REPORT OF THE
INTERNATIONAL CONFERENCE
ON THE ASSESSMENT OF THE ROLE
OF CARBON DIOXIDE AND OF OTHER
GREENHOUSE GASES IN CLIMATE
VARIATIONS
AND ASSOCIATED IMPACTS

VILLACH, AUSTRIA, 9-15 OCTOBER 1985

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FOREWORD

The increase of carbon dioxide in the atmosphere has long been recognized as a potential problem. International scientific organizations have sponsored many meetings on the CO₂ issue over the years but the first joint UNEP/ICSU/WMO assessment of CO₂ was held in Villach, Austria in September 1980. In October 1982, these three organizations met in Geneva and recommended that assessments of the CO₂ issue be held every five years, starting from that first meeting in 1980. (An interim assessment was held in September 1982, which essentially confirmed the conclusions of the 1980 meeting but determined that the range of uncertainties was greater in 1982 than in 1980).

This report contains the conclusions and recommendations of the second joint UNEP/ICSU/WMO International Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts, held in Villach, Austria from 9-15 October 1985. The conclusions of the international scientists who attended the conference about climate changes in the next century are very striking indeed and are of great importance to mankind. Their recommendations for future actions bear close attention by national decision-makers to ensure that this crucial issue of the potential impact of greenhouse gases on climate in the next century is properly considered and that appropriate actions are initiated soon.

On behalf of UNEP, ICSU and WMO, I wish to take this opportunity to thank the several scientists who wrote the background papers for the Conference, as well as Prof. B. Bolin, Prof. B. Döös and Dr. J. Jäger from the International Meteorological Institute in Stockholm, Sweden, who organized the preparation of the document which formed the basis of the scientific evaluation of this issue in the areas of energy use, the carbon cycle, the effects on the physical aspects of climate, and the effects on the terrestrial ecosystem. Similarly, I wish to thank Dr. William Clark of IIASA who wrote a chapter on The Practical Implications of the CO₂ Question. My thanks also go to the many international scientists who participated in a critical review of the IMI and IIASA chapters. Finally, I wish to express my deep gratitude to the scientists who participated in the Villach (1985) conference and whose work is reflected in the pages which follow. I believe that their work constitutes a landmark in the steady progress towards the solution of this important problem.

(G.O.P. Obasi)
Secretary-General
World Meteorological Organization
A joint UNEP/WMO/ICSU Conference was convened in Villach (Austria) from 9 to 15 October 1985, with scientists from twenty nine developed and developing countries, to assess the role of increased carbon dioxide and other radiatively active constituents of the atmosphere (collectively known as greenhouse gases and aerosols) on climate changes and associated impacts. The other greenhouse gases reinforce and accelerate the impact due to CO₂ alone. As a result of the increasing concentrations of greenhouse gases, it is now believed that in the first half of the next century a rise of global mean temperature could occur which is greater than any in man's history.

The Conference reached the following conclusions and recommendations:

1. Many important economic and social decisions are being made today on long-term projects - major water resource management activities such as irrigation and hydro-power; drought relief; agricultural land use; structural designs and coastal engineering projects; and energy planning - all based on the assumption that past climatic data, without modification, are a reliable guide to the future. This is no longer a good assumption since the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century. It is a matter of urgency to refine estimates of future climate conditions to improve these decisions.

2. Climate change and sea level rises due to greenhouse gases are closely linked with other major environmental issues, such as acid deposition and threats to the Earth's ozone shield, mostly due to changes in the composition of the atmosphere by man's activities. Reduction of coal and oil use and energy conservation undertaken to reduce acid deposition will also reduce emissions of greenhouse gases; a reduction in the release of chloro-fluorocarbons (CFCs) will help protect the ozone layer and will also slow the rate of climate change.

3. While some warming of climate now appears inevitable due to past actions, the rate and degree of future warming could be profoundly affected by governmental policies on energy conservation, use of fossil fuels, and the emission of some greenhouse gases.
These conclusions are based on the following consensus of current basic scientific understanding:

- The amounts of some trace gases in the troposphere, notably carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), ozone (O₃) and chloro-fluorocarbons (CFC) are increasing. These gases are essentially transparent to incoming short-wave solar radiation but they absorb and emit longwave radiation and are thus able to influence the Earth's climate.

- The role of greenhouse gases other than CO₂ in changing the climate is already about as important as that of CO₂. If present trends continue, the combined concentrations of atmospheric CO₂ and other greenhouse gases would be radiatively equivalent to a doubling of CO₂ from pre-industrial levels possibly as early as the 2030's.

