities. This question dominates all others dealing with the scientific understanding of carbon dioxide:

"[You] remarked that the range of effects between present concentrations and doubling covers no significant thresholds and our conclusions are not completely dependent on the timing [of carbon dioxide increases]. If there doesn't seem to be a significant effect to doubling, where is the critical point? Where do we run into a real problem?" (Scheuer 1980: 31).

"Another type of what might be called a threshold: is there any evidence that you reach a point where the ocean uptake ceases or diminishes drastically... because of saturation effects?" (Brown 1981: 82).

"Is there a trigger point when the dynamics take over?" (Gore 1982: 10).

In summary: A systematic documentation of the full range of political perspectives on the carbon dioxide question would almost surely enrich our ability to design, evaluate, and implement social responses. In the meantime, even the preliminary perspectives highlighted here suggest some potentially useful directions for thinking about the practical implications of the carbon dioxide question.

Perhaps the most important of these is that policy makers seem to be much more interested in responses than in impacts. They want to know what difference alternative actions could make to the practical implications of the carbon dioxide question. They do not want, and probably would be very skeptical of, the sorts of detailed cost-benefit or yield reduction assessments that continue to entrance most segments of the academic impact assessment community. The profound implications of this action orientation for efforts to design useful research on the carbon dioxide question will be a central theme of the remainder of this paper.

More generally, it is clear from even the sample of policy maker opinions cited here that the carbon dioxide question reaches into many dimensions of political life. Its practical implications are intimately associated with pressing problems of East - West and North - South relations, of energy and agricultural policy, and of the need for long range social planning. A useful understanding of what the carbon dioxide question means for societies must at least attempt to address these broader contextual issues.

3. The Carbon Dioxide Question in its Environmental Contexts

The previous section suggested that when publics and their politicians think about the carbon dioxide question, they do so primarily in terms of alternative activities that would change its practical implications. To a somewhat lesser extent, they think in terms of the sensitivity of important environmental properties like climate and sealevel to carbon dioxide-related environmental changes.

We know, however, that many of the policy responses discussed in the political context of the carbon dioxide question would also have important practical implications for environmental problems otherwise unrelated to carbon dioxide. For example, many of the alternative energy strategies considered by the US Congressmen quoted in section 2 would have significant implications for acid rain concerns as well. In addition, the environmental properties that concern policy makers in the context of the carbon dioxide question are often influenced by other human disturbances. A currently popular example is the important role of "greenhouse" gases other than carbon dioxide in any future climate change (Cicerone et al., 1985).

The political perspective is ill-suited to perceive the often complex linkages forged by physical, chemical, and biological processes between policy actions and the state of the environment. Nonetheless, it is precisely those linkages that must be understood for the design of effective social responses to the practical concerns raised by carbon dioxide and related questions. In addition to the political perspective called for earlier, efforts to deal with the practical implications of carbon dioxide therefore require tools for viewing policy makers' concerns about carbon dioxide within their overall environmental contexts.

An atmospheric example: One step towards the kind of synoptic environmental framework that is needed has been developed by Drs. Paul Crutzen of the Max-Planck Institute for Chemistry, and Thomas Graedel of ATT-Bell Laboratories, as part of their contribution to the program on "Ecologically Sustainable Development of the Biosphere" being carried out at the International Institute for Applied Systems Analysis (1). Crutzen and Graedel focus on the atmospheric environment and the ways in which chemical processes influence its nature, composition, and response to disturbance. Their analysis is therefore far from comprehensive. It is worth examining in some detail, however, because it sketches a useful framework to which complementary studies of soils, water and the biota could be added.

The approach adopted by Crutzen and Graedel can usefully be viewed as a form of environmental impact assessment (Clark, 1985c). For the purposes of this essay, I have adapted their work to show where carbon dioxide fits in the broader pattern of relationships among human activities, natural fluctuations, and the state of the atmospheric environment.

Experience in environmental impact assessment shows the importance of beginning with an explicit statement of valued environmental components, ie. properties of the environment that are thought to be most worthy of attention or protection in a given assessment context (Beanlands and Duinker 1983). As such, valued environmental components (should) reflect the judgements of the broader political and social communities as well as those of scientific experts. This is why the analysis of political concerns relating to carbon

dioxide is such an important aspect of any attempt to assess its practical implications. Experience also shows that the list of valued environmental components should not be restricted to properties known to be directly influenced by the activities or policies under consideration in a given assessment. Rather, to allow for the possibility of indirect or unanticipated effects, they should cover all the properties sufficiently valued that some significant segment of society would want to know if any significant change were to occur in them. The list of valued environmental components appropriate for a given assessment will therefore vary in detail according to specific social, political, and environmental circumstances. But for our illustrative purposes here, the valued environmental components identified by Crutzen and Graedel and described in Table 1 will suffice.

Environmental impact assessment aims to establish the causal relationships between such valued environmental components and potential sources of environmental disturbance. Atmospheric science has contributed to this goal by addressing relevant relationships at the deeper level of atmospheric constituents and processes. The last decade has brought about major advances in our understanding of atmospheric chemistry and its interactions with the biosphere (National Research Council, 1981; National Research Council, 1984; Bolin and Cook, 1983). This understanding now lets us begin systematically to connect sources of atmospheric perturbation to higher level atmospheric properties in terms of fundamental chemistry and physics.

Determinants of atmospheric components: Present knowledge regarding the relevance of changes in specific atmospheric chemicals to changes in the valued atmospheric components of major social and scientific concern is given qualitative expression in Figure 1. Note that the convention used in the figure is to indicate only direct effects. Thus changes in ozone concentrations are shown to affect the valued atmospheric component of "Ultraviolet absorption" because it is ozone molecules themselves that have the ultimate impact. Halocarbons (eg. 'Freons') and nitrous oxide, though assuredly relevant to ultraviolet energy absorption, are not shown to affect this valued atmospheric component because their action occurs indirectly, by changing the concentration of ozone. The rationale for this "direct effects" convention will become clear shortly.

Carbon dioxide is somewhat unusual among the atmospheric chemicals listed in Figure 1 in that it directly affects only one of the valued atmospheric components, namely the thermal radiation budget or climate. (I will argue later that Crutzen and Graedel's list should be expanded to include the direct impact of atmospheric chemicals as nutrients or toxins for living organisms). In this respect assessment of the practical implications of changes in atmospheric carbon dioxide should be relatively simple as compared to, say, the implications of changes in atmospheric sulfate compounds. Complications arise, however, because carbon dioxide is not the only chemical to affect significantly the thermal radiation budget. Figure 1 reflects the finding of recent studies that changes in other radiatively active gases such as methane, nitrous oxide, certain halocarbons, and ozone could have a cumulative impact comparable to those of carbon dioxide on climate. Any attempt to assess the practical implications of the changing concentration of carbon dioxide will therefore have to include an analysis of possible changes in the concentrations of these other gases as well.

Sources of change: What are the sources of change in radiatively active atmospheric constituents? Present knowledge regarding the effects on specific atmospheric chemicals of natural fluctuations and human activities is given qualitative expression in Figure 2. Again, the convention of indicating only direct effects is employed. Note that a significant number of atmospheric chemicals -- including carbon dioxide and most of the radiatively active gases -- are cumulatively affected by multiple sources. Useful assessments will have to consider the simultaneous implications of policies or other actions that influence each of these sources. Variability of the natural environment will also have to be taken into account for most of the chemicals listed here. Once again, because of the linkages among environmental processes, the carbon dioxide question cannot be treated in isolation.

To complete the chemical connection between sources and valued atmospheric components, it is finally necessary to attend to the matter of indirect effects -- the fact that source-induced changes in chemical species 'a' may affect a given valued atmospheric component only through an intermediate influence on chemical species 'b'. (We have already alluded to an example of such indirect effects in the case the "ozone problem". Industrial processes add halocarbons to the atmosphere. These affect the ultraviolet energy absorption only via intermediate impacts of halocarbons on ozone.) Tracking the indirect effects of chemical interactions is one of the central tasks of contemporary atmospheric science. The immense complexity of even the relatively well understood interactions precludes their discussion here. An excellent overview of the field is provided in the recent U.S. National Academy of Sciences report on Global Tropospheric Chemistry (National Research Council, 1984). Conceptually, however, the substance of such a discussion could be captured in a matrix constructed along the lines of Figure 3.

A synoptic framework: The three figures discussed above can be combined to provide a framework for assessing the overall implications of human activities and policies on selected components of the atmospheric environment. In particular, they can be used to suggest the specific environmental context within which a useful understanding concerning the practical implications of the carbon dioxide question should be possible. As shown in Figure 4, we can begin with a valued atmospheric component like "thermal radiation balance" and its immediate chemical determinants (Figure 1), trace these back through their interactions with other atmospheric chemicals (Figure 3), and finally identify the sources responsible for initiating those interactions (Figure 2). The ultimate product is a matrix showing the impact of each potential policy action or other source of disturbance on each valued atmospheric component (2). Figure 5 shows the results of Crutzen and Graedel's initial effort to incorporate in such a matrix our present knowledge of the relative magnitudes of the various impacts.

Each cell entry of Figure 5 indicates the relative impact of the specified perturbation source on the specified valued atmospheric component, assessed across all relevant chemicals. This can be seen more clearly in terms of the specific example of the impact of coal combustion on the thermal radiation budget (Location 'a' in Figure 5). The entry in this cell is derived by first assessing from the information summarized in Figure 1 all the atmospheric chemicals that could significantly impact the thermal radiation budget, namely particulate carbon, carbon dioxide, methane, nitrous oxide, oxides of sulfur, plus certain halocarbons and ozone. We then work backwards through the information summarized in Figures 2 and 3 to identify all the sources of major perturbations to these chemicals. An additional assessment of the strength and possible interactions of those impacts leads to the qualitative assessment

given in cell 'a' of Figure 5. Obviously, the details of such an assessment can be enormously complicated. Large research programs, scientific monographs, and official reports have focussed on just one or two cells of the matrix (eg. the many works on "energy and climate": (Jaeger 1983, National Research Council 1977, Bach et al. 1983). Even these relatively narrow efforts inevitably end up pushing scientific understanding to and beyond its limits. For this reason, some estimate of the relative confidence that the scientific community has in its inevitably incomplete and uncertain assessment is essential. Crutzen and Graedel have therefore included a qualitative expression of relative uncertainty in each of the cell estimates given in Figure 5.

Column assessments: The most useful aspects of the framework developed by Crutzen and Graedel are not their individual cell assessments, but rather the synoptic perspective gained by viewing the relations among those cells. Two dimensions of this synoptic perspective merit special attention. First, consider the "cumulative impact assessment" that comes from looking down any individual column of Figure 5 and noting all of the natural fluctuations and human activities that significantly affect a specific valued atmospheric component. In the case of the thermal radiation budget, the figure summarizes our understanding that while fossil fuel combustion is now the dominant source of chemically mediated climate change, other factors including certain industrial processes, biomass burning, crop production, and changes in the biological activity of natural vegetation and soils all may play a significant role. (I emphasize that Crutzen and Graedel's framework includes only chemically mediated impacts. Physically mediated impacts can also be important and would have to be included in any truly synoptic framework for analysis. I will return to this issue later). As several recent reports have emphasized, efforts to understand the likely course and implications of climate change must move beyond a preoccupation with individual chemicals like carbon dioxide, to include a comprehensive appreciation of the multiple sources involved.

Row assessments: The second synoptic dimension of environmental perspective summarized in Figure 5 comes from looking across individual rows. This view shows all of the valued atmospheric components significantly affected by a specific source of natural fluctuations or human perturbation. It is the aspect of the Crutzen and Graedel framework most immediately responsive to the "action" orientation of policy makers indicated in section 2. The figure shows that policy measures taken to change the source of perturbation to one valued environmental component will almost inevitably affect other environmental components as well. To continue our earlier example, action to reduce coal combustion because of its impact on climate (Location 'a' in Figure 5) could also be expected to have a significant effect on photochemical oxidants, the acidity of precipitation, visibility, materials corrosion, and probably the absorption of ultraviolet radiation. The extent of the effect would obviously depend on the details of the policy adopted. But one conclusion is inescapable: When policy makers are led by their concerns about carbon dioxide to ask "If we were to double coal production, what do you think would happen to the atmosphere?", assessments will have to transcend not only carbon dioxide as an isolated chemical, but also climate as an isolated property of the environment before they can produce truly useful answers.

Expanding the framework: As noted earlier, the framework developed by Crutzen and Graedel would have to be expanded before it could provide a truly synoptic environmental framework for assessing the practical implications of the carbon dioxide question. A relatively easy addition would be one or more valued environmental components reflecting the role of atmospheric chemicals as direct fertilizers or toxins for plants. Such a modification would allow integrated treatment of such phenomena as the stimulation of plant growth by carbon dioxide and its inhibition by sulfur oxides -- both products of fossil fuel combustion (3). Somewhat more ambitiously, the approach could be expanded beyond its present chemical focus to include appropriate physical and biological processes, and the sources of disturbance to them. Dickinson's (1985) recent attempt to sketch a comprehensive framework for understanding the impact of human activities on climate shows the potential of such an integrated approach (see also Bach 1981). Ultimately, the need is for a qualitative framework that puts in perspective the impacts of human activities and natural fluctuations not just on the atmospheric environment, but on the biosphere as a whole. This is necessary, among other things, to provide some defense against the well-known pitfall of policy responses that simply shift pollutants from one medium to another.

Are comprehensive environmental frameworks of the sort described here feasible? Are they even desirable, given the obvious likelihood that they would degenerate into even grander versions of the mindless checklists that long plagued conventional environmental impact assessment? Such questions cannot be answered ex cathedra. Useful answers will be obtained only through experiments that apply simple first steps like the Crutzen and Graedel framework to actual assessment problems and evaluate the extent to which useful results are obtained. In the meantime, however, it is clear that most contemporary efforts to address the practical implications of environmental issues remain preoccupied with what, in the context of the Crutzen and Graedel framework, amount to single cell assessments or, at most, cumulative column assessments. The U.S. National Academy of Science report on Changing Climate (National Research Council 1983) and the WMO/ICSU/UNEP assessment of The Impact of an Increased Anthropogenic Input of Carbon Dioxide on the Environment are recent examples of the cumulative column approach, focussed largely on concerns of climate. Such approaches are scientifically challenging and arguably provide the most effective vehicle for advancing our long term understanding of the scientific issues involved. Moreover, some of the more specific questions posed by policy makers can be addressed relatively effectively and efficiently from the cumulative assessment or column total perspective.

But for assessing the broader options of social response raised by policy makers -- options concerning major choices of energy and agricultural strategies -- the narrow perspective of even the best "column" assessments is inadequate. If we are going to produce useful knowledge for guiding such choices, a much greater portion of our assessment resources and energies must be put into row assessments of the net impact of major policy options across a wide range of valued environmental components. This is a difficult but not impossible task. A few studies have attempted partial "row assessments", among them the US National Academy of Science's reports on Nuclear and Alternative Energy Systems and Atmosphere-Biosphere Interactions (National Research Council 1979, 1981). The pitfalls and potential revealed through such studies provides a foundation of experience on which the next generation of assessments on the practical implications of the carbon dioxide question could usefully be built.

4. Social Responses: A Framework for Enriching the Options

The range of possible social responses that has been explored in the context of the carbon dioxide debate remains extremely narrow. The policy makers' questions reviewed earlier in this paper reflect a preoccupation with actions that would reduce the production of carbon dioxide through changes in energy policy. Much less attention was paid to the possibilities for adaptation to changing agricultural conditions and sea level. Other options were virtually ignored. The scholarly community, with few exceptions, has been no more enterprising. The environmental perspective presented in the previous section may help to understand the rich connections of the carbon dioxide question with other problems and human activities. But it provides no mechanism for exploiting this knowledge to design practical response options. Moreover, the environmental perspective is inherently biased towards preemptive policies that change the way human activities affect the environment, rather than adaptive towards policies that change the way in which the environment affects human activities.

In other contexts, expanding the range of actively debated options for action has often been one of the most useful roles played by policy analysts (1). How can this be done for the carbon dioxide question? Needed are tools that can systematically survey possible leverage points across the whole sequence of interactions running from human actions through environmental change to social consequences. In particular, we require approaches that will help to keep visions of what societies might do from being unduly constrained by the names scientists give to problems. As Schelling (1983) has argued, the policy debate surrounding what we call "the carbon dioxide problem" would almost certainly be different if the same concerns had initially become popularized as "the climate problem" or "the water problem". In the same insightful paper, Schelling goes on to sketch a framework for expanding the range of social response options to carbon dioxide-induced climatic change. With minor modifications, his approach can be applied to the fuller set of valued environmental components that section 3 of this paper showed to be entangled in the carbon dioxide question.

A framework of responses

My point of departure is the classic environmental impacts model shown in Figure 6a. (This linear model is obviously too simplistic for most tasks. For the one to which we will put it here, however, it will suffice). In this useful caricature of complex reality, human activities like fossil fuel combustion release pollutants and other substances like carbon dioxide (see Fig. 6b). These substances interact with a variety of other environmental constituents and processes as discussed in section 3. Changes result in one or more valued environmental components like climate. These changes in turn have social consequences through their impacts on important properties like agricultural yield. As noted above, most thinking on possible policy interventions to this sequence has focussed on the two ends, ie. on polluting activities and on agricultural consequences. Schelling (1983), however, has argued that social responses are in general possible at each stage of the sequence. To help guide the design and assessment of specific policy options, he posed a framework consisting of four potential goals for social response, one corresponding to each stage of our simple impacts model. In a form slightly

altered to give greater generality, these potential goals are listed in Figure 6c and described below.

Altering production of pollutants or other potentially disruptive emissions changes the possibility of inducing environmental changes in the first place. Some such changes might, of course, be beneficial. The framework makes no presumption that less production is better than more. Recovering releases of emissions from the environment is another potential option. As Schelling (1983: 463) puts it "If we cannot help producing too much, can we remove some?" Social responses capable of modifying the environment could counteract unwanted changes in valued environmental components, or encourage wanted ones. A long tradition of environmental management, impact mitigation and ecosystem restoration activities reflects efforts to achieve this goal. Finally, the goal of adapting to change can be pursued through a wide range of formal policies and informal actions that seek to mitigate the damages and capitalize on the opportunities associated with changing environments.

Possible means of achieving each of these general response objectives through specific policy actions are discussed in the following sections, which draw heavily on Schelling's (1983) original treatment. The options are summarized in Table 2. Note that at this stage I make no judgement on the desirability or even feasibility of implementing any of these options. As emphasized at the beginning of this paper, different people from different places and generations may be expected to hold very different views on such questions. My objective here is to provide a tool for enlarging the range of options these different people might want to consider in debating and shaping the futures they each might want to build.

Goals of social response: Altering production

Measures to alter production of carbon dioxide and related emissions have dominated the discussion of social response to the carbon dioxide question. Focussing first on carbon dioxide itself, Figure 2 showed six potentially significant sources of perturbations in the natural rate of carbon dioxide emissions to the atmosphere. (Other reviews of the relevant science might add or subtract sources from this list. Such details are crucial for the assessment of specific options; they are not relevant for my present purposes of illustrating a general framework.) It is worth bearing in mind throughout the following discussion that, to a first approximation, equal amounts of carbon now reside in the atmosphere, the living terrestrial biosphere, and the pool of ultimately recoverable fossil fuel resources other than coal. The nonliving parts of the terrestrial biosphere (eg. the nonliving components of soils) contain perhaps twice the carbon of the atmosphere. Ultimately recoverable coal resources contain about five times as much carbon as the atmosphere. The oceans contain more than 50 times as much (Clark et al., 1982; Fig. 1).

Options for energy management: Fossil fuel combustion for energy seems likely to be the largest anthropogenic source of carbon dioxide at present and for any future in which the carbon dioxide question might be of concern to society (National Research Council 1983; Clark et al. 1982). Three classes of energy management options have been widely discussed. The first and most general concerns the total use rate of energy. Given the large share of fossil fuels

in the total energy budget, energy conservation and slower growth in energy consumption are almost certain to reduce carbon dioxide releases to the atmosphere. It is worth pointing out that the greatest changes over the last 10 years in the scientific community's assessments of the urgency of the carbon dioxide question have come from changing perceptions of the likely future growth rates of total energy use. The ways in which changes in energy use rates would alter carbon dioxide emissions have been explored in numerous studies (2).