- The most advanced experiments with general circulation models of the climatic system show increases of the global mean equilibrium surface temperature for a doubling of the atmospheric CO₂ concentration, or equivalent, of between 1.5 and 4.5°C. Because of the complexity of the climatic system and the imperfections of the models, particularly with respect to ocean-atmosphere interactions and clouds, values outside this range cannot be excluded. The realization of such changes will be slowed by the inertia of the oceans; the delay in reaching the mean equilibrium temperatures corresponding to doubled greenhouse gas concentrations is expected to be a matter of decades.

- While other factors such as aerosol concentrations, changes in solar energy input, and changes in vegetation may also influence climate, the greenhouse gases are likely to be the most important cause of climate change over the next century.

- Regional scale changes in climate have not yet been modelled with confidence. However, regional differences from the global averages show that warming may be greater in high latitudes during late autumn and winter than in the tropics; annual mean runoff may increase in high latitudes; and summer dryness may become more frequent over the continents at middle latitude in the Northern Hemisphere. In tropical regions, temperature increases are expected to be smaller than the average global rise, but the effects on ecosystems and humans could have far reaching consequences. Potential evapotranspiration probably will increase throughout the tropics whereas in moist tropical regions convective rainfall could increase.

- It is estimated on the basis of observed changes since the beginning of this century, that global warming of 1.5°C to 4.5°C would lead to a sea-level rise of 20-140 centimeters. A sea level rise in the upper portion of this range would have major direct effects on coastal areas and estuaries. A significant melting of the West Antarctic ice sheet leading to a much larger rise in sea level, although possible at some future date, is not expected during the next century.
Based on analyses of observational data, the estimated increase in global mean temperature during the last one hundred years of between 0.3 and 0.7°C is consistent with the projected temperature increase attributable to the observed increase in CO₂ and other greenhouse gases, although it cannot be ascribed in a scientifically rigorous manner to these factors alone.

Based on evidence of effects of past climatic changes, there is little doubt that a future change in climate of the order of magnitude obtained from climate models for a doubling of the atmospheric CO₂ concentration could have profound effects on global ecosystems, agriculture, water resources and sea ice.

RECOMMENDED ACTIONS

1. Governments and regional inter-governmental organizations should take into account the results of this assessment (Villach 1985) in their policies on social and economic development, environmental programmes, and control of emissions of radiatively active gases.

2. Public information efforts should be increased by international agencies and governments on the issues of greenhouse gases, climate change and sea level, including wide distribution of the documents of this Conference (Villach 1985).

3. Major uncertainties remain in predictions of changes in global and regional precipitation and temperature patterns. Ecosystem responses are also imperfectly known. Nevertheless, the understanding of the greenhouse question is sufficiently developed that scientists and policy-makers should begin an active collaboration to explore the effectiveness of alternative policies and adjustments. Efforts should be made to design methods necessary for such collaboration.

(i) Governments and funding agencies should increase research support and focus efforts on crucial unsolved problems related to greenhouse gases and climate change. Priority should be given to national and international scientific programme initiatives such as (a) the World Climate Research Programme (WMO-ICSU), (b) present and proposed efforts on biogeochemical cycling and tropospheric chemistry in the framework of the Global Change Programme proposed by ICSU, (c) National Climatic Research Programmes. Special emphasis should be placed on improved modelling of the ocean, cloud-radiation interactions, and land surface processes.

(ii) Support for the analysis of policy and economic options should be increased by governments and funding agencies. In these assessments the widest possible range of social responses aimed at preventing or adapting to climate change should be identified, analyzed and evaluated. These assessments should be initiated immediately and should employ a variety of available methods. Some of these analyses should be undertaken in a regional context to link available knowledge with economic
decision-making and to characterize regional vulnerability and adaptability to climatic change. Candidate regions may include the Amazon Basin, the Indian subcontinent, Europe, the Arctic, the Zambezi Basin, and the North American Great Lakes.

4. Governments and funding institutions should strongly support the following:

(i) Long-term monitoring and interpretation with state-of-the-art models of:

(a) radiatively important atmospheric constituents in addition to CO₂, including aerosols;

(b) solar irradiance; and

(c) sea level.

(ii) Study and interpretation of the past history of climate and environment, specially regarding interactions among the atmosphere, oceans and ecosystems.

(iii) Studies of the effects of atmospheric composition and of changing climate and climatic extremes on sub-tropical and tropical ecosystems, boreal forests, and on water regimes.

(iv) Investigations of the sensitivity of the global agricultural resource base with respect to:

(a) direct effects of increases in atmospheric CO₂ and other greenhouse gases;

(b) effects of changes in climate; and

(c) probable combinations of these.

(v) Evaluation of social and economic impacts of sea level rises.

(vi) Analysis of policy-making procedures under the kinds of risks implied by a significant greenhouse warming.

5. UNEP, WMO and ICSU should establish a small task force on greenhouse gases, or take other measures, to:

(i) help ensure that appropriate agencies and bodies follow up the recommendations of Villach 1985;

(ii) ensure periodic assessments are undertaken of the state of scientific understanding and its practical implications;

(iii) provide advice on further mechanisms and actions required at the national or international levels;

(iv) encourage research in developing countries to improve energy efficiency and conservation;

(v) initiate, if deemed necessary, consideration of a global convention.
Mr. Provincial Governor,
Mr. Mayor,
distinguished Delegates!

It is the third time, that at the invitation of the Government of Austria, a high ranking panel of experts meet in the beautiful city of Villach under the auspices of the United Nations Environment Programme, the World Meteorological Organisation and the International Council of Scientific Unions to discuss a topic of outstanding significance for our global environment, namely the role of carbon dioxide and other constituents in climate variations and associated impacts.

It is my honour to especially welcome the Executive Director of UNEP - Dr. Tolba, the Deputy Secretary General of WMO - Mr. Donald Smith, the representative of ICSU - Professor Dooge from Ireland, and the Conference Chairman - Mr. James Bruce from Canada.

Furthermore I should like not only to welcome you all - dear colleagues - on behalf of the Austrian Government and the people of our country, I also should like to thank you for coming again to one of the most picturesque provinces of Austria, thus giving an indication that international organizations and the international scientific community are prepared to accept the fact that environmental policy in Austria is not only directed to the solution of national day-to-day challenges, as e.g. the introduction of the most stringent emission standards for passenger cars and heavy trucks in Europe, but is also deeply concerned with environmental problems which are of a real global dimension.

May I in this respect and as another token of this Austrian philosophy draw your attention to the fact that under the auspices of UNEP in March 1985 the deliberations on the Vienna Convention on the Protection of the Ozone Layer, which in our understanding is a milestone in our common endeavours of formulating a future-oriented preventive environmental policy, were successfully concluded in the Vienna International Center.

I do hope that this positive Austrian climate will prevail for your deliberations, even in discussing inter alia the possibilities of climatic changes due to the emissions of CO₂ and other greenhouse-gases. Taking well into account the possible negative impacts of such a development to our whole planet, it turns out to be evident that this topic - not only in our opinion - is, maybe in combination with the depletion of the ozone layer, one of today's most important long-term environmental problems.
But I feel optimistic - not only on my own behalf, but also on behalf of mankind - that the results of this meeting will form the necessary basis for future discussions of possible changes in our global policy in the fields of energy-use, thus giving us the possibility of avoiding further tremendous negative impact to the planet we live on.

I wish you all the best in this challenging exercise!
OPENING REMARKS BY

MR. J. BRUCE, CONFERENCE CHAIRMAN

Mr. Minister, Mr. Governor, Your Honour the Mayor, distinguished guests and conference participants.

Allow me first on behalf of all the delegates to thank our Austrian colleagues, and particularly the Minister of Health and Environmental Protection, Dr. Kurt Steyerl, for their very warm welcome to Villach and Austria. From personal experience on the issue of long range transboundary air pollution and protecting the stratospheric ozone layer, I know how firmly Dr. Steyerl and Austria have supported positive action on environmental issues. We are pleased today to learn of the continuing strength and breadth of that support and commitment.

The juxtaposition of these three issues - Long Range Transboundary Air Pollution (acid rain for short), stratospheric ozone, and climatic change - should make us consider carefully the underlying, basic reason for the world-wide concern and for this Conference. I suggest that this basic reason is that man's activities are rapidly changing the chemical composition of the atmosphere of this blue and green and lovely planet. The changes are having a number of effects - acid deposition - a serious threat to the stratospheric ozone layer - and our problem for this conference - radiatively active gases and their impact on global climate. These problems are clearly interrelated - solution for one could well be helpful with the others.