The second energy management option concerns the share of fossil fuels in the total energy budget. Replacing fossil fuels by solar, nuclear, sustained yield biomass, or exotic forms of noncarbon energy will all reduce the emissions of carbon dioxide to the atmosphere. Each of these alternatives has the same effect on carbon dioxide emissions for every unit of fossil fuel energy replaced. This fact should cause more awkwardness than it does for nuclear and "soft path" advocates, both of which have used concern over carbon dioxide as propaganda for their own preferred solutions (3).

The third energy management option concerns the share of various fossil fuels in the total fossil fuel budget. This issue arises because different fossil fuels release different amounts of carbon dioxide per unit of heat energy produced on combustion. Fortunately, this is a relatively straightforward matter and the questions posed by policy makers can be answered with some confidence. Natural gas and oil produce about 60% and 80%, respectively, as much carbon dioxide as coal. Synthetic fuels derived from coal require energy expenditure in their production and therefore yield around 150% as much carbon dioxide as coal (Marland, 1982) unless the processing energy is derived from non-fossil sources.

Options for land management: Deforestation and the oxidation of carbon rich soils disturbed by agricultural activity have been significant sources of carbon dioxide emissions to the atmosphere. Bearing in mind the relative sizes of the carbon pools quoted above, however, their future contribution seems likely to be much smaller than will be provided by fossil fuels. Forest clearing is a net source of carbon dioxide to the atmosphere only when trees are burned and not allowed to regrow. The key management issue is control of permanent land conversion out of forests into uses with lower standing carbon densities. It is worth keeping in mind, however, that to equal the current annual fossil fuel releases of carbon dioxide would require the annual permanent conversion and burning of a forested area roughly the size of France. The total area annually deforested in the tropics is actually about one fifth of this (4).

Options for ocean management: Most of the world's carbon dioxide lies in the ocean. The exchange of this oceanic carbon dioxide with the carbon dioxide in the atmosphere is regulated by a variety of physical and chemical processes plus a powerful "biological pump". When the efficiency of the pump is reduced, more carbon dioxide is released to the atmosphere. When it is increased, carbon dioxide is removed from the atmosphere (5). Natural variations in the operation of the biological pump have been associated with significant changes of atmospheric carbon dioxide in the past. There is no a priori reason that intentional management of the ocean's carbon dioxide pump should be omitted from the menu of possible options for altering carbon dioxide production.

Options for managing related environmental constituents: I emphasized in section 3 that valued environmental components affected by carbon dioxide are also affected by other atmospheric constituents (see Fig. 1). In the case of climate, these include particulate carbon, methane, nitrous oxide, oxides of sulfur, plus certain halocarbons and ozone. Our scientific understanding of the sources of these constituents is less complete than for carbon dioxide. Much of what we do know was summarized earlier in Figure 2. It shows that by and large, the same broad classes of management options discussed above will provide means of altering the production of one or more of these other radiatively significant atmospheric constituents. Some of the specific policy options would, of course, differ. For example, switching from coal to gas will not alter nitrous oxide production in the same way that it alters carbon dioxide production. Sulfur can be removed from fuels prior to combustion, while removing carbon is harder (6). An elegant integrated approach to emission management has been outlined by Haefele et al (1985). To contend with the specific sources of these other chemicals, however, several additional options must also be considered.

The importance of methane in the thermal radiation budget requires that our land management options pay particular attention to the nature and extent of wetlands, and to populations of certain ruminant animals. The likely influence of oxides of sulfur, halocarbons and ozone on climate requires that we also consider specific industrial management options that would change the rates of production for these substances (see Fig. 2). Obvious targets for such measures that have received substantial attention include the processing of nonferrous ores (a source of sulfur dioxide) and the industrial and commercial use of fluorocarbons. Recent reviews of the ozone question suggest several additional products of human activity that, because of their effects on ozone and therefore on climate, offer additional managerial options relevant to the earth's thermal radiation budget. A systematic study of less obvious possibilities for controlling the production of products linked with the environmental impacts of carbon dioxide would be useful.

Goals of Social Response: Recovering releases

Carbon dioxide and related chemicals affecting the same valued environmental components can, in principle, be recovered after release and stored in relatively inert forms. In many ways, the options for achieving the goal of recovering releases parallel those for changing production. The various recovery options tend to be more tightly coupled, however, due to the need for places to store the vast quantities of material involved. Once again, most analysis has focussed on carbon dioxide itself (7).

Options for energy management: Carbon dioxide and other byproducts of fuel combustion can be "scrubbed" from emission gases and then disposed of. Several technologies are now available. More effective and efficient ones could doubtless be developed if the need were sufficiently great. Many scrubbing technologies are presently restricted to use on large-scale fuel combustion systems like electrical power utilities. It is worth bearing in mind that something on the order of one half the world's total carbon dioxide emissions now come from such large-scale sources. Disposal options that have been discussed include the deep ocean, depleted oil and gas wells, and depleted salt caverns. One study for the United States suggests that removing and storing 90% of the carbon dioxide from electric utility stack gases is now technically

feasible at costs that approximately double the capital investment required for power plant construction, and increase the production cost of electricity by a factor of 1.5 to 2. Between 10% and 20% of the utilities' output would be required to power the recovery and disposal operations (Steinberg et al., 1984). I will turn in section 5 to a discussion of how long it might take to implement such a strategy if it was judge desirable.

Options for land management: Photosynthesis removes carbon dioxide from the atmosphere and incorporates it in plant tissue. If the plants are eventually oxidized (burned, eaten, etc.), the carbon dioxide is again released to the environment. Permanent removal of carbon dioxide from the atmosphere via terrestrial plants requires that the plants be protected from oxidation. Three basic options for permanent removal of carbon dioxide via photosynthesis have been discussed. The first increases the area of the earth's surface covered in trees -- the plant form with the highest carbon densities. The second increases the amount of carbon stored on presently forested land -- a process that might be aided by the "fertilizer" effect of carbon dioxide. The third has been referred to as "fossilization" -- harvesting trees and protecting them from oxidation by burying them, coating them, and generally accelerating their conversion into future fossil fuels.

The difficulty with all these methods is that they are extremely land intensive. I noted earlier that current annual emissions of carbon dioxide from fossil fuels are equivalent to burning a forested area the size of France each year. Conversely, to recover a year's carbon dioxide emissions from fossil fuels, an even larger area would have to be reforested annually due to the decades required for trees to reach full size. Another way of putting the reforestation options into perspective is to recall that the amount of carbon in the atmosphere and the amount in the entire living terrestrial biosphere are now about equal. To offset the much discussed "doubling" of atmospheric carbon dioxide by means of increased photosynthesis would therefore demand that we find room on earth for twice the vegetation it now possesses. As Schelling (1983: 468) concludes, "irrespective of a hundred years' technological change, 'sweeping' the atmosphere with trees can be no great part of any solution to a carbon dioxide problem."

Options for ocean management: The deep ocean has frequently been discussed as a possible disposal site for carbon dioxide recovered through either industrial scrubbing or photosynthetic sweeping. Technical and economic difficulties abound in such approaches, but there seems nothing inherently infeasible about "sinking the carbon dioxide". A more direct option for ocean management involves the "biological pump" described earlier. Geochemical evidence suggests that if the pump is primed (fertilized?) to run more efficiently, large quantities of carbon dioxide can be pulled from the atmosphere into the deep ocean through natural photosynthetic activity of marine plankton. Questions remain of whether intentional management could supply sufficient priming, of how long the removal process would take, and of what its other -- and almost certainly substantial -- environmental impacts would be.

Options for managing related environmental constituents: Very little work has been done on options for recovering other radiatively active gases from the atmosphere. It is perhaps worth pointing out that, should recovery be possible, the disposal and storage problem would be nowhere nearly as great as in the case of carbon dioxide. The amount of carbon dioxide likely to be added to the atmosphere over the next century is more than one hundred times (by volume) the

amount of methane, and more than one hundred thousand times the amount of individual halocarbons (Dickinson 1985).

Goals of Social Response: Modifying the Environment

Concern about carbon dioxide and related issues arises because they may cause modifications of valued environmental components as an inadvertent byproduct of human activities. But what people can modify by accident they can also modify on purpose. Measures that would counteract or amplify environmental changes resulting from the increase of atmospheric carbon dioxide and related substances therefore should be considered in any systematic treatment of social response options. The most important of these measures involve intentional modification of weather and climate. A decade ago an active debate was conducted on this subject (8). Less attention has been devoted to it in recent years, at least in the English-language literature (eg. American Meteorological Society 1985). Schelling (1983: 470) has suggested that a significant practical implication of the carbon dioxide debate may be a renewed interest in intentional weather and climate modification that could well persist independent of how the carbon dioxide question is resolved.

Options for managing the thermal radiation budget: Many of these options have already been alluded to under the goal of altering production. Each of the radiatively active substances listed in Figure 1 could be produced and distributed in the atmosphere for the explicit purpose of changing the thermal radiation budget. The production would not necessarily have to come as a by-product of fossil fuel combustion, since most of the substances listed could significantly affect climate through additions of far smaller volumes than required of carbon dioxide. As Schelling (1983) notes, a world that has already harnessed atomic energy and brought men back from the moon is almost surely a world that could develop technically feasible technologies for climate cooling if suitably motivated. Some have argued that at least for tropical regions, the motivation already exists (Bandyopadhyaya 1983). Whether such solutions would be politically feasible is another question.

A related way of modifying climate at various spatial scales is through changing albedo -- the amount of incoming light reflected back to space. The present planetary albedo of about 30% is mostly due to atmospheric reflection by dust, aerosols and, above all, clouds and water vapor. Only 6% or so of the incoming light is reflected at the earth's surface (Dickinson 1985). At the global scale, human options for significantly altering planetary albedo therefore seem largely restricted to options for changing the reflective properties of the atmosphere through management of cloudiness or stratospheric aerosols. For example, Broecker et al. (1982) have suggested that the warming effects of carbon dioxide and related gases might be counteracted by constructing artificial "volcanoes" -- probably fleets of aircraft -- to spray sulfur dioxide into the stratosphere. As originally pointed out by Budyko (1974), this would be converted to sulfate aerosols that would increase overall albedo, thereby cooling the surface. They would also presumably lead to a number of the other environmental changes associated with oxides of sulfur indicated in Figure 1.

Total changes in surface albedo associated with deforestation, desertification, and extensive use of solar collectors seem unlikely to change the planetary thermal radiation balance by even one tenth as much as changes expected to result from carbon dioxide over the next century (Dickinson, 1985). The

incremental difference that could be induced by intentional management is even smaller. At the regional scale, greater leverage on albedo and climate could possibly be exerted. It has been suggested, for example, that the extent of summer arctic sea ice could be significantly reduced by sprinkling its surface with low albedo substances like soot. Because of the important role of arctic ice cover in the earth's heat balance, the consequences of such action could be significant, if hardly a counter measure for unwanted warming.

Options for managing water: Much of the interest in intentional weather or climate modification has focussed on the possibilities for controlling precipitation and the atmospheric motions that bring it to or keep it away from specific locations. Assessments of possible options are provided in the reviews listed at the beginning of this section. At present, however, management of water is accomplished primarily by moving it around once it has reached the ground. The existence of dams and irrigation systems, of transport canals and of long-distance pipelines for water transfer testify to the ability and willingness of societies to manage their water supplies in the face of uncertain or inadequate climates. The massive schemes for river diversions now being discussed in China, the Soviet Union and Canada suggest that even larger interventions may be in store for the future (9). Large-scale water management has, of course, been undertaken for reasons other than climate changes associated with carbon dioxide and related emissions. As I will discuss in more detail in the following sections, however, the long time scales associated with large scale water management programs could make them particularly sensitive to long term climate changes.

Options for managing other environmental components: As emphasized in section 3, climate is not the only important component of the environment that may be affected by carbon dioxide, related substances, and the actions taken to control them. With respect to the direct effects of increased atmospheric carbon dioxide as a potential plant fertilizer (Lemon 1983), it should be kept in mind that increases in plant growth, if desired, could often be encouraged with intentional fertilization and management schemes. If greater plant growth is not desired, a host of management tools including herbicides and cultivation practices are available. The debate on the impacts of carbon dioxide fertilization should not neglect these conventional managerial options.

A useful analysis of the practical implications of changing carbon dioxide would have to account for both the impacts and management options associated with other environmental constituents that would be changed by efforts to control carbon dioxide releases. Consider the following example of how this requirement affects the present effort to develop a framework for increasing the range of possible social responses. Figure 2 raises the prospect that policies of fossil fuel management designed to alter the production of carbon dioxide would also be likely to alter the production of sulfur oxides. I have suggested that because of the wide range of environmental impacts associated with sulfur dioxide, this coupling of the two issues might increase the force of arguments for controlling carbon dioxide. It is important to emphasize, however, that a balanced assessment of such arguments would have to consider the options for modifying the environmental impacts of sulfur dioxide. If we have or can develop the means to undo some of the undesirable impacts of sulfur oxides at a reasonable cost, then sulfur oxides becomes less of a reason for controlling carbon dioxide. In fact, some of the adverse impacts of sulfur oxides can be modified through liming and restocking of acidified lakes. A systematic appraisal of other options for modifying or restoring the environment in ways that would counteract the unwanted impacts of carbon

dioxide-related environmental constituents is beyond the scope of this paper. But such an appraisal could well be useful in attempts to cope with the practical implications of the carbon dioxide issue.

Goals of Social Response: Adapting to Change

Actions through which societies could adapt to the changes caused by carbon dioxide and related emissions have received considerable attention from both policy makers and scholars. Discussion has focussed on agriculture and, to a lesser extent, on the concerns about of rising sea level. But a number of other areas also deserve consideration in efforts to build a synoptic framework of possible social responses. These are discussed below under categories reflecting basic needs of society. Even more than for other response goals, options for adaptation are likely to be considered and implemented at the local and national scale. Societies' adaptive response will be the result not so much of big policy decisions but rather of very many small local and national adjustments. The majority of these adjustments will be taken for reasons that are at most loosely tied to the carbon dioxide debate (Meyer-Abich 1983; Schelling 1983). The phrase "management options" in the following paragraphs should be interpreted against this background.

Options for adapting agriculture: Environmental changes associated with increasing atmospheric carbon dioxide are likely to cause geographical shifts in the boundaries of relative advantage held by alternative agricultural activities (Parry 1985). In extreme cases, carbon dioxide-related changes will shift the margins between forestry, grazing, and crop production as the preferred agricultural land use. More commonly, the shift will be between different crop types and planting practices. These shifts will have important environmental implications of their own (Crosson 1985). It cannot be overemphasized that most such shifts will also be strongly driven by processes of human development and environmental change unrelated to carbon dioxide.

On the supply side of what has been called "The World Food Equation" (Mellor and Johnston, 1984), four basic adaptative options are therefore available. These could be applied alone or in concert. First, land now being used for crops, grazing or forestry can be changed to one of the other uses. Second, within one of these major classes, the specific products grown can be changed, eg. substituting wheat for corn as rainfall in an area decreases. Third, efforts can be made to adapt a given crop, grazing animal, or tree species to the changing environmental conditions. Improvements in water-use efficiency would probably be especially important. Cultivation practices and technologies, genetic engineering, and conventional breeding methods could be expected to contribute. Finally, mechanisms for trade and exchange of agricultural products among regions can be adapted to the changing geographical patterns of supply. Somewhat analogous options exist for fisheries management, where climate-mediated changes in primary productivity or water temperature may alter the locations at which particular species can be found or cultivated (Cushing, 1982). The increasing trend towards cultivation of high value fish and crustacean species (eg. salmon, oysters) suggests that the potential for effective adaptation in this area should not be underestimated.

On the demand side of the equation, changes in diet and the use patterns of agricultural fibers could serve as powerful adaptations to changes in agricultural production.

Options for adapting habitation: Environmental changes associated with increasing atmospheric carbon dioxide will affect the places that people live and conduct their activities through changes in temperature, humidity, rainfall and sea level. Migration is the most generalized adaptive strategy, and also one with the greatest historical precedent. Most climate changes will shift the locations of existing climates rather than create novel ones. People have always moved in response to changing climate and will doubtless continue to do so, though their opportunities may be limited by increasing population and political control.

People who do not migrate will have available a wide range of adaptive options to make the environments they inhabit more to their liking. Technologies for heating and cooling of buildings, enclosing large area sports arenas and placing entire commercial complexes underground are already well developed. Whole areas like the US Southeast have been transformed through air conditioning. There is no reason to doubt that even larger scale control of the working and living environment will take place over the next century, with or without carbon dioxide effects (10).

The most dramatic challenge to human habitation associated with carbon dioxide-related climate warming involves rising sea level (11). Several adaptive strategies could be used by societies (Hoffman et al., 1983: Table 5-1). Locational adaptations could be made by taking future sea level changes into account in selecting the sites of new housing, industrial, and transport developments. Structural adaptations would design coastal zone facilities to make them less sensitive to slow sea level changes. This could involve the use of mobile or short lifetime structures, as well as sea-level resistant ones. Protective adaptations include construction of dikes, dams, and levees. Schelling (1983) reminds his readers that this option has proven attractive for the Dutch for several centuries, whose current technologies are adequate for protection against mean sea levels 5 or 6 meters above ground level. He points out, however, that while protecting wealthy concentrations like Boston might well be feasible, the prospects are grimmer for low lying, low income areas like Bangladesh.

Options for adapting in other ways: No systematic effort has been made to assess the many other options for adapting to carbon dioxide-related environmental changes. Schelling (1983) lists construction, transport, military operations, and compensation payments as areas of social activity for which adaptive responses might be especially significant.

Adaptations would be particularly important in high latitude areas, and have been discussed in assessments of the overall development potential of those regions (eg. Hare, 1981). On land, areas of permanent and discontinuous permafrost would certainly shrink under climatic warming, requiring changes in the design of overland vehicles, construction equipment, pipelines, and buildings. Experience with adaptations of this sort already exists. Hare (1981: 108) concludes "There is no reason to doubt that we can find technical solutions, as long as we are aware of the environmental change." On sea, a warming climate would dramatically alter the distribution, character, and abundance of ice that now hinders navigation and undersea resource exploration. The extent of permanent pack ice, the area and period of summer melting in the nonpermanent pack ice, and the ice discharge from glaciers would all be affected. Again, present experience with high latitude development suggests the complex kinds of problems, opportunities, and adjustments that such changes would entail. Changes in ice conditions can also be expected to have significant geopolitical implications, and to trigger significant geopolitical

adaptations. The present role of sea ice in the international games of hide-and-seek played with ballistic missile submarines is only the most obvious example.

A final set of options for adaptation involves transfer payments through which those segments of society that gain from carbon dioxide-related changes could compensate those that lose. Such transfers have some contemporary precedents at national and regional scales. In the international context, emergency drought and disaster relief are already common if inadequate social responses to acute environmental changes. Long term, global scale transfer payments are envisioned as part of many discussions on possible new international economic orders. It is not inconceivable that climate and other environmental resources, as well as internationally-induced changes in those resources, could become included as an explicit agenda item in such discussions in the future. One factor militating for their inclusion is a growing belief that "the great climate anomaly" should be viewed as one of the significant features underlying the North - South dichotomy (12).

5. Scale Perspectives on the Assessment of Response Options

The framework sketched in section 4 provides a tool for expanding the range of options that societies might want to consider as responses to the increasing atmospheric concentration of carbon dioxide and related issues of environmental change. To avoid prematurely limiting the discussion, considerations relating to the efficacy of alternative responses were explicitly excluded from the framework. I left for this section the task of developing complementary tools to help societies determine what all those options are likely to be good for in coping with the practical implications of carbon dioxide-related environmental changes (1).

It is best to recognize at the outset that even the best general assessment tools will be of limited use. Experience in other areas of environmental management warns that the efficacy and feasibility of response options depends to a great extent on details specific to particular times, places, and people (Beanlands and Duinker 1983; Holling 1978). On the other hand, most contemporary assessments of response options to the carbon dioxide question are so badly flawed that even the crudest of appropriate tools can hardly help to improve the quality of analysis offered to publics and policy makers. Case study chronologies and consequences have been transferred indiscriminately around the globe, with little regard for the special circumstances of place or the stage of historical development. Some studies have assumed that no adaptation is too great for societies or ecosystems to make. Others have imposed instantaneously climates and atmospheres from the next century on today's distributions of crops and people, allowed no adjustments, and reported the disruptions.