In addition to being highly interrelated, these problems also have a characteristic that our nations deal with only with very great difficulty. The economic benefits causing the emissions which change the atmosphere often accrue in one country or region, but the environmental and economic disbenefits occur elsewhere, or perhaps to us all. As a world community we do not have the mechanisms or sometimes even the will to address such issues - but we must learn to do so and soon.

This conference has two important tasks:

- to develop a consensus statement on the present state of our scientific knowledge of increases in CO₂ and other radiatively active gases, and the physical and socio-economic impacts, and

- to develop sound recommendations for action by countries and by international agencies, based on this scientific consensus.

This is a difficult task which will require the best efforts of all participants over the next few days. But it is an important and urgent task. A major change in climate can have enormous economic and social impacts. Evidence is growing that man's decisions can profoundly affect the rate of change. Economic and investment decisions being made today with pay-offs over the next 50-100 years could be made with much more efficiency if we had better
predictions of future climate. I feel a real sense or urgency on this issue – it is not a matter for decisions in the next century but for major decisions in the next few years.

The talents and knowledge assembled here in Villach can give us our best chance ever at summarizing our situation on climate. I know we can produce a valuable statement and count on everyone's active participation to achieve this goal.

Thank you.
Mr. Chairman, Distinguished Participants,

The world's climate is in a constant state of change. Until the last two or three generations, the human impact on the climate was negligible. The agricultural and industrial revolutions have changed all that. We may already have reached the point where the activities of four and a half billion human beings is the main motor of change.

There is no point at all in debating whether it is a good thing or a bad thing that human activity can affect the Earth's climate. As your recent studies reaffirm, for the time being we must accept that this is a fact of life.

To date human intervention in the world's climate has been almost entirely inadvertant. Over the coming decades that picture may change. As our understanding of the greenhouse effect grows, it may well be possible to control the industrial emission of greenhouse gases and thereby slow down the anticipated global warming. But for the moment we don't know for sure that such a course of action could be implemented or if implemented could be effective.

We have to start thinking a great deal more seriously about the possible impacts of current trends. As a matter of urgency we must regularly review monitoring and research developments. If we fail to do this we run the risk of being overtaken by events, and of having to deal with a global warming for better or for worse when it is already too late to do anything about it or to deal with its impacts.

Mr. Chairman,

You all know past developments regarding this problem. It has been known since the turn of the century that a build-up of carbon dioxide in the atmosphere could in theory affect the world's climate. It has been the role of scientists to measure and predict that effect. By the late 1960's it was confirmed that the concentration of CO$_2$ in the atmosphere was indeed rising, and that human activities were largely responsible. By using increasing amounts of fossil fuels and by burning off the world's forests, we were releasing trapped carbon into the atmosphere as carbon dioxide. In this situation a first step was to improve monitoring and assessment capabilities.

The monitoring and assessment stage is well underway. As early as in the Study of Man's Impact on the Climate report of 1971 some primitive and preliminary model calculations were ready. It was estimated that by the turn
of the century the annual global mean temperature would rise by about 0.5°C. It was predicted that about the year 2030 the concentration of CO$_2$ in the atmosphere would have doubled, and that the global annual mean temperature would have increased by 2°C or thereabouts.

The main concern at that time was to begin a programme that would give us a clearer picture of the path ahead. The Stockholm Conference on the Human Environment reflected that concern in 1972 when it called for increased monitoring and research into carbon dioxide build-up. In the years following the Stockholm Conference the United Nations Environment Programme, WMO and ICSU combined to place the study of the "greenhouse effect" on a more sound scientific footing.

A major problem facing a concrete assessment of the phenomenon is the uncertainty over global energy demand and projected fossil fuel requirements in the coming decades. The oil crises of the 1970's, for example, dramatically affected many existing climate-change models. Scenarios for future energy demand had to be adjusted downwards. But later scientific findings changed the picture much more dramatically. In the wake of reduced global energy demand in the 1970's the first CO$_2$ conference in Villach in 1980 estimated that in 2025 the atmospheric CO$_2$ concentration would be about 450 ppm. This model extrapolated that the time required for CO$_2$ concentration in the atmosphere to double would be almost 100 years - a very different time frame from the one outlined in 1971 at the high noon of the oil bonanza. Further research brought us full circle. The discovery of the role of other trace gases has brought many scientists back to a position not far from the one spelled out in the SMIC report with respect to the projected date for doubling of the greenhouse effect.

I am aware that the debate continues as to the effect of industrial emission regulation on the rate of climate change. I am also aware that scientific consensus at the present seems to favour a more cautious view. I know that some experts argue that even drastic cuts in fossil fuel use would delay a projected global warming by only a limited number of years.