In most of these cases the difficulties stem not so much from ignorance or inadequate scholarship, but rather from the lack of usable perspectives from which to view and order the accumulating range of studies, methodologies and theories. The problem is bad enough within the individual natural and social science disciplines involved in the study of interactions among changing environments and societies. It is worse when, as is often the case, the nature of the investigation requires that disciplines be bridged and that results, methods, and explanations be exchanged among them. Needed to complement these individual investigations is a synoptic perspective that can help to show how the individual impact assessment studies relate to each other, what the case studies of the past can and cannot tell us about the implications of environmental change in the future, and which collections of human activities and environmental variations need to be considered together if we are to achieve balanced, realistic assessments of the options for social response.

Dimensions of assessment: What should such a synoptic perspective encompass? Experience with policy analyses in other fields, and the political contexts of the carbon dioxide question reviewed in section 2, suggest at least three important dimensions. First are what Schelling (1983) has called "background changes". Concerns related to the carbon dioxide question take us many decades, even centuries into the future. The world in which most of the practical implications of carbon dioxide-related environmental changes are experienced will therefore be a very different world from today's. Independent of carbon dioxide, significant changes will almost certainly have occurred in the number and distribution of people on earth, the technologies they use for energy conversion and transportation, the crops they grow, their value systems, and so on and on. In some cases these background changes may swamp the

implications for welfare and policy of carbon dioxide-related environmental changes. Without exception, they will significantly alter those implications and the options for dealing with them. Useful assessment tools should therefore provide means of viewing carbon dioxide-related environmental changes within the context of other background changes relevant to the implications of environmental change for societies.

A second concern focusses on matters of timing. How long would it take for solar energy to displace significant quantities of carbon dioxide-producing fossil fuels? How soon will the scientific uncertainties surrounding the carbon dioxide question be sufficiently reduced to warrant policy recommendations? How soon do we have to act? Such timing questions arose repeatedly in the policy makers' discussions of the carbon dioxide question that I reviewed in section 2. Academic policy analyses repeatedly conclude that the time lags associated with problem development, social perception, and policy response pose some of the greatest barriers to the design of effective solutions (eg. Haefele et al., 1981). Useful tools for assessing the carbon dioxide question should let us see relationships among the timing of environmental changes and the timing of the various kinds of social responses discussed in section 4.

A third concern is for the distributional implications of alternative social response options. Again, this concern has been prominent in the carbon dioxide debate in both the political and the academic communities. Both the possible impacts associated with carbon dioxide-related environmental change, and the costs and benefits associated with alternative social responses to those changes have the potential for very uneven distributions across different peoples, nations, and generations. Perceptions of these distributions are likely to affect strongly judgements of political fairness and feasibility. The current debate over ostensible "winners" and "losers" has done little to provide the factual input required for more accurate perceptions. Needed are tools to show the ways in which both impacts and responses are linked through space and time.

A scale perspective: Following Yoshino (1975, 1983) I have argued elsewhere (Clark 1985a, 1985b) that one useful perspective for viewing the needs outlined above can be obtained by considering the temporal and spatial scales of the environmental, ecological and social phenomena involved. Scale analysis has little to say about the thresholds, complex interactions, costs, political feasibilities and other features likely to be important in assessing the efficacy of alternative options for social response. Nevertheless, it has a long tradition of use in applied mathematics and the physical sciences. In addition, however, it has been creatively applied by geographers and life scientists, thus providing a possible shared language between some important participants in the carbon dioxide debate.

Scale analysis can provide preliminary guidance on a number of fundamental qualitative relationships often overlooked in environmental assessments. Are carbon dioxide-related environmental changes "fast" or "slow" relative to other background changes in the environment? Which social and ecological processes are so fast relative to environmental changes that it is reasonable to assume that they will be usually be in a state of well adapted "equilibrium" with respect to the environments in which they find themselves? Which processes are so slow that they will "see" carbon dioxide-related environmental changes as little more than background "noise"? How large are the areas likely to experience similar carbon dioxide-related environmental changes, relative to the areas integrated by economic and political processes

(2)? The remainder of this section attempts to lay some simple but solid foundations on which more reliable answers to such utterly basic questions can be built. In section 6 I will turn to some of the higher order questions concerning nonlinearities, thresholds, and response to extreme events that can not be fully illuminated from the scale perspective.

What are the characteristic scales of variation for components of the environment related to the carbon dioxide question, of background trends relevant to their impacts, and of social processes related to policy response? A tremendous literature is relevant to this question - a literature that I have neither the wit nor the space to do justice to here. What I have found useful, however, is to analyze, using consistent quantitative definitions, a sample of empirical scale data for some of the most relevant processes and patterns. These are presented below as guides for further and more complete investigation. A fuller discussion of data sources and interpretations is given in Clark (1985a,b). Technical definitions of the "characteristic" time and space scales used here are given in the notes (3). Further development of the scale approach is presented in Yoshino (1983) and Parry et al. (1984).

Scales of environmental variation: We begin our examination of characteristic scales of the atmospheric environment with the chemical constituents already introduced in Figures 1 and 2. Research on the interactions among those chemicals (cf. Figure 3) has allowed most of them to be characterized in terms of the time and space scales at which chemical processes remove them from the atmosphere. Recent results reported in Figure 7 should be accurate to within a factor of 2 or 3. It is immediately clear that most of the radiatively active constituents defined in Figure 1 are removed from the atmosphere very slowly, over a period of decades to centuries. This is sufficient time for them to be distributed around the globe. It also means that a "greenhouse effect", should it develop, will persist long after release rates are altered or even reduced to zero. Other atmospheric constituents entangled in the carbon dioxide question have shorter lifetimes and more local distributions. Natural processes would remove these constituents from the atmosphere shortly after a reduction in release. Their long lasting influence comes not from their impact on the atmosphere but rather through interactions with soils, water, and the biota (see below).

Physical processes of transport and deposition also dissipate local concentrations of atmospheric chemicals. These physical processes have been well studied by meteorologists, and can also be assigned characteristic scales of operation as shown in Figure 8 (4). Data on the longer time scale climatic phenomena are much less systematic, at least for periods of less than 100,000 years (5). Figure 8 summarizes several examples that could contribute to the "background trends" in climate during the next century of carbon dioxide-related climate change. Patterns in rainfall variability are characterized by the North American Great Plains drought of the 1930s (Warrick, 1980) the Sahel-Sudan drought of the 1910s (Nicholson, 1982) and a typical regional "dry summer" phenomenon, in this case for the United Kingdom in 1976 (Parry and Carter 1984). I suspect that other examples could be found to fill the gap that appears in Figure 8 between these two extreme forms of drought. Interestingly, however, the gap is not filled by recent studies (Vines, 1984) of spatial and temporal cohesion in long-term rainfall records for North America (6).

The remaining entries on Figure 8 characterize long-term hemispheric to global scale warming trends. As an historical example, I have used the long-term warming of the northern hemisphere that occurred from the mid-19th to mid-20th century (Jones and Wigley, 1980). A systematic treatment of similar trends is given by Morner (1984). The future climate warming that might result from anthropogenic release of carbon dioxide and related greenhouse gases is positioned in the figure using the assessments of a recent study by the U.S. National Research Council (1983) with adjustments taken from Dickinson (1985), Cicerone et al. (1985) and Wigley and Schlesinger (1985). This is not a particularly satisfactory characterization of even global climate changes related to carbon dioxide, for reasons I will address in section 6. For present purposes, however, its approximate position towards the upper right corner of the figure is all that matters. Many more (and more critically analyzed) data could be added to this collection of climate scales, but the picture emerging in Figure 8 is adequate for present exploratory purposes. I turn next to a characterization of the scales of social and ecological phenomena potentially involved in interactions with changing environments.

Time scales of ecological and social processes: Characteristic time scales for a wide range of ecological and social processes are summarized in Figure 9. For this discussion I omit physiological and behavioral processes and begin with the "intrinsic rate of natural increase" for several insects and mammals. These figures reflect physiologically maximum rates of reproduction in an optimal and unlimited environment. Longer time scales characterize rates of population increase achieved by similar animals under natural conditions, rates of biomass accumulation in vegetation, rates of soil accumulation through primary and secondary succession, and the rates at which various tree species expanded their ranges to current positions following the most recent deglaciation of North America (?).

An analogous treatment is possible for social processes potentially relevant to the interactions of environments and societies (8). The fastest social processes plotted in Figure 9 reflect rates at which single crop cycles (planting to harvest) and industrial construction projects are completed. Five substitution processes are shown next, reflecting the rates at which societies have changed from one production process to another (9). The figure shows data for substitutions of crop varieties (eg. the adoption of high-yield grains in mid-century America and contemporary developing countries); of manufacturing processes within industries (eg. replacement of open-hearth by electric steel-making); of basic energy sources (eg. oil for coal); and of work force structure (eg. decline of the share of agriculture in the total work force).

Many indices reflecting combinations of these basic rates are also possible. Illustrated are the results of a particularly interesting study by Doran and Parsons (1980) in which the rise and fall of various nations' shares of total world power is given relatively objective quantitative expression. Figure 9 also shows a more conventional expression of social time scales: the aggregate annual growth rates of national economies, food production, and population (World Bank, 1982).

The overall time scale perspective of Figure 9 suggests that substitutions of new agricultural crops or industrial processes have historically occurred on time scales one to two orders of magnitude faster than comparable demographic changes in population or labor force. Processes dealing with fundamental elements of social structure (e.g., market shares held by various primary energy sources or by various countries in basic industrial products) change at

intermediate time scales. Cesare Marchetti, to whom I am indebted for many of the data, has pointed out a tendency of time scales to become shorter, the more recent the initiation of the process being described (Marchetti, 1981). The view also suggests that in the course of whatever environmental changes do occur over the next century, we should not be surprised to see several complete turnovers of the crop varieties grown in particular locations. Over the same period a whole new generation of basic industrial processes is likely to replace those now in use. The world is likely to be getting most of its energy from sources it does not use today. Many opportunities for radical social response to carbon dioxide-related environmental changes will therefore arise at every stage of the option sequence suggested in Figure 6.

Space scales of ecological and social pattern: Characteristic spatial scales are summarized in Figure 10. To provide context, the world's oceans, continents, seas and major river basins are assigned a "characteristic length" equal to the square root of their area. Analogous data are presented for some typical lake drainage basins of the previously glaciated parts of the United States.

Terrestrial ecological patterns are notoriously difficult to treat in a spatial scale context. The vegetational data in Figure 10 are drawn from Delecourt et al. (1983) who reviewed a large variety of potential classification schemes in terms of their utility for assessing the ecological implications of changing environments. In general, the largest or "zonal" scales cover the entire range in which a given species or higher order taxonomic group is likely to be found. This is truncated on the upper end by the size of continents, which pose a major barrier to most vegetational ranges (10). At finer scales, "stand" patterns reflect small collections of individual plants often sharing common histories and growth rates. At the individual scale we are concerned with the fate and sphere of influence of single trees, shrubs and herbs. An analogous treatment is given to characteristic scales for the animal Kingdom, drawing primarily on data from Rapoport (1982). Again, the largest scales plotted reflect the distribution ranges for major taxonomic groupings. Not surprisingly, these tend to be of the same order as the primary distribution of vegetation. The smallest scale for animals in this plot reflects the individual "ambit", or area covered by a single individual in its lifetime (Caughley, 1977).

Consider next the characteristic spatial scales of social phenomena. Figure 10 shows the wide range of spatial scales characterizing individual farms throughout the world, with median values for Asia, Latin America, and the U.S.A. Individual farms are grouped into crop regions and larger crop zones. These zones, as commonly defined by the World Bank and the FAO, reflect major agricultural "styles" and "cultures" at least as much as they indicate the predominance of a particular crop with particular environmental requirements. Because many of the atmospheric pollutants discussed in section 3 have their major sources in areas of high density human settlement, Figure 10 also plots the average distances between large cities (>500,000 people) for the nations of the world. The sizes of those nations are also presented. These range in area over three orders of magnitude, though most are of the order of one million square kilometers. Together with the continental data already discussed, the city and nation-state data reflect the characteristic scales for much of the world's political and economic activity.

Scales of interaction: Even the incomplete data I have presented here indicate some rough relationships between characteristic scales of various ecological and social phenomena, and the central concerns of scholars studying those phenomena. To help illustrate the relationships, I have rearranged some of the data from Figures 9 and 10 into the common space- by- time format of Figure 11.

Turning first to ecological concerns, Figure 11 reflects a continuous series of scales drawn from Delacourt et al. (1982). It begins with the broad zonal phenomena of continental scale changes in the range of higher taxonomic categories and ecological associations, and extends down in this presentation to the level of the individual tree. The labels are conveniences only and should not be taken too literally. The important point is that in terrestrial ecology, as in other fields, scholars working in different parts of the space- by- time field focus on very different questions and modes of explanation (11).

The social structures shown in Figure 11 reflect the more detailed attention I have given to social pattern and process in my analysis of characteristic scales. Again, the labels are less important than the general indication of a wide range of distinctive interests and concerns. At the center of the space- by- time field is a region I have called "local farm activities." This is defined by the "crop cycle" and "farm size" data of Figures 9 and 10. Concerns here focus on basic farm- level decisions about planting and harvesting, perception of risks, and individual decisions to adopt innovations. (Note from Figure 6 the substantial overlap with the characteristic time scales of a variety of construction projects.)

At the extreme high scale end of the social spectrum is a cluster I have labeled "global political/ demographic patterns." This reflects the long time scales that have characterized the shifting international distribution of political and economic power. At an even more basic level, these patterns are dominated by the slow tempo of population growth and agricultural labor force transition that characterizes "long duration" social transformations discussed by Braudel (1979).

Merging with the global patterns just discussed, but characterized by generally finer and shorter scales, is a cluster I have called "national industrial modernization." This is defined by the rates at which nations substitute new basic industrial and energy producing processes for ones that have become inefficient or unproductive. Though such substitutions can be observed at both sub- and supra- national scales, national characteristics, cultures, and policies often seem to play an important role in their phasing. Much of the last couple of decade's work on technological forecasting and energy policy analysis has focused here.

"Regional agricultural development" is characterized by scales that are an order of magnitude finer and faster than those of the global political/demographic patterns. I have defined this last cluster of Figure 11 in terms of the size of crop regions and zones around the world, and the characteristic rates at which new higher yield or higher profit crop varieties replace their predecessors in such regions. Concerns at these scales seem heavily influenced by the writings of development- oriented economists of both market and Marxist persuasion.

The gap in Figure 11 between the clusters of farm activities and regional agricultural development is almost certainly an artifact of my opportunistic data set. I suspect that a variety of cooperative or market-related patterns and processes would fill it were the relevant data available. Community-level sociological and microeconomic concerns probably provide the relevant scholarship (12).

We are now in a position to compare the scales of social and ecological phenomena with scales of environmental variation. Figure 12 overlays the scale characterization of climate first presented in Figure 8 with the scale characterization of social and ecological phenomena from Figure 11. Note the three dominant bands constituting weather phenomena, climate plus social phenomena, and ecological phenomena. This quantitative picture confirms several qualitative impressions mentioned earlier. In particular, at any given spatial scale, background changes and intentional adjustments in human society will tend to occur at rates comparable to changes in climate. Ecological patterns will remain relatively constant during those changes, while (not surprisingly) weather will be changing so fast as to appear as background noise rather than any secular trend. The comparable scales of climatic and social change raise the prospect of particularly strong interactions between the two. Figure 12 suggests, for example, that the social options for dealing with major droughts could realistically include significant regional to national scale changes in crop types and industrial production processes. A preoccupation with short term relief and welfare measures may leave such potentially effective options unexplored. Similarly, long term global warmings of the sort experienced from the middle of the 19th to the middle of the 20th century are sufficiently widespread and slow to be accompanied by major changes in the distribution of power and people on earth. Attempts to assess the practical implications of similar climate changes in the future -- whether related to carbon dioxide or not -- will have to contend with the likelihood of comparably extensive "background" restructurings of the world's geopolitical stage.

Interactions from a temporal perspective: Certain aspects of the relationships suggested in Figure 12 can be seen more clearly and at higher resolution by scanning vertically the plots of time scales already presented in Figure 9 and of space scales from Figure 10. Focusing first on the temporal domain, several relationships stand out. To begin with, the "violent weather" that has been the focus of so many studies of environmental hazard clearly comes and goes on much faster time scales than most of the processes reviewed here. Recall that this is intentional. I purposefully omitted from the study fast scale social and ecological adjustments of the sort discussed by Burton, Kates, and White (1978) and Ford (1982) on the grounds that these have been relatively well explored. My work only confirms that, to a first approximation, scholars interested in the social and ecological impacts of violent weather events can consider processes such as those listed in Figure 9 as sufficiently slow to be effectively constant over the time scale of the weather event.

A much different and less obvious relationship holds for the very slow scale climate change represented in the figures by the historical global warming of the late 19th and 20th centuries, and by the future global warming predicted to result from anthropogenic production of various "greenhouse" gases. Changes in precipitation may be more important than those in temperature, but even rough estimates of their time scales are lacking. Relative to such climate variations, the characteristic time scales are very fast for animal and vegetation biomass accumulation, for the crop growth cycle, and even for the regional substitution of high yield crops for traditional ones. To a first

approximation, such ecological and social processes may thus be expected to keep pace with climate warmings. At any given time in the warming, existing biomass or crop types are likely to be well adapted to prevailing conditions.

This perspective sheds some interesting light on the many studies purporting to analyze agricultural impacts resulting from a hypothetical carbon dioxide-related environmental change. Most such studies proceed by imposing an instantaneous warming, rainfall change, and perhaps fertilization influence on present crops, and then using within-year statistical or simulation models to assess the resultant change in yields. But the perspective developed here suggests that the use of the instantaneous change assumption is wholly inappropriate and misleading. For the climate change is likely to occur so slowly relative to normal patterns of crop improvement and replacement that it is not the crops represented by present yield models that will be responding, but rather crops that have been bred and selected in "changed" conditions very close to those they will experience in the field. This point was made explicitly by Paul Waggoner in his contribution to the recent U.S. National Research Council study on Changing Climate (NRC, 1983). Waggoner argued that the yield decreases expected in American crops because of carbon dioxide-induced climate changes between now and the end of this century would be swamped by rapid genetic-based improvements in yields expected to occur over comparable time scales.

Figure 12 also shows that certain ecological processes can be significantly slower than the climatic warming predicted to result from increased greenhouse gases. Large-scale range extensions of trees such as those following the last Pleistocene deglaciation may have operated on a time scale of thousands of years compared to the hundred years or less of the predicted warming. Some processes of soil formation are almost as slow. This means that vegetational range responses could fail to keep up with climate changes of the sort likely to be associated with a carbon dioxide-related warming. In this case (unlike the case of crop yields) the climate change would appear as essentially instantaneous relative to the rates of range extension. To a first approximation, efforts to analyze large-scale range responses of vegetation to a carbon dioxide-related warming probably would be justified in treating the warmed climate in equilibrium terms (e.g., in terms of model predictions of equilibrium climate under doubled carbon dioxide). Its dynamic interactions with the extending vegetational ranges could be ignored. This is in essence what Emanuel et al. (1985) have done in their application of the Holdridge ecological classification to analysis of the global ecosystem impacts of a long-term climate warming.

An additional insight can be gained from Figures 9 and 10 by focusing on the social processes that operate on a time scale comparable to that of a carbon dioxide-related global warming. Other things being equal, such processes can be expected to interact closely with each other and with the changing climate. Of the processes studied here, time constants like that of the forecast carbon dioxide-related warming are shared by demographic transformations of agricultural societies, the market share of various nations' principal industrial commodities, and the relative share of total energy demand met by particular fuels. This means that on the same time scale as significant climate change seems likely to occur, we can expect significant urbanization and market integration of today's less developed countries, significant changes in the focus of the world's economic and political power, and significant changes in the form and source of the world's energy base. Any convincing assessment of the impacts of a carbon dioxide-related warming seems obliged to address such social changes.

The same approach can be used to examine the relations among social phenomena, ecological processes, and environmental variations in rainfall and the other valued atmospheric components identified in Figure 1. Rather than going through the analysis here, I will leave it to the interested reader. (I discuss the implications of scale for assessing response options relevant to the non-radiative environmental components in Clark 1985c). Significantly, Figure 12 suggests that the social and ecological time scales relevant to even the longest drought episodes lie well below those characterizing the forecast carbon dioxide-related warming. This means that even the best climate impact studies of the North American Great Plains or Sahel droughts have had no reason to become concerned with the very long term processes of political, demographic or national industrial change. Such drought studies are therefore dubious analogs of interactions between societies and a carbon dioxide-related climate warming. Perhaps even more significant, scholars drawn to the study of climate-society relationships through case work on droughts and shorter-term climatic variations anomalies are most likely to think in terms of relatively short-term perspectives of micro-economics, policy analysis and sociology. The long-term perspectives of economic and political history necessary for analysis of carbon dioxide and related questions have simply not been in the mainstream of recent thinking on how to study climate-society interactions.

Interactions from a spatial perspective: Several additional, if not particularly surprising, relationships among climates, ecosystems, and societies are suggested from a comparison across spatial scales (see Figures 10 and 12). Global scale, long-term environmental changes constitute all-encompassing fluctuations for all the social and ecological patterns discussed here. The globally averaged aspects of the change define a single global environmental event for all farms, nations, and continents alike.

These spatial relationships become more relevant for the design and interpretation of social response options when medium scale environmental fluctuations are examined. Average-size droughts, for example, pose relatively local environmental fluctuations for the world as a whole, for continental masses or for the largest nations. Global ecological or economic patterns and even truly national indicators (e.g., gross domestic economic production) of large nations will be little affected by such droughts. Conversely, however, individual vegetation associations, farms, all but the largest drainage basins, and small nations experience even intermediate-sized droughts as all-encompassing environmental fluctuations. Important ecological and social properties at these scales may be greatly perturbed by the occurrence of a drought.

Hermann Flohn (1980) has suggested that a nation's size may be important in determining its general sensitivity to climatic variations. The same hurricane, drought or heat wave that causes only acute local difficulties for a country the size of China can affect every person, farm, or forest for a country the size of Bangladesh. Intranational transfers of people, food, or financial aid may be all that is necessary to cope with the climate fluctuations in the former case. In the latter, international aid and the obligations it entails may often be the only recourse. His analysis suggests that nations larger than one million square kilometers or so (the median size of the world's nations) should be significantly less vulnerable to a variety of climate fluctuations than their small neighbors. This expectation, as well as the general tendency of vulnerability to decline with increasing size, is partially borne out by the data on variability in wheat production discussed by Oram (1985, Table III) and plotted as a function of arable land area in Figure 13 (13). Other factors relevant to yield are obviously involved as well, but

more explicit attention to the size component of vulnerability would almost certainly help to clarify the current debate on climate sensitivity and impact.

Concluding remarks: The analysis presented here has illustrated the vast range of scales over which the earth's environment, and particularly its climate, interact with its ecosystems and societies. These scales span more than seven orders of magnitude in both the spatial and temporal domains. Climatically, they include such diverse phenomena as the virtually instantaneous local impacts of tornadoes and the century-long trends in globally averaged temperature. From an ecological perspective, everything from the behavioral responses of individual organisms to the biogeographic patterns of speciation are involved. And the relevant social phenomena range from individual farmer's planting decisions to global patterns in the development and wealth of nations.

Each of these scale-defined areas represents a legitimate focus of inquiry. But it is probably unrealistic to believe that a single "field" of environmental policy analysis and management will ever evolve that can do full justice to the range of diverse concerns and perspectives they encompass. This need not be a problem, so long as participants in debates about the interactions of environments and societies concede that causal explanations, variables, and generalizations relevant at one set of scales are unlikely to be appropriate at others. The challenge is not to establish the preeminence of any particular scale, but rather to match scales of explanations, processes, and patterns in a realistic and effective way.

The most obvious implication of the perspective developed here is that the choice of which ecological or social processes to include and which to exclude in assessments of social response options to carbon dioxide-related environmental changes should be made with much more explicit attention to the time and space scales at which the changes are expected. No simple rule can automatically select the "proper" scale for attention. The elementary distinctions between fast and slow, big and small that I have employed here have a certain rough-and-ready utility. They can also be enormously misleading (14). But unless and until some general theory can be developed and tested, I believe that a useful first approximation in the conduct of response assessments would be to focus attention on social or ecological processes characterized by approximately the same scales as the environmental change of immediate interest.

Other things being equal, processes occurring on much smaller and faster, or much larger and slower scales than the environmental change itself are unlikely to interact with it as strongly as those of comparable scale. Thus, for long-term, large-scale environmental changes like those associated with carbon dioxide are considered, useful impact studies must seriously address the possible significance of long-term, large-scale social changes. Those associated with demographic transitions, shifts in the centers of world production of major commodities, and turnovers in the technologies of basic energy production would seem to be of major importance. Whether such processes would turn out to dominate the practical implications of climatic and other environmental changes associated with carbon dioxide can only be determined through careful analysis of particular cases and circumstances. But a beginning must be made to break away from the current habit of focussing on the same familiar fast and small scale social and ecological responses, regardless of whether one is investigating the impact of highland cold waves, regional droughts, or global warming.

To the extent that such basic choices of scale in the analysis of social response options can be brought under intellectual control, there opens a range of prospects for the shaping of usable knowledge on the practical implications of the carbon dioxide question. Some of the more urgent and promising of these prospects are discussed in the next and concluding section of this essay.

6. Prospects for Usable Knowledge

Previous sections of this essay have sketched elements of a framework for thinking about the practical implications of the carbon dioxide question. Perhaps the greatest immediate obstacle to constructing truly usable knowledge upon this framework is the mismatch between the characteristics of carbon dioxide-related environmental changes most relevant to societies and the characteristics most studied by scientists. I have already alluded to several of these discrepancies. Here I will touch on three of the more important ones for which recent studies have suggested real prospects for progress: risk assessment, frequency of extremes, and policy exercises. My goal is not to provide a comprehensive review but rather to focus attention on topics where additional investment of effort might be expected to yield particularly high returns of usable knowledge.

A question of risk assessment

I believe that the greatest single blunder in contemporary efforts to understand the practical implications of the carbon dioxide question is the continuing focus on "most likely" rather than "possible" impacts and consequences (1). In the short run, the greatest single addition to usable knowledge about the carbon dioxide question might well come from recasting it as a problem of risk assessment and management.

Every responsible scientific assessment of the last several years has noted (if not always emphasized) how thoroughly uncertainties pervade the carbon dioxide question. Both the policy makers cited in section 2 and the scientists who write the assessments are concerned that continued releases of carbon dioxide and related substances might bring about changes in the planet's climate, sea level, water flow, forest productivity, and agriculture that would be sufficiently large to fundamentally alter the structure and function of modern civilization. On the other hand, the changes might not occur and, even if they do, might be beneficial or might not be big enough to matter. How to weight these contending possibilities in assessing the practical implications of the carbon dioxide question is not clear. But experience with other situations presenting a small chance of big changes makes it seem virtually certain that the most useful approach will not be one which simply assumes that the actual outcome will lie half way between the extremes.

For most environmental questions where scientific uncertainty is important, the policy analysis community has come to view its task as one of risk assessment and management. For the carbon dioxide question, the policy analysis community has, almost without exception, ignored the uncertainties and their implications altogether (2). This lack of analytic attention has left the uncertainties in the carbon dioxide debate open to unconstrained use as propaganda by all extremes of the political spectrum sketched in section 2. Those governments and other parties that simply don't like the policy implications of treating possible impacts of carbon dioxide and related issues seriously have found it convenient to declare that the uncertainties make any assessment premature. Those who do like the policy implications have used the same uncertainties to support their arguments for precipitous action "just in case". A risk assessment approach could not be expected to eliminate such posturings. It might, however, constrain them and provide more usable knowledge for those

parties seriously interested in understanding the practical implications of the carbon dioxide question (3).

The methods of risk assessment are relatively well developed, and a healthy critical dialog now exists regarding their strengths and weaknesses (4). General frameworks for risk assessment in the context of climate change have been discussed by several authors (5). Early applications to problems of long term environmental change were flawed in ways that could have been avoided through better familiarity with the basic methodological literature. An example is the National Defense University's naive use of expert judgement distributions to characterize the probability of various climate changes to the year 2000 (Stewart and Glantz 1985). Several examples of good practice with useful results do exist, however, including the work of the Tukey Committee on Impacts of Stratospheric Change (National Research Council 1979a,b) and of Morgan et al. (1985) on deposition and impacts of sulfur emissions from power plants. These could serve as models for useful work on the carbon dioxide question. The major obstacle to their application is the absence of usable uncertainty estimates from the scientific research community.

Scientific uncertainties in the carbon dioxide question: Until very recently, little effort had been made to provide systematic, quantitative estimates of the scientific uncertainties relevant to the carbon dioxide question. At the level of basic data measurements and model calibration, of course, conventional error bars have often been provided. But these are not generally aggregated to give "higher level" uncertainty estimates of atmospheric concentrations of carbon dioxide or climate response. The few higher level confidence limits that have been given, such as the Charney Committee's frequently cited average global temperature increase of 1.5 to 4.5 degrees C for a carbon dioxide doubling, have lacked explicit methodological foundation and almost certainly suffer from the same kinds of biases identified by Stewart and Glantz for the NDU study (6).

An example of what can be done through systematic efforts to estimate higher level uncertainties in the carbon dioxide context is provided by Nordhaus and Yohe's (1983) study of possible global carbon dioxide emissions and concentrations to the year 2100. The authors used a simple globally aggregate model of energy economics, coupled it to an even simpler model of atmospheric retention, estimated uncertainties for the component parameters, and calculated the resulting range of emissions and concentrations using Monte Carlo simulation. A sample of their results for the year 2100 is given in Figure 14. Note that these calculations give a 95% confidence limit of about 450 to 1450 ppm.

The implications for climate of such uncertainties in the levels of future carbon dioxide concentration have been explored by Dr. Robert Dickinson who, through his work with the previously mentioned Tukey Committee, probably has as much experience with the derivation of aggregate uncertainties as anyone in the atmospheric science community. Drawing on the Nordhaus and Yohe analysis, and including his own estimates of uncertainties for emissions of other radiatively active trace gasses and for climate sensitivity to such emissions, Dickinson (1985) calculated the range of possible "greenhouse" warmings of the earth's average climate. He concludes that by the year 2100 this could total more than 9 degrees C with a probability of about 10(-2) and more than 15 degrees C with a probability of 10(-3) to 10(-4). Either possibility would produce "conditions as warm as the Cretaceous era of 100 million years ago when polar temperatures were 10 to 20 degrees C warmer and tropical temperatures were perhaps 5 degrees warmer than present" (Dickinson 1985). A substantial rise in

sea level, perhaps accompanied by disintegration of the West Antarctic ice sheet and an ice free Arctic Ocean, would almost certainly accompany such a drastic change.

If we knew for certain that environmental changes of the magnitude described by Dickinson would accompany continuing releases of carbon dioxide and other gasses to the atmosphere, a number of extreme social responses could be both economically justified and politically feasible. Common habit, however, has been to let the very small probabilities of drastic warming totally rule out consideration of such responses. To determine whether this habit is justified or rational would require that the probabilities of drastic impacts related to carbon dioxide be compared with probable drastic impacts of measures that might be taken in response to increasing concentrations of carbon dioxide and other greenhouse gasses. The necessary analysis has not been done. As an illustrative example, however, it may be useful to consider some of the risks associated with possible responses to the carbon dioxide question that involve substitution of nonfossil energy sources.

The relative risks of response options: Large hydropower dams, for example, have a probability of failure of about 10^{-4} per dam-year (Weinberg 1985). A given new dam therefore has something on the order of a 10^{-2} chance of failing by the year 2100 -- the same chance that Dickinson gives a 9 degree C global warming. The U.S. Nuclear Regulatory Commission has set a design goal that would have light water reactors experience core damaging accidents at about the same rate as dams fail, ie. with a chance of 10^{-4} or less per reactor-year, or 10^{-2} per reactor by the year 2100 (Nuclear Regulatory Commission 1983). Most such accidents, like the one at Three Mile Island, would not kill anyone. In contrast, the worst-case nuclear power accident envisioned by the Rasmussen Reactor Safety Study is predicted to cause 3000 early fatalities, 45000 early illnesses, and a highly uncertain number of delayed cancer deaths among the 10 million people exposed to radiation in the accident scenario (Nuclear Regulatory Commission 1975). Note that the predicted casualties are thus of the same order as those actually resulting from the chemical disaster at Bhopal. The worst-case nuclear reactor accident was given by the Rasmussen Study a probability of 10^{-9} per reactor-year. Under reasonable assumptions about the growth of the nuclear power industry (ie. 100 to 1000 LWRs in operation), this means that the chance of such a worst-case nuclear power accident occurring somewhere in the world before 2100 is probably between 10^{-4} and 10^{-5} .

To the extent that one believes any of these figures, the chance that the world of 2100 will have witnessed a single local nuclear power catastrophe is probably 10 and perhaps 100 times less than the chance that everyone in the world will be living in a Cretaceous-like hothouse, perhaps with beaches several meters above their present levels. This assessment jars common sense, which is exactly why careful risk assessments of the carbon dioxide question and the possible social responses to it should become a priority task. To enable such assessments, the first need is for more scientific research to be focused directly on estimating the uncertainty of important higher level components of the carbon dioxide question. Moreover, it may be that research designed to define and bound the uncertainties will be of a qualitatively different nature than research designed to refine estimates of most likely outcomes (Dickinson 1985). These possibilities need to be seriously investigated and taken into account in funding priorities for research on the practical implications of the carbon dioxide question.

Changing frequencies of extreme environments

Most efforts to assess the practical implications of the carbon dioxide question have focussed on predicted or postulated changes in mean properties of the environment. Relevant studies of climate impact, for example, have usually dealt with changes in annual or seasonal values for temperature or precipitation. We know, however, that some significant impacts of the environment on societies and ecosystems are due to extreme events, i.e. to fluctuations around the mean condition. And some of the best recent impact work has shown that one of the most useful forms in which climate change forecasts can be presented to policy people is as changes in the frequency of significant climate anomalies (Parry et al., 1986).

Extremes in time: Most of the literature on extremes deals with fluctuations in time. Some analysts have written of a split between analysts emphasizing the "slow change" and "extreme event" views (Warrick et al., 1985). The academic split has been reinforced by the political disagreements noted in section 2 over the relevance of short term versus long term impacts. This is not, however, a useful dichotomy. The overwhelming message of the data reviewed in section 5 is that the environment varies at all scales, and societies can respond to such variations at all scales. If carbon dioxide and related emissions change the climate, they will change the global means and the spatial distribution and the frequency of climatic anomalies. Societies could and probably would simultaneously respond to such changes at the global and regional and local scales suggested in Figure 12. As I argued in section 5, the challenge is not to select one scale as the key to understanding, but rather to understand the interactive roles played by environmental changes and social responses across the overall spectrum of spatial and temporal scales. Efforts to meet this challenge should benefit substantially from recent studies on the role of extreme events in determining the response of social and ecological systems to environmental change. Here I will try to clarify some of the central themes of that writing, and to suggest some useful points of departure for further research.

The general thrust of the "extreme event" argument in climate impact studies was developed by Martin Parry (1978) and has been summarized by Wigley (1985) as follows: "Impacts accrue... not so much from slow fluctuations in the mean, but from the tails of the distribution, from extreme events. In many cases, an extreme can be defined as an event where a climate variable exceeds some absolute threshold." There are two distinct components to this argument: 1) the relation between changes in mean environmental properties and the frequency with which specified extreme environmental conditions are exceeded, and 2) the nonlinear or threshold responses of social, agricultural, and ecological systems that give those extreme environmental conditions their significance. My discussion will focus (with most of the literature) on the problem of climate change, though the argument should hold for other valued environmental components as well.

Means and higher moments: The most common assumption in the "extreme event" literature is that a shift in the mean climate occurs with no shift in variability. Fukui (1979) introduced this convenient relationship at the World Climate Conference with his oft-reproduced figure of two bell curves of precipitation, identical except for the relative displacement of their means. There is, however, little reason to expect that actual changes in mean climate would preserve variability. Dickinson (1985) has pointed out that the General

Circulation Models (GCMs) presently used to evaluate the mean climate changes resulting from increased greenhouse gasses actually simulate a wide range of weather and climate fluctuations. Their output could be sampled to yield a great variety of more realistic variability statistics. At present, however, the assessment community has generated insufficient demand for particular variability statistics to keep them from being discarded by climate modelers who find more meaning and less confusion in simple means. This waste could be avoided if the impact assessment community could come to agreement on what kinds of variability data would be most useful for the modelers to save. I will have more to say on this shortly.

The probability of exceeding arbitrary values: Because of the bell-like shape of most climate variability distributions, the frequency with which an arbitrary value of climate will be exceeded can be very sensitive to changes in the mean and higher moments of the distribution. Mearns et al. (1984) calculate this sensitivity for changes in weather variability. Wigley (1985) provides a graphical summary for normally distributed properties in the form of Figure 15. He argues that "a change in the mean by one standard deviation would transform the 1-in-20 year extreme to something that could be expected perhaps 1 year in 4, while the 1-in-100 year extreme becomes a 1-in-11 year event. Changes in the probability of two successive extremes are even larger." Which of these transformations is most significant for assessing the practical implications of carbon dioxide-related environmental changes? There is no purely statistical reason to focus on the 1-in-20 or 1-in-100 or 3-consecutive-bad-years scenarios. But if the extreme event perspective is not to become a mindless quest for all manner of variability statistics, then the assessment community will have to tell the climate modelers and other environmental scientists just which changes in what extreme events most concern them. Some general guidelines have been discussed by Parry and Carter (1985). Once again, however, real progress requires that the assessment community devote much more attention to characterizing the specific "thresholds" that matter in particular social and ecological systems.

Thresholds and nonlinear impacts: The key to the whole "extreme event" argument is the existence of threshold or nonlinear responses of social or ecological impacts to changes in climate. If impacts over a given period were directly proportional to the total amount of rain or heat or whatever provided by the fluctuating climate over that period, then knowledge of the mean climate for the period would provide all the information we needed to predict or explain the impact. For some social activities like transportation, such a linear (additive) relationship between climate and impact may indeed be the case (Palutikof, 1983). For many other properties of interest, however, the relationship between climate and impact is highly nonlinear, and the distribution of extremes relative to threshold levels may therefore be significant in assessing the practical implications of climate change.

Figure 16, for example, shows how paddy rice yields in Japan drop off rapidly as mean summer temperatures fall below 20 degrees C. Figure 17 shows that primary productivity of whole ecosystems declines rapidly when annual precipitation falls below 1000 mm. The well known Holdridge Life-Zone Classification reproduced in Figure 18 is constructed on logarithmic scales, somewhat obscuring its property that the same change in temperature or rainfall has a much larger impact on life forms in cold or dry than in hot or wet climates. (This disproportionate ecological impact of temperature change on cold area ecosystems, combined with the disproportionate warming of polar regions predicted for the "greenhouse" effect, is why Emanuel et al.'s (1985)

maps of vegetation in a high carbon dioxide world show such drastic changes in northern latitudes). The response nonlinearities shown in the preceding figures imply that not all climate changes are equally important. In the case of rice, a temperature fluctuation in a given summer of -2 degrees around a mean summer temperature of 23 degrees will have little impact on yields, whereas the same fluctuation around a reduced mean of 21 degrees could be expected to cause major yield declines. A positive fluctuation of comparable magnitude in the following year would not compensate for the lost yields as it would in the linear case.

An additional dimension of the nonlinear response argument is fundamental to (but often only implicit in) the "extreme events" view of climate impacts. Parry's (1978) pathbreaking work on the significance of extreme events in assessing the impact of climate change on society focussed on the abandonment of marginal farming land when successive extremes of bad weather exhausted farmers' adaptive buffers. The key nonlinearity or threshold in Parry's farming system was that once the buffers were exhausted and the farmer abandoned the land, a return of several years of unusually good weather would not bring the land back under cultivation, even though the biological capacity for production had been restored. What had not been restored was the stock of labor, capital and social structure necessary to sustain farming in the area. These could be destroyed by a few years of bad weather, but only restored through a much longer run of good weather.

How many years of what kind of weather are necessary to exhaust the buffering capacity? This depends on many characteristics of the particular social or ecological system, especially those of characteristic time scales discussed in section 5. In the case of the Holdridge diagram, for example, the same 2 or 3 years of abnormally poor weather that sufficed to cause abandonment of Parry's farmland would not be expected to change a dry forest into a steppe. The buffering capacity of the forest system, and the ecological processes involved in reestablishing the steppe system have time constants that are simply too long to respond to such short term variations.