With well-directed research we can find out what effect on the climate of coming decades specific emissions regulations would have. As a precursor to entering that difficult arena UNEP, WMO and ICSU agreed in 1982 on a stepwise investigation of the CO$_2$ problem. Having done this we have again gathered in Villach to consider the results of an extensive assessment effort that has been carried out by the International Meteorological Institute in Stockholm with the support of UNEP, WMO and others.

A number of salient points seem to emerge from these studies.

First, the concentration of CO$_2$ in the atmosphere continues to increase. Net emissions of CO$_2$ from biota due to deforestation and land use change are not expected in themselves to cause significant change in climate, although they contribute to the rate of increase.

Second, some other trace gases in the atmosphere in particular methane, nitrous oxide and other oxides of nitrogen, as well as chlorofluorocarbons, have similar greenhouse effects on climate as CO$_2$. As they also have been found to be increasing in concentration due to human
activity, their warming effect must be added to the one caused by CO₂, and we must examine the option of cutting back on these emissions as necessary.

Third, earlier studies which considered CO₂ alone suggested that levels of CO₂ concentration would have doubled from the pre-industrial period by some time after 2050. It is now estimated that by adding in the warming effect of other trace gases the equivalent of such a doubling may occur as early as 2030. Trace gases seem to be playing a much larger role in bringing about a greenhouse effect than was earlier expected.

Fourth, we have now laid aside most of the doubts as to the effect of the build-up of CO₂, and other trace gases on global climate. The IMI assessment has confirmed that there is almost unanimous agreement that the global average surface temperature would increase in response to a doubling of the greenhouse effect. Differences in the amount of increase arrived at through the application of various modelling approaches are modest, in fact insignificant for our current purposes. It is clear now that scientists are reasonably confident that at current rates of build-up a global mean annual temperature increase of several degrees will probably occur over a period of half a century or so.

Following on from this are the implications of such a change for the Earth's ecosystems. We cannot yet predict with any great accuracy regional patterns of climate change, but there are indications that there may well be a radical redistribution of the world's productive croplands. Such an impact could also alter the pattern and frequency of El Niño events and droughts as well as the rate of desertification. Its net effect may even be beneficial in some cases. At this stage we just don't know. However, such changes could have an immense, but as yet incalculable, impact on the global political system.

Of equal or even greater significance will be the effect on the world's oceans. The predicted thermal expansion of the ocean water body alone could lead to a rise of the world's sea-level of about one metre. The Arctic ice cap could disappear in the summit and the west Antarctic icesheet break away from its continental mooring. Nearly a third of all human beings live within 60 kms of the coast - thus hundreds of millions of city-dwellers from Bangkok to New York would be affected as would the port facilities that sustain the world's trade.

The picture is still clouded with uncertainty, but broadly we can say that a climate change of the predicted magnitude would have enormous social and economic consequences that defy the imagination.

What is required from a scientific community keeping in close touch with the economic and political realities is an agenda for action. The greenhouse phenomenon is not simply an issue for the North. Its scope is certainly global, and there is increasing evidence to show that a number of developing countries are likely to be major contributors to the expected climatic warming - especially in the early decades of the next century - and many developing countries will certainly be affected. So in the preparation of the agenda for action both developed and developing countries are expected to actively participate.
Four elements to be considered in this agenda stand out:

First: We must examine in more detail the options being placed in front of the world's decision makers. There is a need for a serious discussion between governments and industry on the feasibility of reducing industrial carbon dioxide and trace gas emissions. There is certainly a need for a wider debate on such issues as the costs and benefits of a radical shift away from fossil fuel consumption. There is also a need for an evaluation of the political and economic costs of not taking such an action. It is important to carry out a study of which industries are involved in the emission of greenhouse gases, and to begin an investigation of possible actions to be taken by particular industries on a cost/benefit basis. And most importantly, we certainly should start in earnest a very serious debate on what sorts of socio-economic impacts we should be prepared to live with and develop clear options for the decision makers to choose from in responding to the potential impacts of climatic change.

Second: We must have a commitment to further scientific and technical research. Climate models and other projections must be improved greatly if they are to be a credible foundation for political action.

Third: What will the greenhouse effect mean for the person on the street twenty or forty years from now? To date there has been almost no attempt to provide the public and its representatives with any real understanding of the social and economic consequences of the anticipated warning. At the moment we could only provide the barest of ideas. But it would be a start - a foundation to build upon; a context for increasingly informed debate.