Multiple equilibria: The cases cited here provide specific examples of the properties of multiple equilibria and bifurcation found in many nonlinear social, ecological, and physical systems, especially those operating at multiple time scales (7). Typically in such systems, slow variation in one property can continue for long periods without noticeable impact on the rest of the system. Eventually, however, the system reaches a state in which its buffering capacity or resilience has been so reduced that additional small changes in the same property, or otherwise insignificant external shocks push the system across a threshold and precipitate a rapid transition to a new system state or equilibrium. Once this rapid transition has commenced, reversal of the slow variation trend, removal of the external shock, or other returns across the threshold generally do not restore the system to its original equilibrium. Like an automobile driver caught in the one-way streets of a big city, getting back to the place just passed requires a circuitous and time consuming journey. Recent reviews of such discontinuous, imperfectly reversible change in ecological systems (Holling 1985) and sociotechnical systems (Brooks 1985) provide a number of real world examples and the beginnings of a general understanding of the key processes and relationships involved.

The time is ripe for the "extreme event" element of the carbon dioxide debate to tap this emerging understanding. The goal should be to describe what kinds of thresholds are relevant to the way social and ecological systems will

respond to carbon dioxide-related changes, what kinds of events are sufficiently extreme to push those systems across their respective thresholds, and how the frequency of those events will respond to increases in carbon dioxide and related emissions. Progress towards meeting these goals will first of all require analyses of the stress responses of specific social and ecological systems that are sufficiently detailed and realistic to capture the multi-equilibrium, multi-time scale, imperfectly reversible phenomena alluded to above. The research program of Martin Parry and his colleagues at the International Institute for Applied Systems Analysis (8) shows how such studies can be done for a wide range of agricultural systems (Figure 19). Exciting beginnings have also been made in the study of relevant forest ecosystem response characteristics (9).

Still needed are efforts to extract from such studies characterizations of the specific kinds of changes in variability and extremes that impact assessors would find most useful as a research output from climatologists, atmospheric chemists and other environmental scientists. When such specific characterizations have been made of which environmental extremes would have what significant practical implications, it will be reasonable to ask that research in the natural sciences begin to focus on the carbon dioxide-related changes in the the distribution of those extremes that might be encountered in the future.

Extremes in space: The question of extremes in space has been much less discussed than that of extremes in time. It is not clear, however, that the spatial issue is any less important. Experience of the last two decades shows, not surprisingly, that when droughts occur simultaneously in several major grain exporting areas the practical implications for the world food picture are much more serious than when the same overall rainfall deficit is distributed evenly, or concentrated in less critical zones (Hopkins and Puchala 1978). I noted in section 5 Flohn's (1980) suggestion that to the extent that droughts or other climatic anomalies (ie. extremes) have a characteristic spatial scale, nations significantly larger than that scale should be less vulnerable to climate fluctuations than nations significantly smaller. Under changing mean climates, however, the spatial scale and locations of anomalies may also shift. Both model and analog studies of carbon dioxide-related climate changes indeed suggest that the globally averaged values of temperature, precipitation, and other properties can be expected to vary significantly through space. Some regions may even become cooler as the global average temperature increases. The question remains virtually unasked, however, of whether carbon dioxide related climate changes are likely to change the scale and location of anomalies in ways that are particularly significant for societies (10).

As in the case of changes in the temporal distribution of climatic extremes, the first step in addressing the problem must be for the assessment community to specify the kinds of spatial anomalies -- their sizes, locations and relationships to one another -- that could have a disproportionate impact on society. Parry's work on climatically marginal areas again provides one of the strongest beginnings we have, but much more work in this direction is needed (eg. Parry et al., 1986). The climatologists and other environmental scientists could then focus their studies on determining how likely such specific spatial extremes might be in a future of carbon dioxide-related changes.

Policy Exercises: Learning to cope with the carbon dioxide question

This essay has focussed on the design of tools that, I have argued, individual nations and interest groups should find useful in coping with the practical implications of the carbon dioxide issue. Clearly, many of the proposed tools have barely been sketched. None are as well developed as they might be. All would benefit from further efforts directed towards their improvement. But with all tools and would-be practical devices, there is a limit to how much improvement can be expected from theoretical studies divorced from actual conditions of use. And no tool has value independent of the skills of its user -- skills that can only be learned through long and continuing practice. If the tools and approaches suggested here are to evolve into something of practical value for societies, societies must find ways of putting them to work. Only such exercises in application can produce a realistic feel of how we can best use the tools, of what are their actual strengths and limitations, and of where they can best be improved (11).

What might such exercises look like? What skills would they try to develop? How would they provide opportunities to apply and test our incomplete understanding of the carbon dioxide question and possible responses to it?

The need for practice: Practicing with Earth itself obviously has its drawbacks. Scientists may speak of the human releases of carbon dioxide to the atmosphere as "a great geophysical experiment", but the results of this particular experiment may come in a bit late to be of much use for those living in the test tube. The obvious alternative of practicing on various mathematical models of the Earth also leaves much to be desired. Any notion of confidently predicting the practical consequences of alternative response options wilts under the numbing scale and complexity of the carbon dioxide question, the profound uncertainties that remain in our scientific understanding of it, and its dependence on equally complex and uncertain "background" changes in the world's environments and societies. Moreover, even in simpler contexts, formal models have generally not been conducive to the close interaction among scientists, politicians, and other people that would be such an important aspect of social learning to cope with the carbon dioxide question.

More useful means of practicing how to cope with complex interactions of environments and societies are badly needed, not only for the carbon dioxide question but also in a wide range of other problem areas. Considerable attention has been devoted to these needs in the program on "Sustainable Development of the Biosphere" now being carried out by IIASA, the International Institute for Applied Systems Analysis's (12). Following an extensive review and evaluation of experience with alternative approaches (Brewer 1985), the IIASA effort is now developing a program of "policy exercises": organized efforts that bring together policy people, scientists, and technologists to practice writing "future histories" of plausible interactions between societies' development activities and the global environment.

Political exercises and gaming: Policy exercises are derived from approaches developed in support of political-military strategic planning during the late 1950's and early 1960's (Goldhamer and Speier, 1959). At that time, experience had shown that formal models were inadequate to capture the contingencies, the unquantifiable factors, and the contextual richness that seemed central to the main lines of political evolution between the great powers in the period 1955-

1965. The models also tended to strengthen rather than relax the barrier between analysts and practitioners of political and military strategy. In attempting to design more useful integrative approaches, Herbert Goldhamer of the Rand Corporation realized that his "problem was similar to that confronting historians. He was faced with the task of writing a 'future history' to clarify his ideas about the motives and influences affecting the behavior of great powers, their leaders, and others in the real political world." (Brewer and Shubik 1979: 101).

The method devised by Goldhamer and his colleagues to write these future histories was dubbed "political gaming". Teams of human (as opposed to computer) participants were confronted with generally realistic problem scenarios and required to work through responses both to the scenario and to the moves made by other teams. The role of "Nature", which determines the impact on conditions of play resulting from the moves of the teams, the injection of unexpected events, the introduction of constraints on allowable responses, and so on, was played by the control team responsible for organizing the exercise (13).

Brewer (1985) describes four "difficult questions that eluded or exceed the capacity of alternative analytic tools" that were explored by the original political exercises. These questions sufficiently resemble those that confront us in learning to cope with the carbon dioxide question to warrant quoting here:

- * What political options could be imagined in light of the conflict situations portrayed? What likely consequences would each have?

- * Could political inventiveness be fostered by having those acutally responsible assume their roles in a controlled, gamed environment? Would the quality of political ideas stimulated be as good or better than those obtained conventionally?

- * Could the game identify particularly important, but poorly understood, topics or questions for further study and resolution? What discoveries flow from this type of analysis that do not from others?

- * Could the game sensitize responsible officials to make potential decisions more realistic, especially with respect to likely political and policy consequences?

Future histories of the carbon dioxide question: Experience with political gaming indicated that each of the preceding questions could be given an answer of "yes, but only under favorable conditions" (Brown and Paxson 1975; Brewer and Shubik 1979). The same experience led to several additional conclusions suggesting that the political exercises might serve as a basis for designing policy exercises to practice social responses to the carbon dioxide question and other environmental problems. Several of the most important of these potential linkages between exercises in political and environmental policy are summarized below.

- * The political games were found to perform better than alternative approaches in studying "poorly understood dynamic processes... [and] institutional interactions" and in "opening participation to many with different perspectives and special competences, on a continuing basis over time" (Brewer 1985). The need to accomodate multiple political and environmental perspectives in efforts to learn effective responses to the

carbon dioxide question has been emphasized throughout this essay. The "poorly understood" nature of our knowledge of long term, large scale environmental processes and institutional responses likewise requires no further elaboration. Policy exercises might be designed in a way that would let us address these critical issues for the carbon dioxide question.

* "The selection of competent professionals to participate in the political exercise proved to be critically important. This situation is analogous to that in chess or other games when inferior players tend to consolidate their own bad habits rather than being stimulated to improved or inspired play" (Brewer and Shubik 1979: 101). To be useful, policy exercises on the carbon dioxide question would almost certainly have to involve several of the very top scientists who have been involved in recent assessment efforts, plus their opposite numbers from the world of politics, finance, and industry. The political gaming experience suggests that there is little point in carrying out such exercises using second rate consultants and middle level bureaucrats. But securing the participation of sufficiently senior and innovative people may not be as difficult as it sounds. For environmental problems in general and the carbon dioxide question in particular, some of the best scientists and best policy people have been expressing a growing dissatisfaction over their inability to address each other except through stultifying layers of reports and bureaucracy, or in ritualized and guarded public encounters. Carefully designed policy exercises might provide the channel and forum of communication they seek.

* "[O]ne of the most useful aspects of the political game was its provision of an orderly framework within which a great deal of written analysis and discussion took place... [O]ral or written discussion of political problems that arise during the game is one of its most valuable features" (Goldhamer and Speier 1959: 77-8). Finding a way to order, to evaluate, and ultimately to use the great volume of literature now being generated on the scientific and practical aspects of the carbon dioxide question is becoming increasingly urgent. The occasional grand Villach Conference has a role to play in linking theory to its practical implications, but that role is limited. As I have argued repeatedly, we need different opportunities to practice using the awkward tools our limited understanding has provided, and to learn how they can best be applied to the practical problems than confront us. Policy exercises could provide such opportunities.

* The "future history" orientation of the games' output makes them an excellent vehicle for exploring response options in terms of the time sequences of coordinated action they imply. The requirement that such actions taken in the games be internally consistent, and that ways be found to sustain them in the face of new problems, other groups' policy agendas, and wavering social will has often proved to be among the most powerful tools of policy analysis (Schelling, 1984). Some preliminary work in exploring time sequence constraints on social responses to the carbon dioxide question has been done in connection with the market penetration times of nonfossil energy technologies (14). This has yielded some of the more useful insights yet available on what energy policy can and cannot do about the practical implications of the carbon dioxide question. Policy exercises could be designed that would allow such market penetration findings to be explored in a more general context of the time characteristics for other responses and background changes that I discussed in sections 4 and 5.

* The political games helped to refine future research priorities for technical participants and their staffs by exposing them to the kinds of questions their political masters would need answered under a range of often

unconventional but still plausible future histories. This is an extremely important result since "[t]he game... may under favorable circumstances make more effective use of existing knowledge than other modes of intellectual collaboration, but it would be placing an intolerable burden on it to treat it as a machine that displaces theoretical thought and empirical research" (Goldhamer, 1973). Likewise, policy exercises would in no sense be a substitute for the careful research on basic science and response options that are required to improve the basic tools that can be used in fashioning effective social responses. But the exercises might help the research community to learn which answers -- which tools -- are likely to be most needed by policy people across a wide range of plausible future histories for the carbon dioxide question.

If experience with political exercises is any guide, we should expect that many of the ostensibly useful answers now being sought by scientists and analysts are ones for which no policy people are ever likely to ask the relevant questions. (My own bet is that most work on cost/benefit estimates of "the" impacts of carbon dioxide will fall in this category of answers no one ever asks for). Conversely, we are likely to find a number of urgent questions emerging in the course of the policy exercises that scientists could have studied, but haven't. I suggested earlier that such practically important but understudied questions might include "row assessments" of the net impact of carbon dioxide-related policy actions across a range of environmental components, estimates of the "not impossible" as well as "most likely" changes in those components resulting from carbon dioxide and related emissions, and studies of nonlinear and threshold responses to carbon dioxide-related environmental changes. More generally, I suspect that the design of global environmental monitoring and data systems would benefit tremendously from such policy experiments. In the final analysis, however, it is only by working through specific future histories of the carbon dioxide question and social responses to it will we have an opportunity to move beyond mere individual opinions to a critical, perhaps even consensual, assessment of what might turn out to be truly usable knowledge.

In conclusion: The carbon dioxide debate has now reached a stage at which further advances in coping with its practical implications will require much closer integration of political and environmental perspectives than has until now been the case. Some form of policy exercise, aimed at writing future histories of the carbon dioxide problem and societies' responses to it, seems to offer the most likely prospects for fostering such integration. Over the interval leading to the next Villach Conference, several experimental policy exercises might profitably be conducted, each involving perhaps a dozen of the most informed and creative scholars and policy people concerned with the carbon dioxide question. The only way to discover whether we would really learn something useful from such an experiment will be to try it. At a minimum, I suspect it would be fun.

NOTES

Section 1

1) See especially National Research Council (1983) and WMO/ICSU/UNEP (1985). The most concise statement of these central features is given by Schelling (1980), in a document that has substantially influenced the approach of this paper and on which I shall draw extensively.

2) A large and increasingly perceptive literature exists on the uselessness of most forms of well-intentioned policy analysis. A smaller but more interesting literature has begun to confront the challenge of producing usable knowledge in the face of incomplete scientific understanding and politically fragmented messes (Lindblom and Cohen 1979; Wildavsky 1979). I deal with these issues in the context of development policy in Chapter 1 of Johnston and Clark (1982). World-scale "messes" are often termed "the global problematique".

3) The notion that incomplete science applied in policy contexts can usefully be viewed as a tool has been developed by philosopher of science Jerome Ravetz (1985).

4) Richard Warrick, Senior Research Associate, Climate Research Unit, Univ. of East Anglia, Norwich NR4 7TJ, United Kingdom.

Section 2

1) See, for example, WMO (1984) and Bandyopadhyaya (1983).

2) Personal communication to R.E. Munn at World Climate Conference, 1979.

3) For this survey I reviewed published transcripts and my own notes of US Congressional hearings from 1976 to 1982 bearing on the carbon dioxide question. Full references for sources are given in the bibliography as U.S., Congress, ... (1976, 1979, 1980, 1981, 1982). I extracted all the questions posed by the Congressmen to their expert witnesses, and grouped them according to topic. In the selection used here, I have tried to present a representative sample of questions, leaving out only those relating directly to program management and budget of the US research program on carbon dioxide.

4) All subsequent citations in this section give the name of the U.S. Congressman who asked the quoted question. Pages and years given in the citation refer to Congressional hearing transcripts cited in the bibliography as U.S., Congress, ... (1976, 1979, 1980, 1981, or 1982). Thus "Bumpers; 1980: 109" signifies a question asked by Senator Bumpers on pg. 109 of U.S., Congress, ... (1980). The bibliography does not list the Congressmen individually.

Section 3

- 1) IIASA's study on "Sustainable development of the biosphere: managing interactions between the world economy and the global environment" is directed by William C. Clark, IIASA, A-2361 Laxenburg, Austria. The study is briefly sketched in Clark and Holling (1985) and is the subject of a forthcoming book edited by Clark and R.E. Munn (1985). The particular aspects of the study referred to here are dealt with in more detail in Clark (1985c).
- 2) This approach was initially described for general environmental impact assessment in Munn (1975:72).
- 3) For an overview of the key issues, see the special issue of Atmospheric Environment (18/3, 1984) on "Air pollution - health and management".

Section 4

- 1) See, for example, Lindblom and Cohen (1979); Wildavsky (1979); Clark et al. (1979).
- 2) Reviews are provided by WMO/ICSU/UNEP (1985), Edmonds and Reilly (1985), Ausubel and Nordhaus (1983) and Perry (1982).
- 3) The carbon dioxide question has taken on something of the character of the legendary North American Schmoor -- an unlovely beast that nonetheless provided almost anything you could imagine asking of it. Thus concern over carbon dioxide has been cited as a reason for pushing everything from fusion energy (Nuckolls 1982), to zero energy growth (Lovins et al. 1981). Section 2 suggested how very strange can be the political bedfellows brought together by the carbon dioxide question.
- 4) Carbon densities of major forest systems are given in Olson et al. (1983). Deforestation rates are from Gwynne et al (1983) and Clark et al (1982).
- 5) For an overview of the exchange of carbon dioxide between ocean and atmosphere, see McElroy (1985). An elegant graphical treatment of the carbon dioxide pump is given in Baes (1982). The long-term natural fluctuations of carbon dioxide in the atmosphere are reviewed in Sundquist and Broecker (1985).
- 6) Carbon has been increasingly removed as use of fossil fuels has shifted from wood towards gas. Marchetti (1976) shows the trend of the H/C ratio in fuels and speculates on the prospects for an all hydrogen energy economy.
- 7) Reviews are provided by Bach (1984, Chs. 6.2 and 6.3) and Baes et al. (1980).
- 8) See eg. Hess (1974); Kellogg and Schneider (1974); Mordy (1975).
- 9) For a recent review see Micklin (1985).

10) It bears mention that transformation of the built environment has already resulted in most school children and office workers of the developed countries spending much of their lives breathing carbon dioxide in concentrations well above those likely to occur in the atmosphere for several centuries (Clark et al., 1982; note 56).

11) A significant rise in sea level is likely to accompany any significant warming of the global climate. Recent studies suggest that the increase would most probably average something on the order of 10 millimeters per year over the next hundred years or so. The uncertainties in these estimates are substantial. Even less certain is the possibility that towards the end of the next century, breakup of the West Antarctic ice sheet could increase the rate of sea level rise by an order of magnitude, yielding a total increase of 5 to 6 meters over the next several centuries (National Research Council 1983; Hoffman et al., 1983; WMO/ICSU/UNEP 1985). These numbers can be put in perspective by noting that the average rate of sea level rise over the last 15,000 years (ie. since the last glaciation) is about the same as the rate predicted to result from climate warming over the next century: 10 mm per year. But these figures are higher than the abnormally low rate of 1-2 mm per year that has characterized recent history.

12) For perspective on this view see Bandyopadhyaya (1983), WMO/ICSU/UNEP (1985) and Chisholm (1982).

Section 5

1) This section draws heavily on Clark (1985a,b).

2) The practical implications of such changes for a farm or nation or other spatial unit can obviously be quite serious if the entire unit experiences the same environmental impacts. If, on the other hand, the impacts are sufficiently small scale or spotty, then there will likely be "good" areas that can be used to set off damages to the "bad" ones.

3) The phrase "characteristic time" has been used in different disciplines to cover a variety of properties relating to exponential decay rates, frequencies, residence times, doubling times and the like. All of these "characteristic" times are related, and all are useful. They are not, however, the same. For the purposes of comparisons in this paper, I have arbitrarily expressed all temporal scales in terms of "e-folding" time, T_e . This is the "natural" time scale for expressions of exponential growth or decay such as $N_t = N_0 e^{at}$, since the time T_e required for an e-fold increase (i.e., $N_t/N_0 = e$) in such a system is a constant $1/a$. For periodic, logistic, or other forms of system behavior, the e-folding time (or any other time characteristic) changes with system state. For example, an e-fold increase will take longer near the peak of a periodic cycle than at its mid-point. To permit meaningful comparisons, I therefore define T_e in such cases to be the e-folding time for a change centered on a point half way between the system's maximum and minimum values. (In particular, T_e equals the time to go from $N_1 = (e/2+1)$ to $N_2 = (e/2+1)$, where the total range of system variation is scaled between 0 and 1.) Traditional definitions of residence times, frequencies, and such can be expressed as simple multiples of T_e as shown in the Appendix to Clark (1985a).

The characteristic length scales reported here are defined, as appropriate for given cases, in terms of the square root of the area covered by the phenomenon, or its wave-length, or as the short dimension of long, narrow phenomena such as fronts and some drought zones.

4) Sources are Smagorinsky (1974); Jaeger (1983); Dickinson (1985).

5) See also Webb et al. (1985) and McElroy (1985).

6) Needed would be an anomaly pattern of a 6-8 year periodicity, cohesive over scales on the order of a couple of hundred kilometers.

7) The original data for the range extension figures are derived from pollen records, and reflect a complex interaction of processes of climate change, soil accumulation, and seed dispersal. If, as some would argue, the vegetational distributions are essentially in equilibrium with the climate, then these data are misleading in a section on ecological processes. They would then simply reflect the rate of climate change (see, for example, Webb 1982).

8) A general conceptual framework for thinking about the time scales of various human adjustments to natural hazards has been developed by Burton, Kates, and White (1978). They give particular attention to the short-term behavioral responses of people faced with disruptive environmental events. In what follows I will try to complement their work by focussing on some of the longer-time scale processes that may be particularly important in the interactions of societies with slowly changing environments.

9) These are based on a series of remarkable papers by Marchetti (Marchetti and Nakicenovic, 1979; Marchetti, 1981, 1983).

10) See data of Williams (1964) and Preston (1960) as plotted in Clark (1985a).

11) For example, ecologists at the high scale end of the regions shown in Figure 11 emphasize environmental influences on global patterns of productivity, speciation, and the like. Those at the low scale end tend to focus on dynamical models of animal mortality or plant yield reduction, factors triggering pest outbreaks, and such.

12) Yoshino (1983), cited in Yoshino (1986), has presented a space-time relationship for social activities that differs substantially from the one presented here, in that it overlaps with the band of weather rather than climate phenomena in my Figure 12. I have not yet been able to consult Yoshino's original paper to determine the reasons for this discrepancy.

13) I suggested in two earlier publications (Clark 1985a,b) that Flohn's hypothesis might be confirmed by Oram's data on all staple foods. Further examination of the data suggests, however, that the relationship I reported is dominated by the high variability of a group of nations whose admittedly small arable areas are also disproportionately in semi-arid zones. I am therefore less convinced than I was earlier that the significant factor in the observed relationship is size per se. This difficulty does not seem to exist for the wheat yield data.

14) A variety of ecological, climatological, and marine systems are known in which small and rapid fluctuation "cascade" up- scale through nonlinear processes to alter long- term, large patterns of system behavior. For the same systems, slow trends in other variables can change conditions in ways that radically alter the impact and propagation of acute local perturbations (Steele, 1978b; Lorenz, 1984; Holling, 1985). The continuing debate in historical research over the role of exceptional individuals or events versus the role of long- term, large- scale trends has much the same character of possible "cross- scale" influences. The greatest need is for careful case studies that distinguish which possible cross- scale influences are important in a given instance and which can be safely ignored.

Section 6

- 1) It is generally accepted that among the greatest blunders of military and political analysis is focussing on what one's adversary will probably do, to the exclusion of what he might. See, for example, Brewer and Shubik (1979: 98-99).
- 2) The most notable exception is Nordhaus and Yohe's (1983) analysis of uncertainties in energy emissions performed for the US National Research Council (1983) study of the carbon dioxide question. The carbon dioxide studies of the US Environmental Protection Administration have made some useful beginnings on the treatment of uncertainties. The US Department of Energy's has repeatedly spoken of its plans for addressing uncertainties of the carbon dioxide question. The studies implementing those plans were not officially available for review at the time this essay was completed. It seems, however, that the joint work of J. Edmonds, J. Reilly and R. Gardner on uncertainties in carbon dioxide emissions and atmospheric retention will provide a significant additional perspective to that of Nordhaus and Yohe.
- 3) I have explored this question in some depth in Clark (1985d).
- 4) See, for example, the forthcoming proceedings of the US National Academy of Engineering's "Symposium on Hazards: equity, incentives, compensation" (Washington, June 3-4, 1985); National Research Council (1982); and SCOPE (1980).
- 5) See, for example, Heal (1984) and Winkler et al. (1983).
- 6) See, for example, National Research Council (1979d, 1983) and Rotty (1979).
- 7) The general phenomenon is known as "hysteresis" in the literature of topology and catastrophe theory. For specific applications see Holling (1985) for ecological systems, Day (1981) for economic systems, Lorenz (1984) for climatological systems, and Brooks (1985) for sociotechnical systems.
- 8) This program is briefly described in WMO (1984) and documented in full in Parry et al. (1986).
- 9) See, for example, Shugart (1984), Emanuel et al. (1985), Kauppi and Posch (1985) and Solomon et al. (1984).

10) I am not aware of any analysis of spatial changes from GCM results. Some useful perspectives are provided by various efforts to construct scenarios of warmer climates based on historical data. See, for example, Jaeger and Kellogg (1983), Williams (1980), Wigley et al. (1980), Vinnikov and Kouyneva (1983), Pittock and Salinger (1982), and Palutikof et al. (1984). Flohn (1980) is one of the few scholars to address directly the question of changes in spatial scale that might accompany a changing climate.

11) For discussions of policy analysis and applied science in general as "craft work" see Ravetz (1971), Wildavsky (1979) and Lindblom and Cohen (1979). The "tool" analogy is from Ravetz (1985).

12) See Note 1, section 3.

13) Exercises of this sort have been described under the term "free-form, manual games" in the American literature. See Goldhamer and Speier (1959) Brown and Paxson (1975), Brewer and Shubik (1979), and Brewer (1985).

14) See Marchetti (1975, 1979), 1981), Marchetti and Nakicenovic (1979), Perry et al. (1982), Edmonds and Reilly (1985) and Laurmann (1984).

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Tables

Table 1: Definitions of valued atmospheric components and sources of disturbance: This table provides definitions of terms used in the text, adapted mainly from Crutzen and Graedel (1985).

Valued Atmospheric Components

Ultraviolet energy absorbtion: This property reflects the ability of the stratosphere to absorb ultraviolet solar radiation, thus shielding the earth's surface from its effects. This property is commonly addressed in discussions of "the stratospheric ozone problem".

Thermal radiation budget alteration: This property reflects the complicated relationships through which the atmosphere transmits much of the energy arriving from the sun at visible wavelengths while absorbing much of the energy radiated from earth at infrared wavelengths. The balance of these forces, interacting with the hydrological cycle, exerts considerable influence on the earth's temperature. This property is commonly addressed in discussions of "the greenhouse problem".

Photochemical oxidant formation: This property reflects the oxidizing properties of the atmosphere, caused by concentration of a variety of highly reactive gasses. The treatment here focusses on local scale oxidants that are often implicated in problems of "smog", crop damage, and degradation of works of art.

Precipitation acidity: This property reflects the acid-base balance of the atmosphere as reflected in rain, snow, and fog. It is commonly addressed in discussions of "acid rain".

Visibility degradation: Visibility is reduced when light of visible wavelengths is scattered by gasses or particles in the atmosphere.

Material corrosion: This property reflects the ability of the atmosphere to corrode materials exposed to it, often through the chloridation or sulfidation of marble, masonry, iron, aluminum, copper and materials containing them.

Table 1 (cont.).

Sources of Perturbation

The sources are largely self explanatory. Notes will provided here are confined to special considerations important in the text. For more details, see Crutzen and Graedel (1985).

Oceans and estuaries: includes coastal waters and biological activity of the oceans.

Vegetation and soils: does not include wetlands or agricultural systems, for which see below; does include activities of soil microorganisms.

Wild animals: does not include domestic or marine animals, for which see elsewhere; does include microbes except for those of soils, for which see above.

Wetlands: an important subcomponent of vegetation and soils; does not include rice, for which see below.

Biomass burning: includes both natural and anthropogenic burning.

Crop production: includes rice but not forestry; includes fertilization and irrigation.

Domestic animals: includes grazing systems and the microbial flora of the guts of domestic animals.

Petroleum combustion: includes impacts of refining and waste disposal.

Coal combustion: includes impacts of mining, processing, and waste disposal.

Industrial processes: includes cement production and the processing of non-fuel minerals.

Table 2: Goals of social response. Adapted from Schelling (1983)

Goals of Social Response

<u>Alter Production</u>	<u>Recover Releases</u>	<u>Modify Environment</u>	<u>Adapt to Change</u>
<p>Energy management</p> <ul style="list-style-type: none"> -total use -fossil fuel share -low carbon fossil fuels <p>Land management</p> <ul style="list-style-type: none"> -forest conversion <p>Ocean management</p> <ul style="list-style-type: none"> -biological pump <p>Managing other gasses</p> <ul style="list-style-type: none"> -all of above -industrial releases 	<p>Energy management</p> <ul style="list-style-type: none"> -scrubbing stack gasses -disposal problems <p>Land management</p> <ul style="list-style-type: none"> -increase forested area -increase forest density -fossilize trees <p>Ocean management</p> <ul style="list-style-type: none"> -prime biological pump <p>Managing other gasses</p>	<p>Thermal radiation budget</p> <ul style="list-style-type: none"> -greenhouse gasses -albedo <p>Water</p> <ul style="list-style-type: none"> -reservoirs -river diversions <p>Other gasses</p>	<p>Agriculture</p> <ul style="list-style-type: none"> -change land use -change crop -improve crop -improve trade -change diet <p>Habitatation</p> <ul style="list-style-type: none"> -migrate -"air conditioning" -sea level adaptations <p>Other adaptations</p> <ul style="list-style-type: none"> -construction -transport -military operations -compensation

Figure 1: Major impacts of atmospheric chemistry on valued atmospheric components. The '+' entries indicate that the listed chemical is expected to have a significant direct effect on the listed property of the atmosphere. Definitions of the atmospheric properties are given in Table 1. Data are from Crutzen (1983; Table 3.1) and National Research Council (1984; Table 5.2), modified as a result of personal communications from P.J. Crutzen and R.C. Harris.

Chemical Constituents	Ultraviolet energy absorption	Thermal radiation budget alteration	Photochemical oxidant formation	Precipitation acidification	Visibility degradation	Material corrosion
C (soot)		+			+	
CO ₂		+				
CO						
CH ₄		+				
C _x H _y			+		+	
NO _x			+	+	+	
N ₂ O		+				
NH ₃ /NH ₄ ⁺				+		
SO _x		+		+	+	+
H ₂ S						+
COS						
Organic S						+
Halocarbons		+				
Other halogens						+
Trace elements						
O ₃	+	+	+			

Figure 2: Sources of major perturbations to atmospheric chemistry. The '+' entries indicate that the listed source is expected to exert a significant direct effect on the listed chemical. Definitions of the sources are given in Table 1. Data sources as for Figure 1.

Chemical Constituents	Oceans and estuaries	Vegetation and soils	Wild animals	Wetlands	Biomass burning	Crop production	Domestic animals	Petroleum combustion	Coal combustion	Industrial processes
C (soot)					+			+	+	
CO ₂	+	+			+	+		+	+	
CO	+	+			+			+	+	+
CH ₄		+	+	+	+	+	+			
C _x H _y	+	+			+	+				
NO _x	+				+	+		+	+	+
N ₂ O	+	+			+	+		+	+	
NH ₃ /NH ₄ ⁺		+	+	+	+	+	+		+	
SO _x								+	+	+
H ₂ S	+	+		+		+				
COS	+	+		+						
Organic S	+	+		+						
Halocarbons										+
Other halogens	+							+	+	+
Trace elements	+				+			+	+	+
O ₃										

Figure 3: Chemical interactions in the atmosphere. A framework for assessing interactions among the chemical compounds listed in Figures 1 and 2.

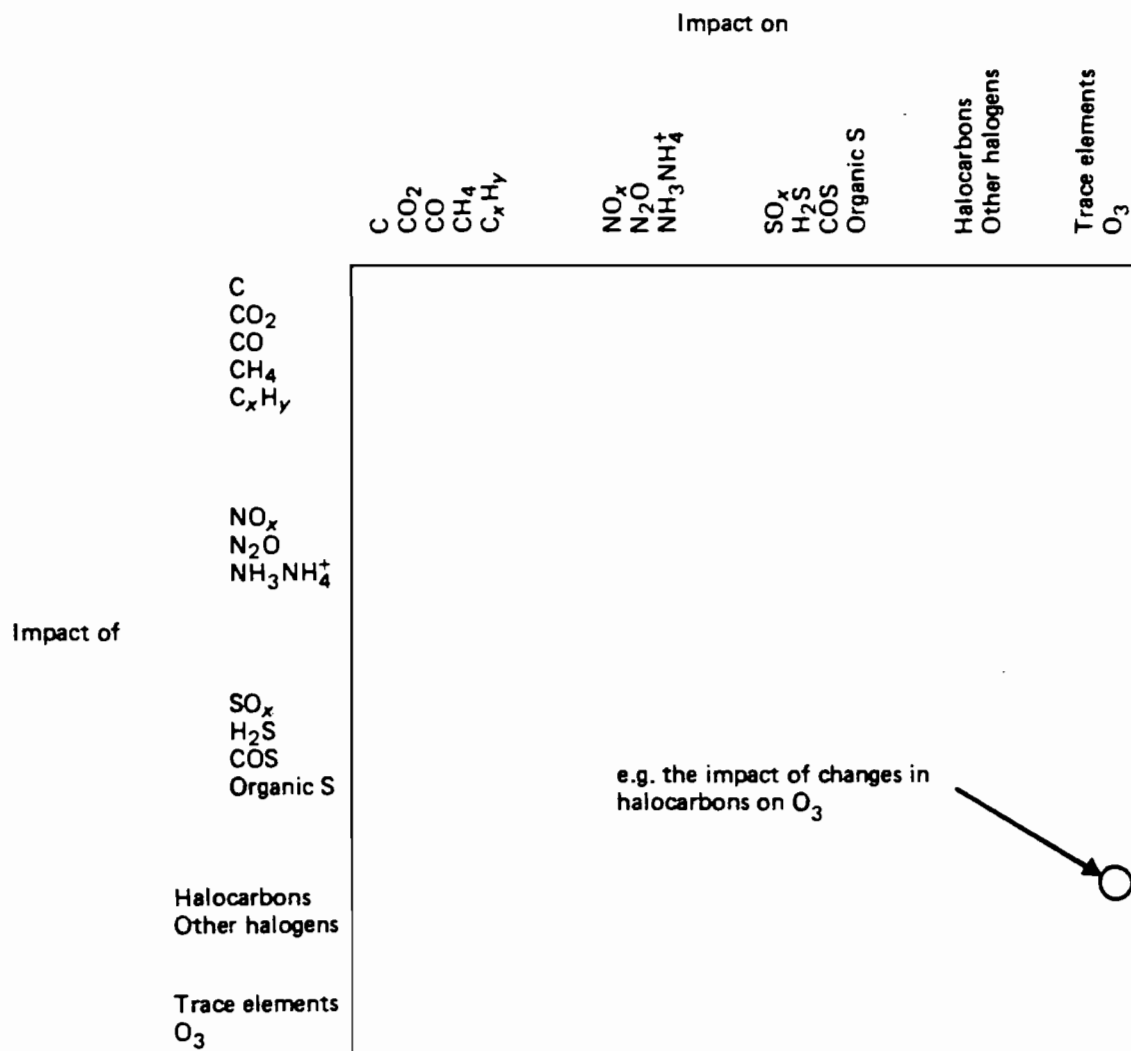


Figure 4: The science of impact assessment. An integrating framework for determining the relation ('D' in this figure) between valued atmospheric components and the sources that perturb them as a function of the relationships shown in Figs. 1 ('C') in this figure, 2 ('A') in this figure, and 3 ('B') in this figure.

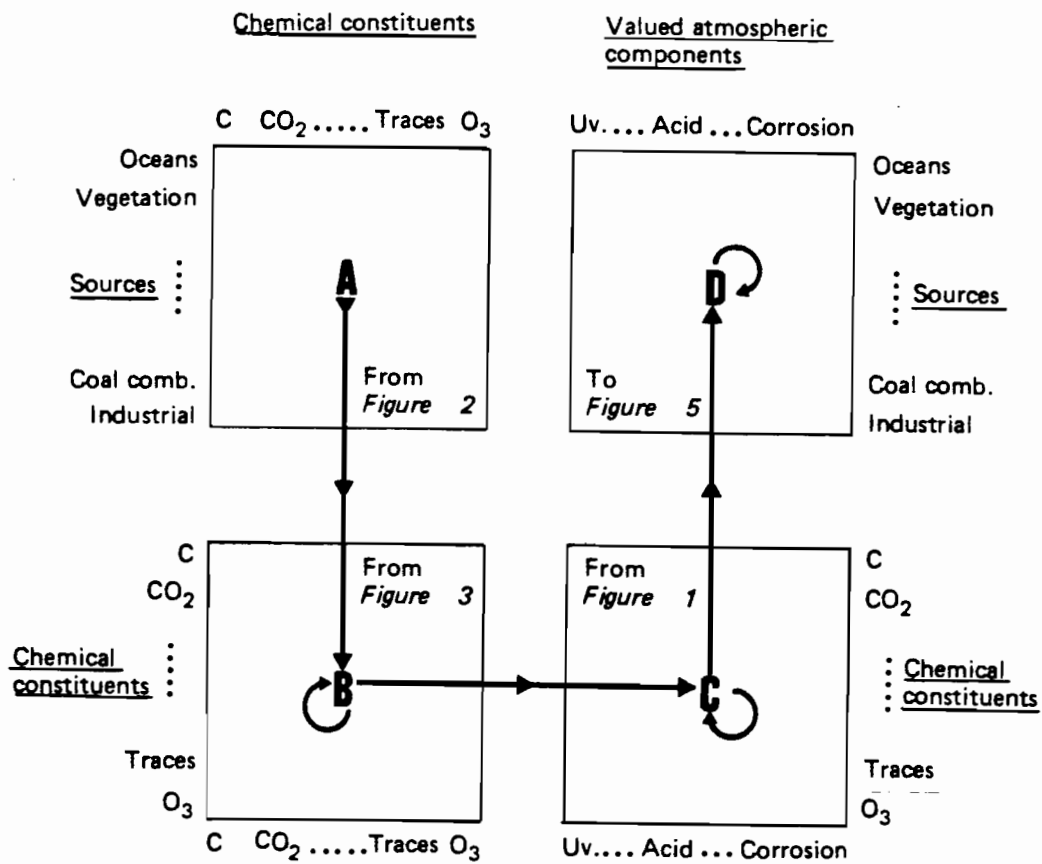
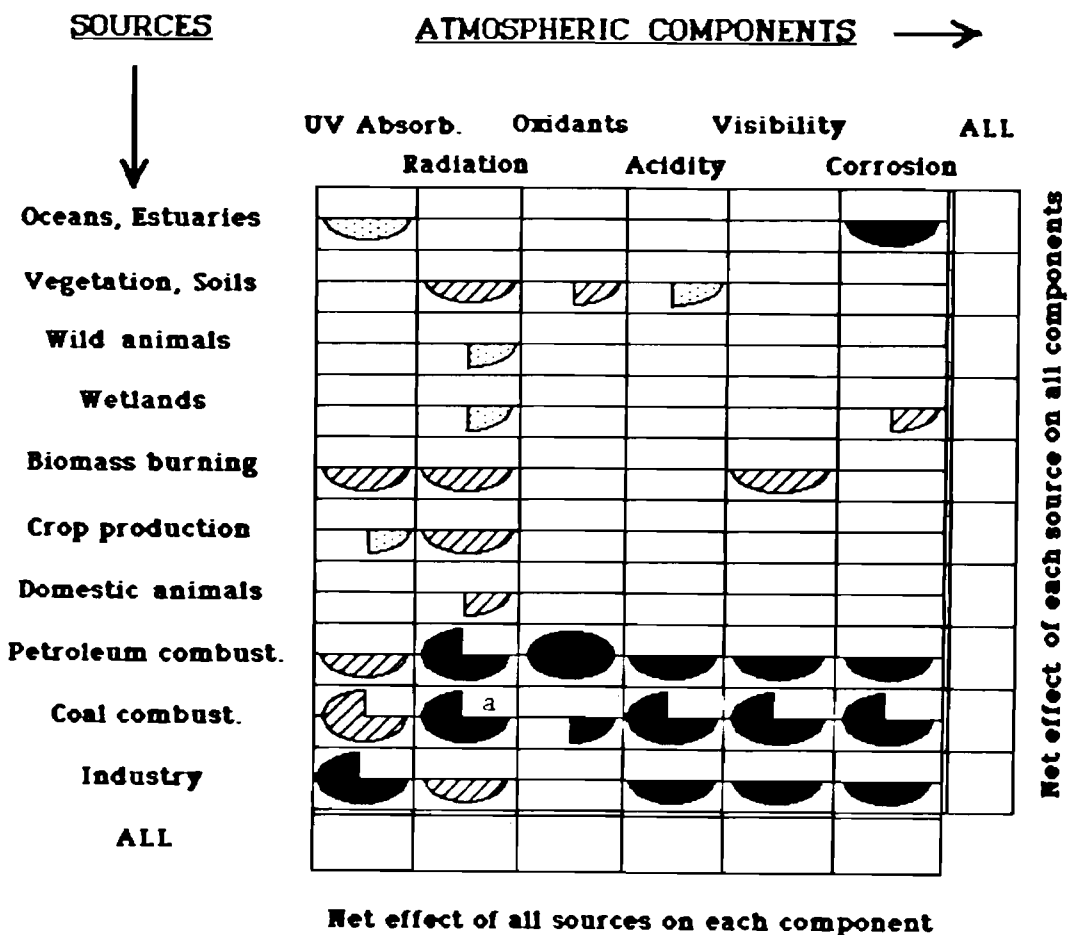


Figure 5: A synoptic assessment of impacts on the atmosphere. This figure, adapted from Crutzen and Graedel (1985) gives a completed version of panel 'D' from Fig. 4. The valued atmospheric components defined in Table 1 are listed as the column headings of the matrix, the sources of perturbations to those components are listed as row headings. Cell entries assess the relative impact of each source on each component, and the relative scientific certainty of the assessment. "Column totals" would, in principle, represent the net effect of all sources on each valued atmospheric component. "Row totals" would indicate the net effect of each source on all valued atmospheric components. These totals are envisioned as judgemental qualitative assessments rather than as literal quantitative summations. The significance of the letter in cell 'a' is defined in the text.