Fourth and lastly, is the need to create a machinery to set this ball rolling. I invite discussion on the possibility of establishing an international co-ordinating committee on greenhouse gases. Such a committee could encourage and review monitoring and research developments in such areas as the ones I have just mentioned and issue statements to governments, international organizations and the public at large regarding the need for particular actions and the options open in response to a potential warming of the global climate.

Mr. Chairman,

The greenhouse problem brings science to a new dawn. In spite of a host of uncertainties, it remains clear that the world's climate is now subject to the intervention of human beings. Debate - I believe - must focus on how best to handle this intervention. By this I mean channelling available resources in such a way that will allow us to understand, anticipate and possibly even direct changes in the global climate for the benefit of humanity. If we have the power to alter the climate, why shouldn't we harness that power for the good of humankind? It is an exciting prospect. Scientists can lead this debate.

Ladies and Gentlemen, I have shared with you a few ideas, I look forward to hearing your own views and I wish you every success in your deliberations.

Thank you.
STATEMENT BY MR. DONALD SMITH,
DEPUTY SECRETARY-GENERAL
WORLD METEOROLOGICAL ORGANIZATION

It gives me very great pleasure to welcome you on behalf of the WMO to this Conference on the Assessment of the Role of Carbon Dioxide and other Radiatively Active Constituents in triggering climate change and the associated impacts.

I would like to thank the Government of Austria most warmly for hosting this conference. This is not the first time the Government of Austria has demonstrated its interest in atmospheric matters. At its invitation, in 1873, the first inter-governmental conference in meteorology was held in Vienna, a conference which led to the creation of WMO's forerunner, the International Meteorological Organization. In terms of linking the atmosphere and environmental concerns, an earlier assessment of the Role of CO₂ was carried out here in Villach some 5 years ago. The commitment of Austria to the protection of the environment has also been witnessed by the hosting, earlier this year, of the Conference of Plenipotentiaries on the subject of the Global Convention for the Protection of the Ozone Layer, appropriately named the Vienna Convention. On behalf of WMO, I would like to express the sincere thanks of the Organization to the Government of Austria for hosting our session.

I extend WMO's welcome, and thanks, on behalf of the Secretary-General, Professor G.O.P. Obasi, who has been prevented by unforeseen circumstances from participating in the Conference. He has asked me to convey his regrets and his personal best wishes for a successful meeting.

Turning now to the subject of this conference, the concept that increasing carbon dioxide in the atmosphere could lead to a global warming of the surface of the Earth has been known for some time. In fact, this topic has been a subject of scientific curiosity since 1863 when Tyndall first raised it. But society's concern about the potential global consequences of the CO₂ increase has been much more recent.

There is yet another concern for us today. Nearly 20 man-made chemical substances whose presence has been detected in the troposphere could, as their atmospheric concentration increases, add substantially to the warming trend expected from carbon dioxide. Chief among these are methane, nitrous oxide, and two fluorocarbons that calculations show to be depleting the ozone layer. The change in the ozone layer itself has a climatic consequence. It is clear, then, that we can no longer exclude the consideration of these other greenhouse gases from our deliberations on climate change.

In the past, the atmosphere has been regarded as having a fixed composition and as being essentially stable with respect to the stresses placed upon it. It has indeed remained largely unchanged at least for the duration of human history. Recently, the greenhouse issue has raised a question about these assumptions. The composition of the atmosphere is finely balanced, yielding conditions such that most of today's life forms may
flourish on earth. Its composition renders the intake of solar energy possible, and through the use of this energy leads to winds and clouds and rain and snow, and photosynthesis and, in turn, to agriculture, animal husbandry, fisheries, and so on to the multifarious activities of humans. One is tempted to say that tampering with atmospheric composition may be tantamount to tampering with civilization. We must be concerned about any changes.

We know for a fact that the concentration of CO$_2$ and other greenhouse gases in the atmosphere (barring stratospheric ozone) is increasing. The rates of increase are subject to many factors with both man and nature playing a role in determining the trends. In the case of CO$_2$, for example, on the one hand energy demand and the rapidity with which fossil fuel is utilized depends upon man's needs and is intimately tied to the development of nations. On the other hand, the natural uptake of CO$_2$ by the oceans will control the actual atmospheric content of this gas; this process is dependent upon ocean chemistry, ocean circulation and the exchanges at the air-sea boundary. Uncertainties in these factors make it difficult to predict precisely when the concentration of atmospheric CO$_2$ will double. The presence of the other greenhouse gases complicates the issue. However, whatever the uncertainties, most experts in this field agree that man's influence on the greenhouse gases will produce higher surface temperatures than would otherwise be the case. How quickly that relative warming occurs is important because it will influence the courses of action that humanity will have to follow to minimize and counteract a potential calamity.