KEY:

Potential importance: (ca. 1985)		Assessment Reliability: (ca. 1985)	
controlling	moderate	high	low
major	some	moderate	

Figure 6: Social responses and environmental impacts. a) A conceptual model of anthropogenic impacts on the environment. b) A specific example: carbon dioxide and climate. c) Goals of social response at each stage of the impacts model. As noted in the text, the "models" suggested by this figure are gross simplifications of the feedback-laden, multiply-causal world of reality. They nonetheless serve to indicate the points of access for social response measures.

a) A General Model of Environmental Impacts

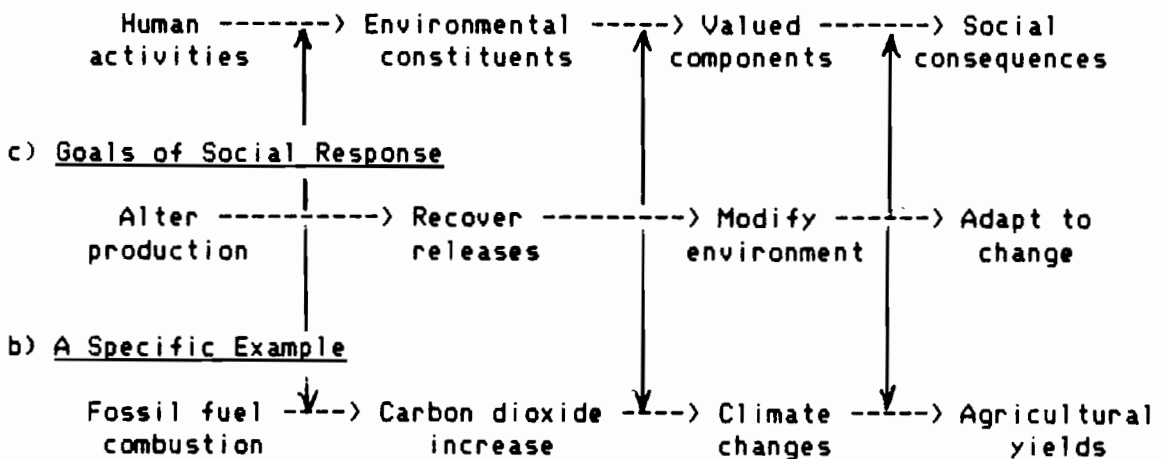


Figure 7: Characteristic scales of atmospheric constituents. The figure applies to the clean troposphere above the boundary layer. The abscissa indicates the amount of time required for the concentration of the listed chemicals to be reduced to 30% of their initial value through chemical reactions. The ordinate indicates the mean horizontal displacement (square root of EW times NS displacement) likely to occur over that lifetime. Data are from Crutzen (1983), modified as a result of personal communications from P.J. Crutzen and R.C. Harris.

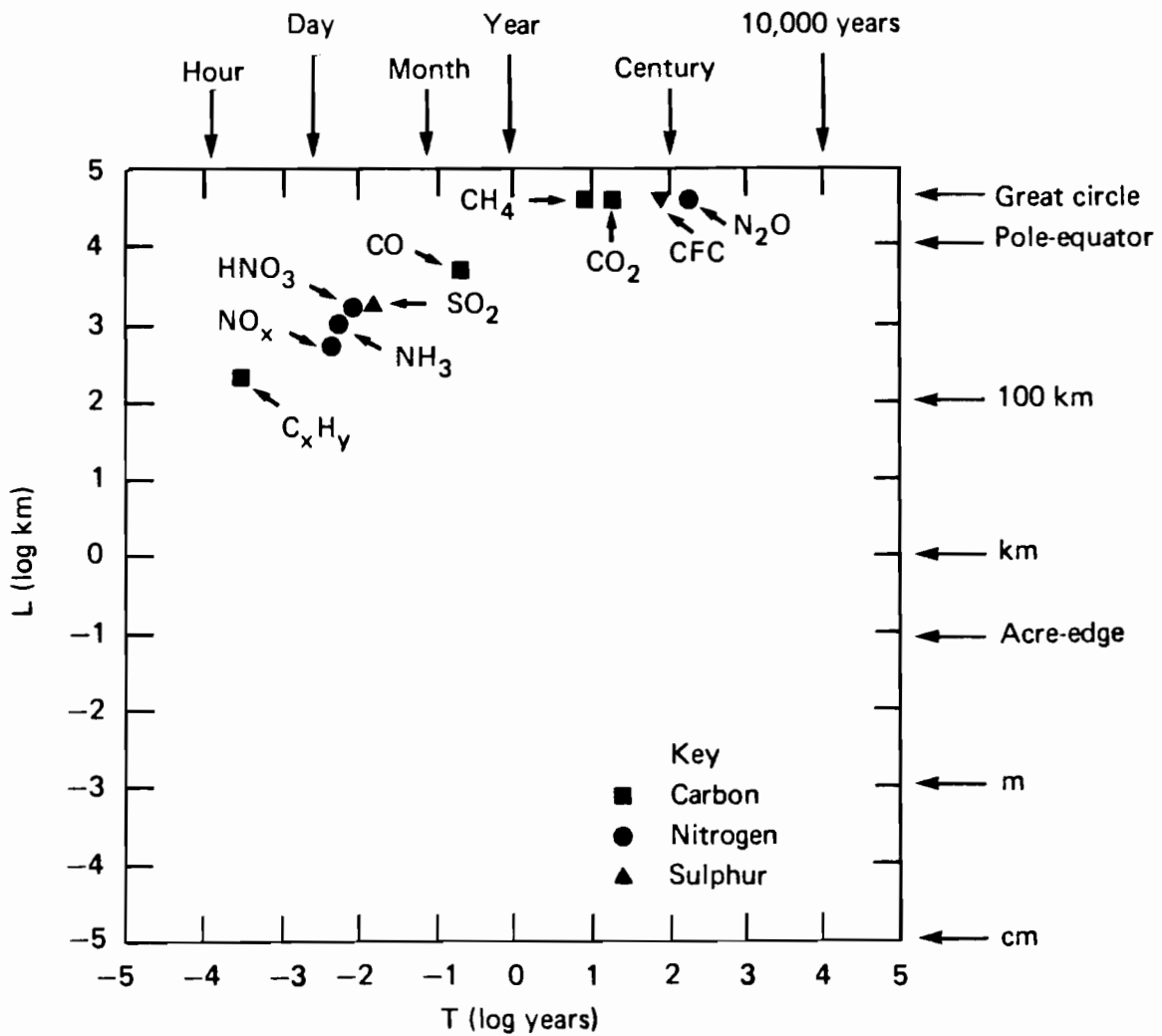


Figure 8: Characteristic scales of meteorological and climatological phenomena. Conventions are as in Figure 6. Data sources are those described in text plus others cited in Clark (1985c), supplemented with information from Dickinson (1985). The dotted lines plot Yoshino's (1975) equations for the time - space relationships of meteorological phenomena in Japan. See text.

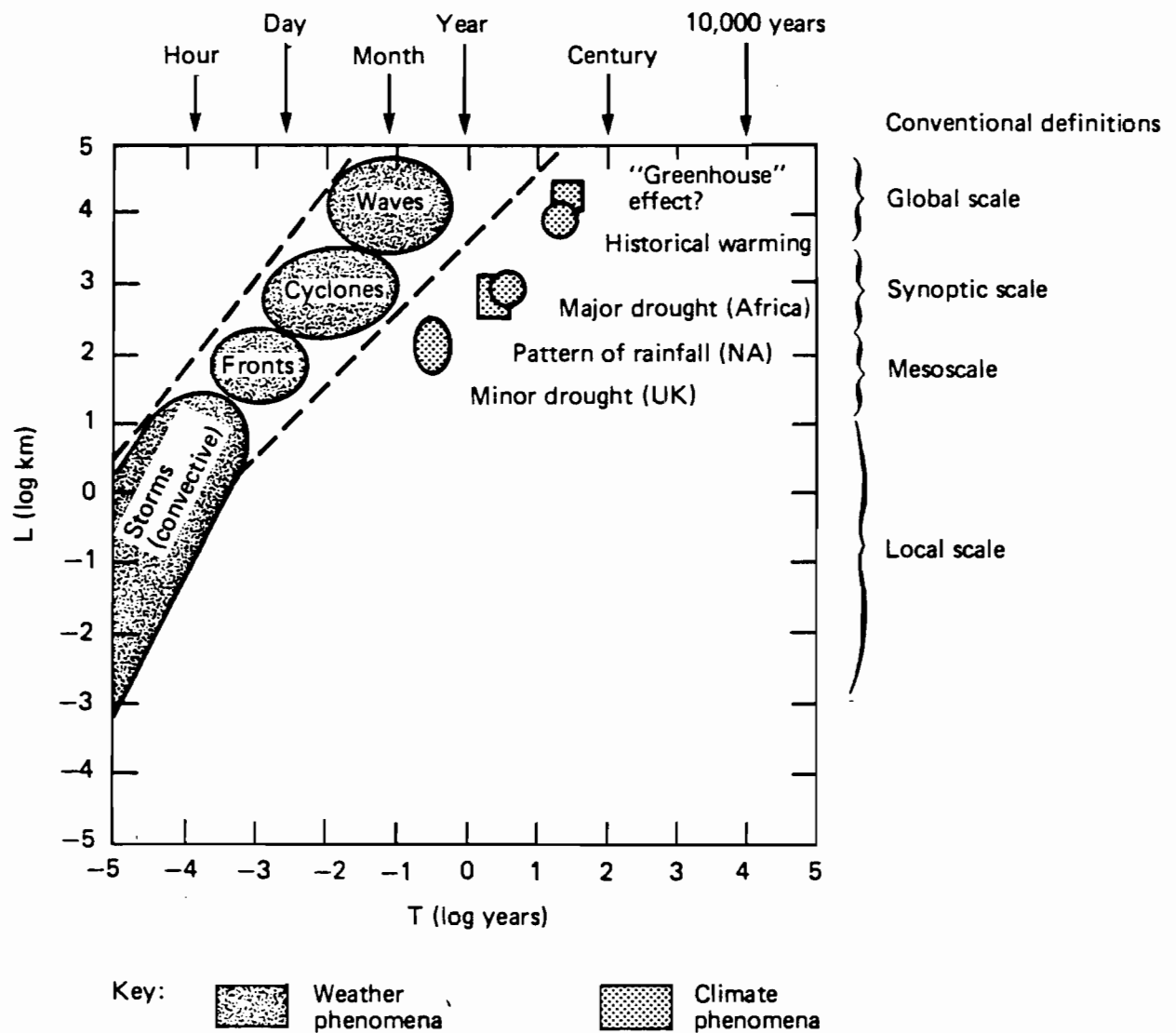


Figure 9: Characteristic time scales for climatic, social, and ecological processes (Sources documented in Clark 1985b).

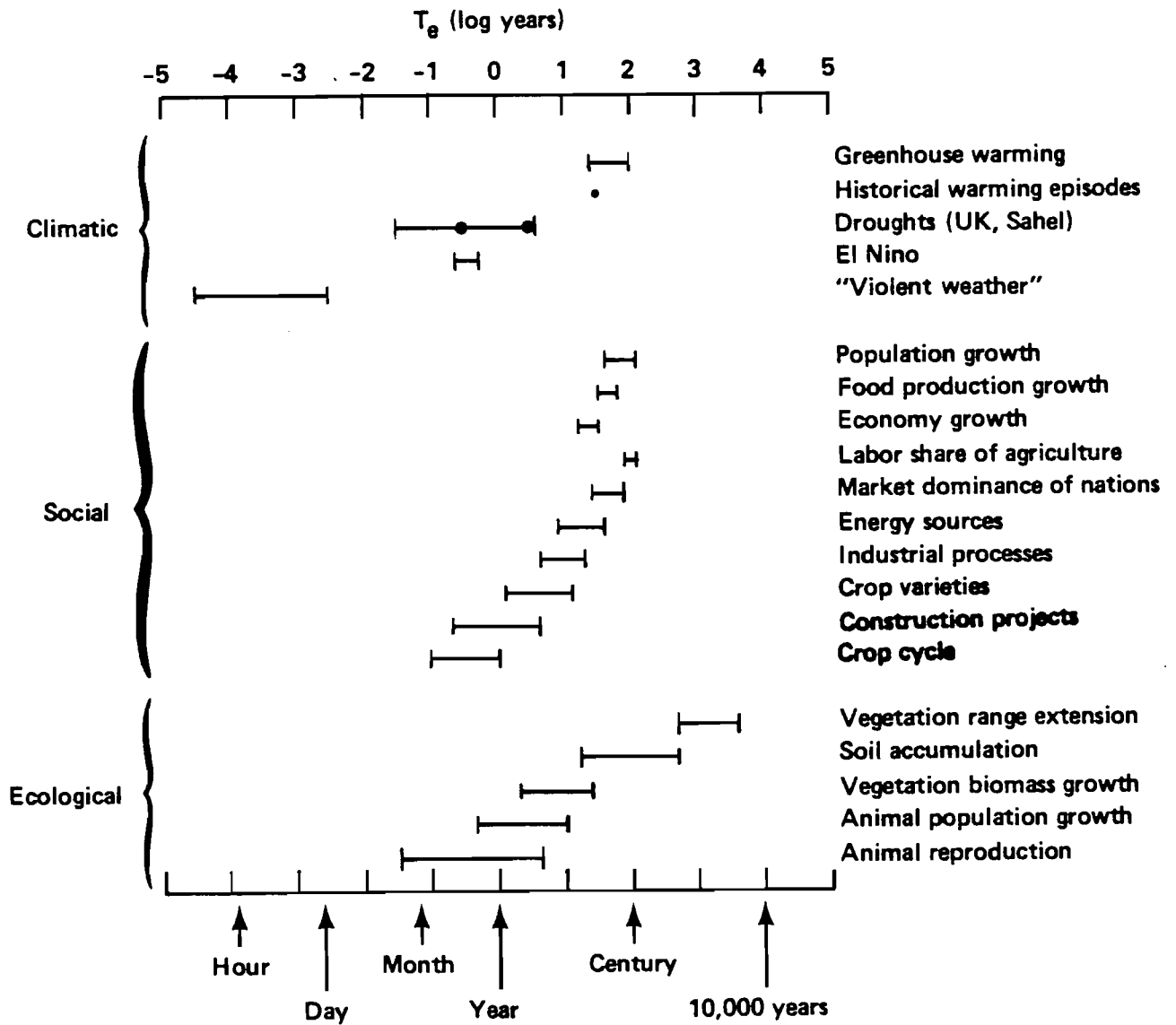


Figure 10: Characteristic space scales for climatic, social, and ecological pattern (Sources documented in Clark 1985b and text).

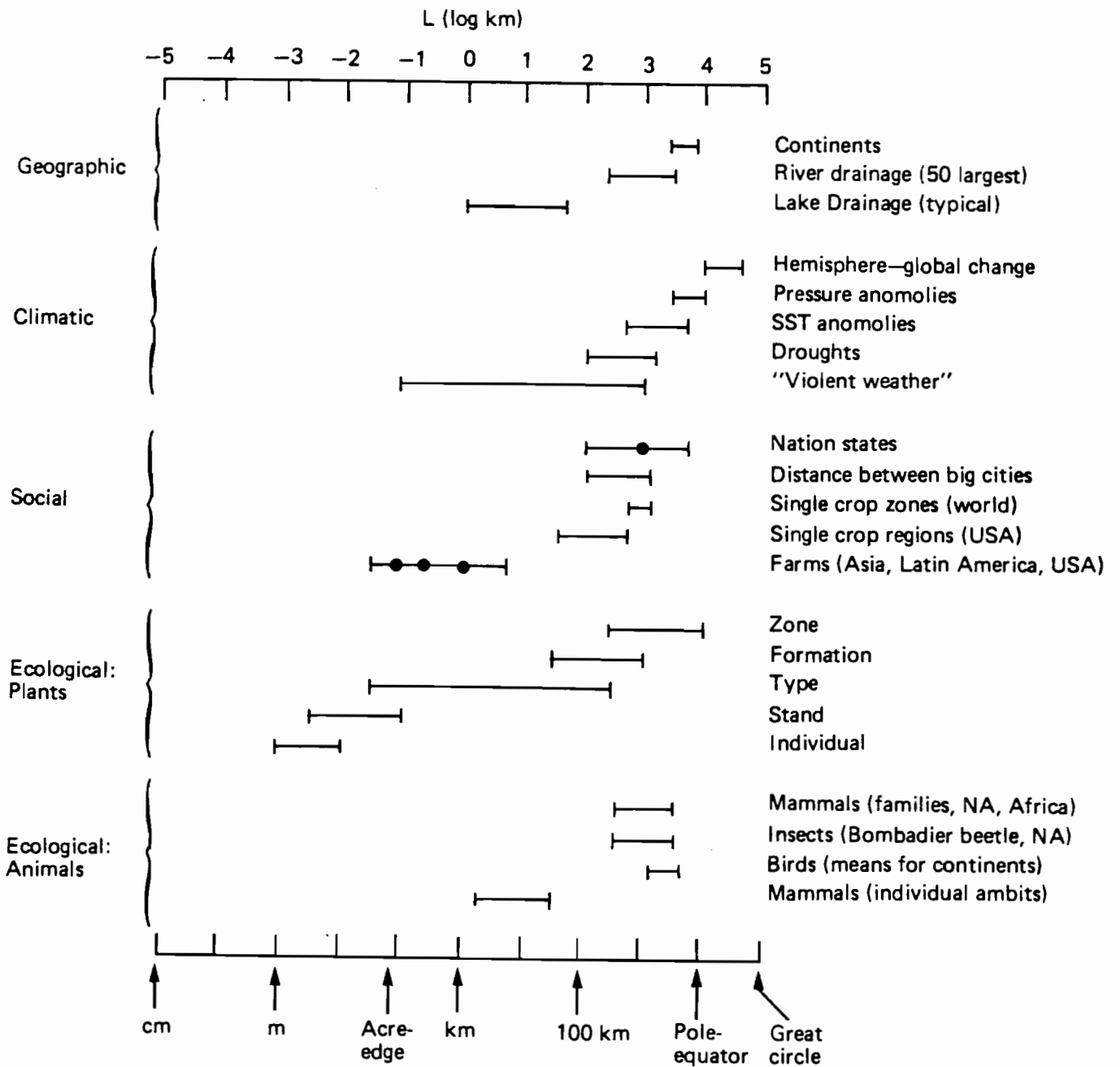


Figure 11: Scales of social and ecological phenomena. Characteristic time scales (log years) and space scales (log kilometers) for selected clusters described in Figures 9 and 10.