Choosing appropriate courses of action also depends on the effects of man-induced warming on a host of geophysical, biological and socio-economic factors. That these issues provide formidable challenges to many scientific disciplines and to many organizations is well illustrated by the attendees here today.

Of the international organizations with a contribution to make to meeting the challenge, WMO is heavily involved in addressing four of the many issues.

First, we monitor changes in atmospheric composition. This is achieved largely through the WMO Baseline Air Pollution Monitoring Network, a component of UNEP's GEMS, and through the global ozone network.

Second, we monitor the climate system. This is done through a global network of reporting stations, through the use of satellite observations and, increasingly, through the use of all available observations in sophisticated numerical models to obtain analyses of the global atmosphere. Climate System Monitoring is handled by the World Climate Data Programme, one on the four components of WMO's umbrella World Climate Programme.

Third, in a joint activity with ICSU, we address the question of what will happen to the world's climate as the greenhouse gases increase. This research is the responsibility of the World Climate Research Programme, guided by the Joint Scientific Committee of ICSU and WMO. This programme also addresses the complex questions of ocean-atmosphere linkages in the climate system, in co-operation with the International Oceanographic Commission.
Finally, WMO's World Climate Applications Programme, with priorities in the food, water and energy sectors, is closely allied to the World Climate Impact Programme in which UNEP takes the lead.

With all this work in hand, and much more elsewhere, the public and the policy makers may well be puzzled when we continually caution them about the uncertainties. How is it, they may ask, that at a time when we can send a vehicle into outer space and predict its precise position at any time, we are not able to predict, say, the temperature between 20 and 30°N latitudes in the year 2070? This is a legitimate question and our supporters deserve an honest answer. The answer, of course, is that, for global environmental calculations, the variables that determine the answers are so many and their interactions so very complex that precision is still not possible. Only by continually improving our knowledge of the variables and their relationships can we hope to increase our confidence, to narrow the range of uncertainty, in the answers.

We have already come a long way, having reached a consensus on trends, and can look ahead with considerable optimism. Our experience over the last few decades has taught us that new tools, new techniques and new knowledge are becoming available with increasing rapidity in the environmental areas. Also, scientists from many disciplines and from many organizations have learned to work together so as to study and better understand very large and complex systems and their inter-relationships. Should there not yet be a global consensus on the necessary social and economic actions, there is every prospect that the uncertainties in the current evaluations of the issues can be narrowed to the point where such a consensus can be reached. That will indeed be a welcome situation, because environmental preservation and economic development have become inextricably intermingled. Environmental degradation has a cost associated with it and economic development which ignores the environment will exact a penalty, at the very least in the form of lowered long-term benefits.

The behaviour of the atmosphere, the limits of its predictability, the linkages between the atmosphere and other geophysical, ecological and socio-economic systems – all these issues can be addressed in only one way: namely through the scientific process.

As I see it, the challenge before the community of atmospheric scientists and their organizations such as WMO is this: to identify the precise nature of the most important uncertainties associated with environmental assessments of atmospheric factors and to find objective ways of dealing with them. In so doing, we might bear in mind a statement of Albert Einstein's: "Concern for man himself must always constitute the chief objective of all technological effort, concern for the big, unsolved problem of how to organize human work and the distribution of commodities in such a manner as to assure that the results of our scientific thinking may be a blessing to mankind and not a curse".

I think that this Conference shows that we are indeed heeding this advice, by concentrating on three outputs: first, a comprehensive statement of current knowledge, for the information of policy makers, on changes in atmospheric composition and subsequent effects; next, guidance for future work on assessing socio-economic consequences; and finally, recommendations for future research.
My first words this morning must be to convey to you the regrets of Sir John Kendrew, the President of ICSU, and of Professor Lars Ernster, the Secretary General, that they cannot be present at this important meeting. Conflicts of dates are an affliction that trouble Inter-Governmental and Non-Governmental organisations alike and a common forum such as we have here in Villach is particularly vulnerable. At this moment both the President and the Secretary General are attending a special study conference on the present role of ICSU and on the appropriate strategic plan for the organisation in the years ahead.