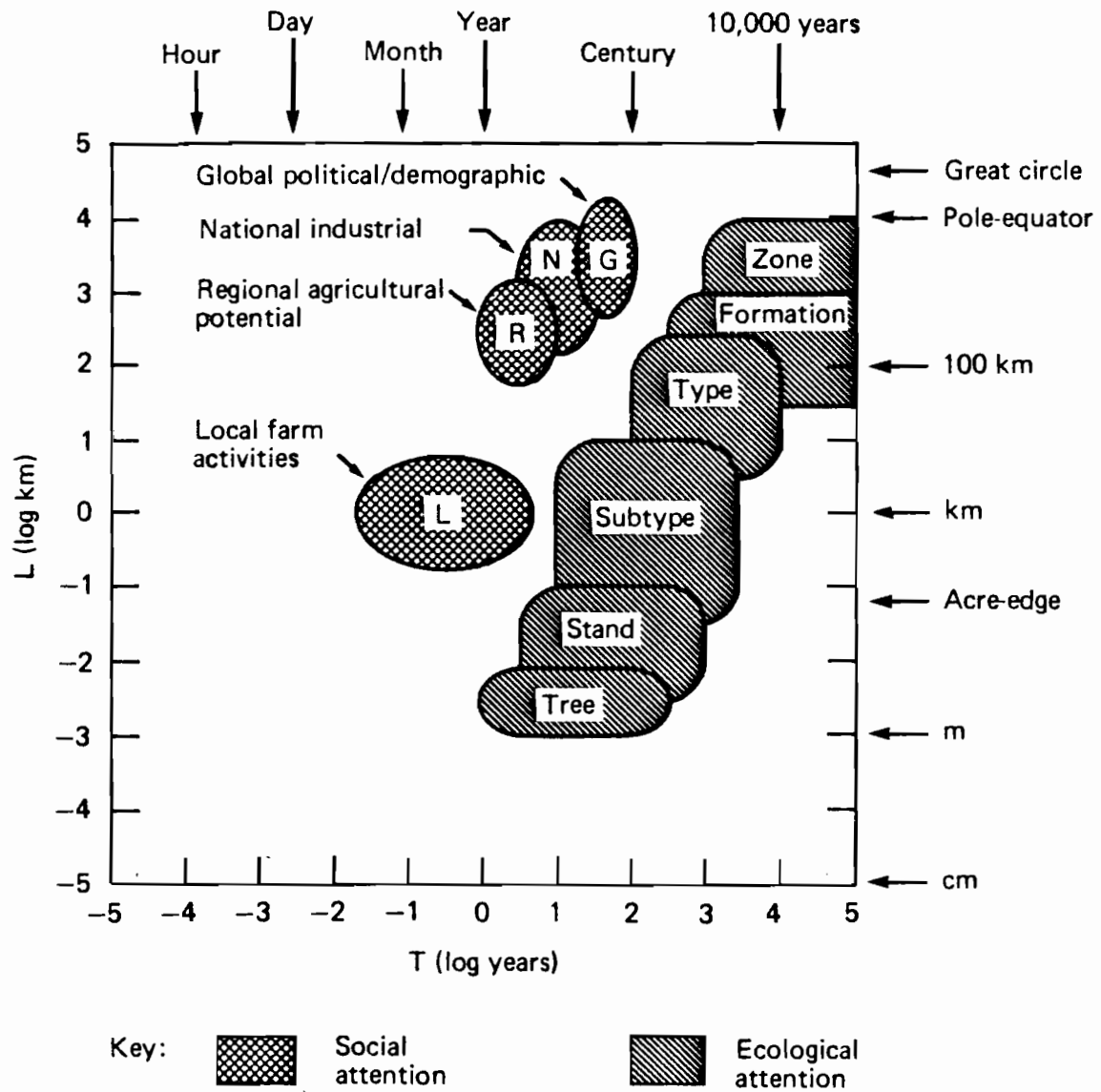


Figure 12: Scales of interactions among climates, ecosystems, and societies. This figure overlays Fig. 8 on Fig. 11. Four bands of phenomena are evident. At a given spatial scale, ecological processes are slowest, meteorological processes are fastest, and social and climatic processes overlap at an intermediate time scale. See text.

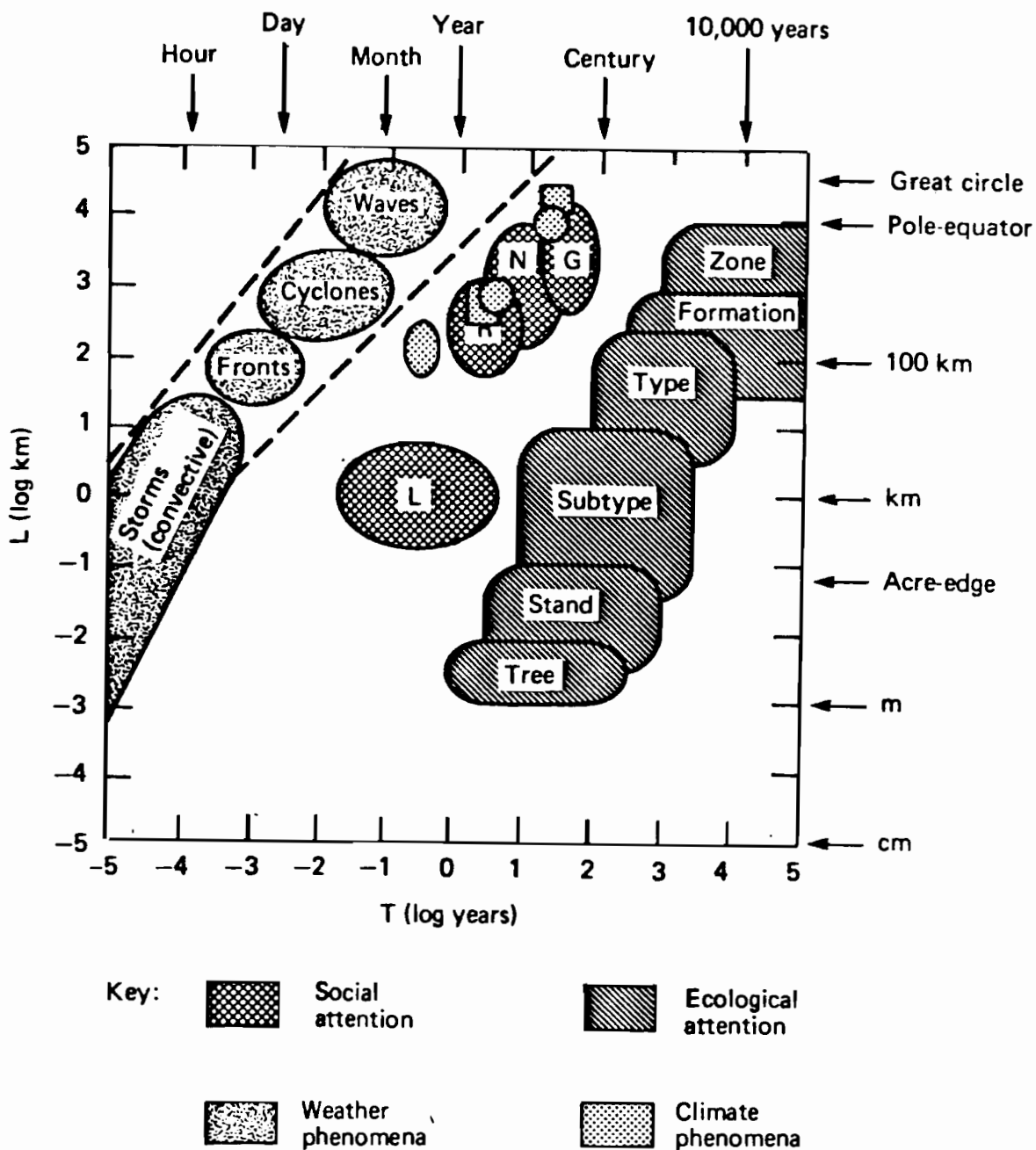


Figure 13: Coefficient of variation for wheat yields in various nations and regions as a function of the logarithm of the area planted. Variation data for 1970-77 are from Oram (1985); area data are from the FAO Production Yearbook for 1977. From the left of the graph, keys are as follows: SAH is Sahel; SA is South Africa; EA is East Africa; AR is Argentina; AU is Australia; WA is West Africa; CDA is Canada; NA is North Africa and the Near East; SEA is South East Asia; SAM is South America; CHI is China; IND is India; USA is the United States; USSR is the Soviet Union.

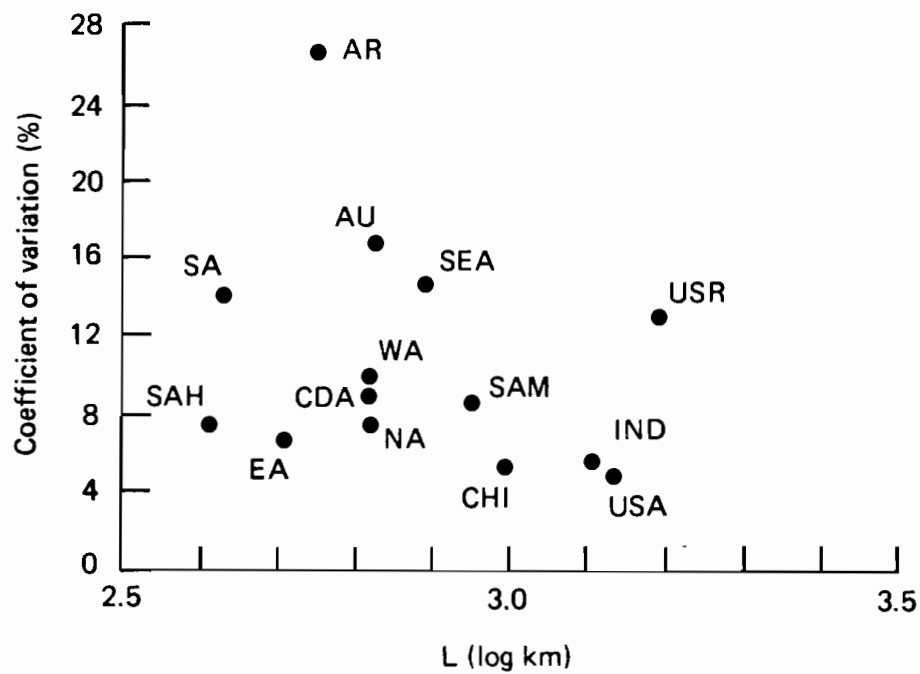


Figure 14: Distribution of atmospheric concentrations of carbon dioxide in the year 2100. Figure is taken from Nordhaus and Yohe (1983) and reflects the results of 1000 runs of their stochastic emissions model.

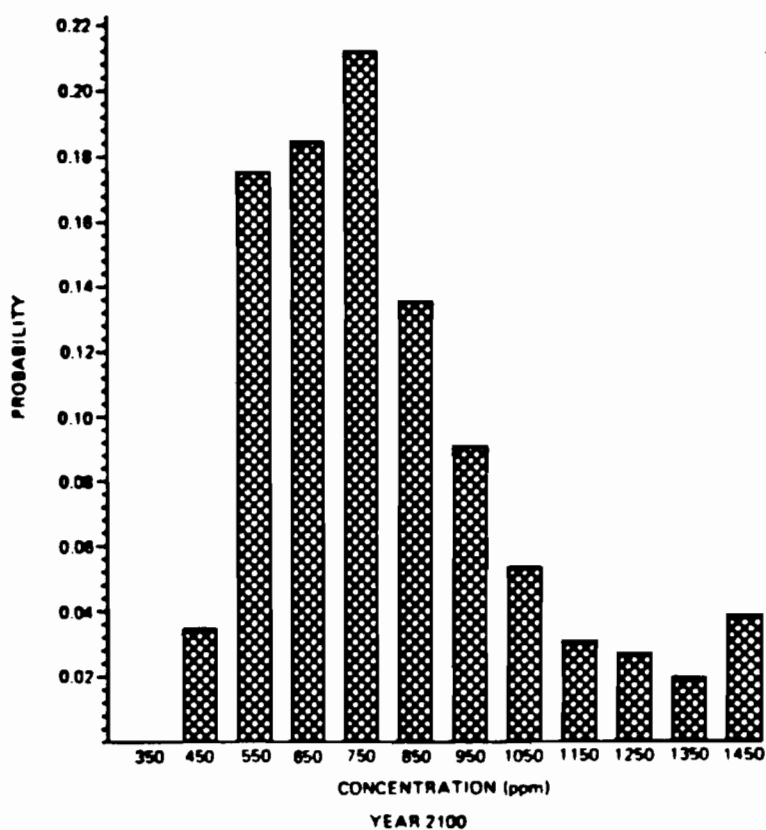


Figure 15: Change in probability of extreme events as a function of changes in the mean of a normal distribution with constant variance. Figure is taken from Wigley (1985) who notes "The diagram shows how sensitive the frequency of extreme events can be to changes in the mean... The abscissa shows the change in the mean as a multiple of the standard deviation, while the ordinate shows the resulting change in the probability of an extreme for extremes with initial probabilities (P_1) of 0.1, 0.05, and 0.01." See text.

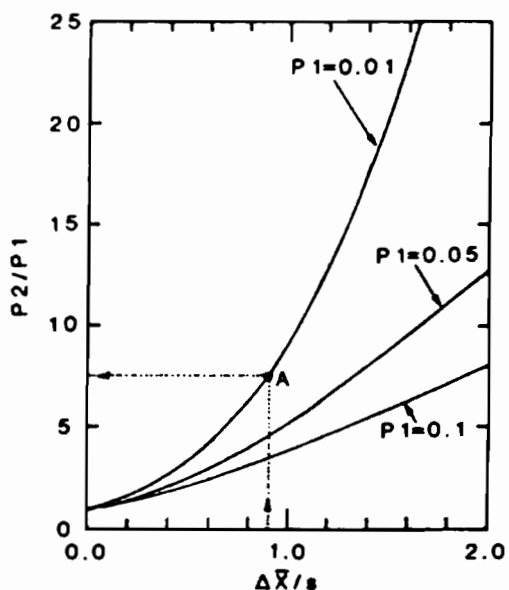


Figure 16: Nonlinear effect of temperature on crop yield. Data are for paddy rice in Hokkaido. Figure is from Tani (1978).

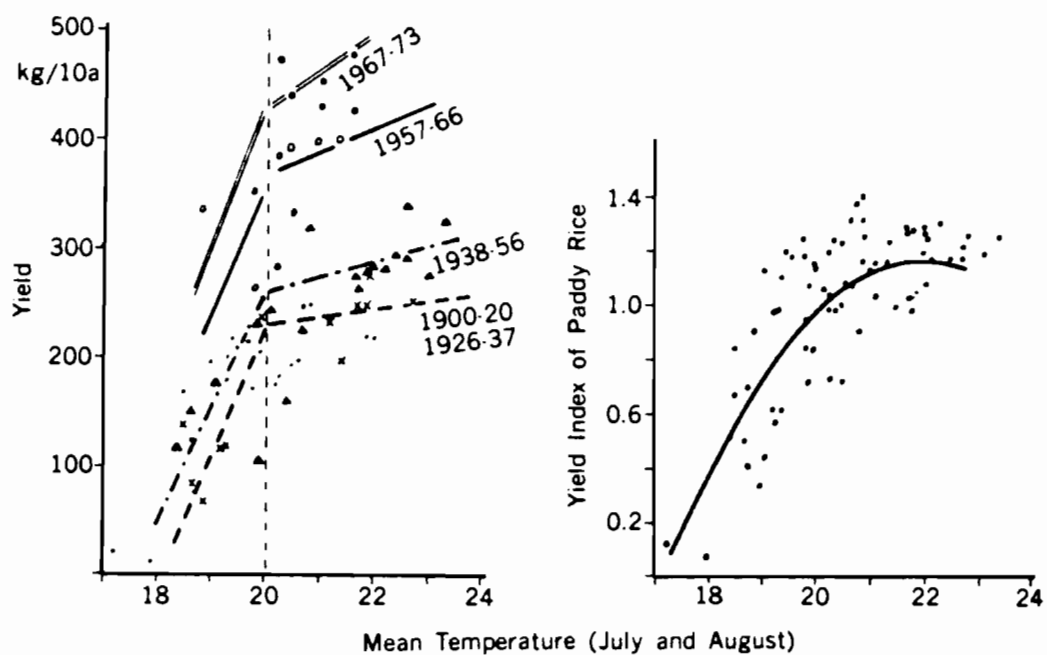


Figure 17: Nonlinear effect of precipitation on primary productivity. Data points represent natural ecosystems throughout the world. Figure is from Lieth (1975).

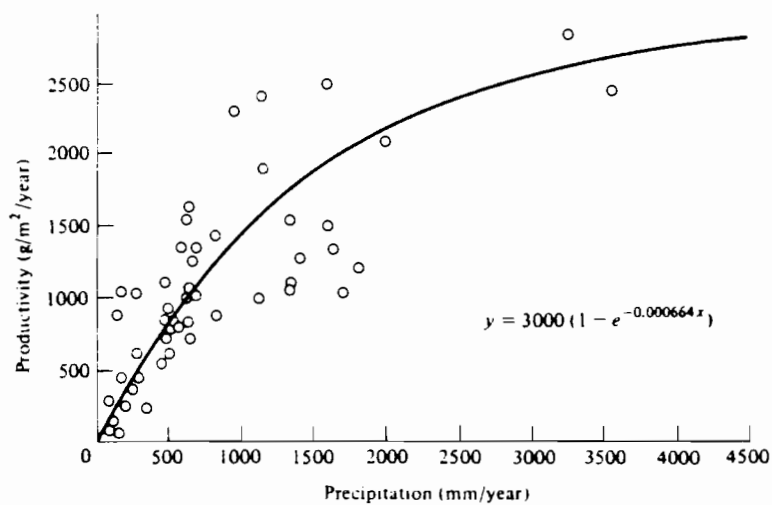


Figure 18: Nonlinear effect of temperature and precipitation on life forms. Figure shows the Holdridge Life Zone Classification for the world's ecosystems. This plot is from Emanuel et al. (1985), who apply the classification to an assessment of ecological implications of climate change.

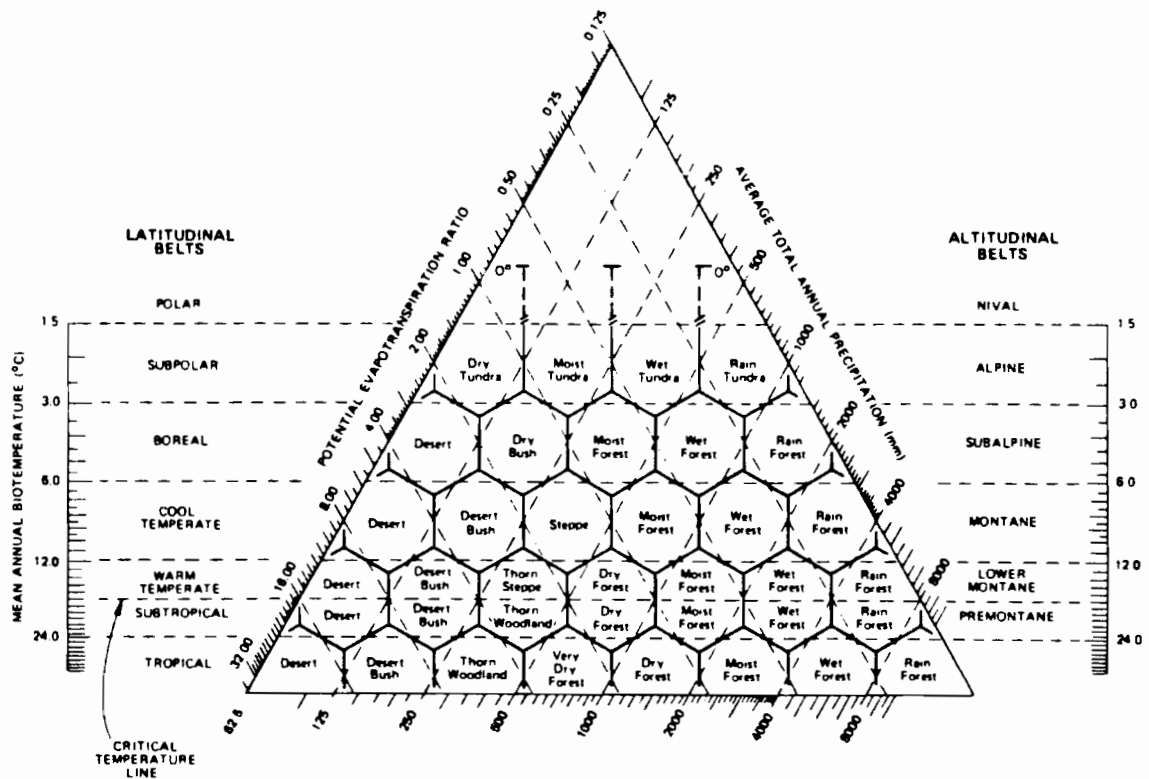


Figure 19: A hierarchy of models used for the assessment of climate impacts and evaluation of policy responses. The diagram illustrates the conceptual framework of the IASA project on "Integrated approaches to climate impact assessment". The figure is taken from a forthcoming report on the results of that project (Parry et al., 1986).