Their absence does not reflect any lack of interest in this important meeting, and Sir John Kendrew has asked me to convey the following message to you:

"Deeply regret our inability to be with you at Villach Conference because of overlap of dates with ICSU meeting in Munich. Please reaffirm ICSU commitment to continuing programme of basic research into CO₂ and other radiatively important gases and transmit our best wishes for a successful conference".

When the topic of co-operation between IGO's and NGO's is discussed at the ICSU meeting in Munich, reference will certainly be made to the successful co-operation in the field of Climate of which this Conference is a reflection. The success of the collaboration between ICSU and WMO in relation to the Global Atmospheric Research Programme (GARP) has been followed by similar close collaboration in the World Climate Programme with both WMO and UNEP. This collaboration has given rise to innovative structures for planning and implementation such as the Joint Scientific Committee (JSC) and Joint Planning Staff (JPS) for the World Climate Research Programme (WCRP), which operate under a WMO - ICSU agreement, and the Commission for Climate Changes and the Ocean which is a joint creation of the Inter-Governmental Oceanographic Commission (IOC) of UNESCO and the Scientific Committee on Oceanic Research of ICSU. Under these and other collaborative arrangements, ICSU can call on experts in the many diverse physical and biological sciences to assist in the planning of important international programmes.

It was inevitable that the attention of ICSU as well as of WMO and UNEP would turn to the question of the global effects of carbon dioxide and of other radiatively active gases. As you are all aware, the three organisations combined in sponsoring the first Villach meeting in November 1980 at which a group of experts made a preliminary assessment of this problem. The conclusion of the 1980 Villach meeting that CO₂-induced climatic change is a major environmental issue encouraged the three sponsoring organisations to promote further study of the problem and to prepare for a more detailed and authoritative assessment at the present Conference.
The main purpose of the present Conference is to evaluate the scientific basis for the assessment of the impacts of an increased concentration of atmospheric carbon dioxide on the interaction between the climate and the biosphere. In tackling this question, it has been possible to build on the foundation of knowledge and expertise acquired over a number of years under the programme on bio-geochemical cycles of ICSU's Scientific Committee on Problems of the Environment (SCOPE). The importance of socio-economic impact studies has not been as highly developed in this vital area at this Conference.

I would like on behalf of ICSU to commend those responsible for the preparations for this Conference. The efforts of Professor Bolin and his co-workers and their reviewers have resulted in an authoritative statement of our present scientific knowledge on carbon dioxide emissions on their physical and biological effects. Dr. Clark has admirably surveyed the field of socio-economic impacts and suggested a number of ways of seeking to bridge the gap between scientific knowledge and policy decisions. We are also indebted to the Austrian Authorities for their support and for the excellent arrangements for the Conference.

The rest is up to us - the members of the Conference. It is our task under the leadership of our Chairman to prepare a statement that will have the overwhelming support of the Scientific Community as an authoritative statement on the scientific facts and at the same time will state clearly, not only the most appropriate ways of removing remaining scientific uncertainties and improving our ability to evaluate socio-economic impacts, but also will provide a first approach to a sound foundation and appropriate guidelines for the development of the necessary policies at the national and international level.

Though ICSU's expertise is in the basic sciences, ICSU would welcome the movement of the international effort in the area of radiatively active gases beyond the initial phase in which the major emphasis was on the physical and biological effects. The impacts are global and require both joint study and joint action by all the nations of this planet. It will, of course, be necessary at the same time to maintain the long-term monitoring stations, perhaps to establish new ones, and also to endeavour to fill in the gaps in our knowledge that create a number of serious uncertainties. The two broad general lines of action, one concerned with science, the other with policy, are not antagonistic or incompatible and indeed can reinforce one another through interchange of information on problems and results. It is for this Conference to state how such an interchange can best take place. On behalf of ICSU, I wish the Conference well and look forward to participating in it.
The amounts of some trace gases in the atmosphere, notably carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), chlorofluorocarbons and tropospheric ozone, have been increasing. All of these gases are transparent to incoming short-wave radiation, but they absorb and emit long-wave radiation and are thus able to influence the Earth's climate. They are referred to in this report as greenhouse gases.

Increased concentrations of CO₂ and other greenhouse gases lead to a warming of the Earth's surface and the lower atmosphere. The resulting changes in climate and their impacts (e.g. on sea level, agriculture, and forestry) can be estimated without associating the origin of the warming to any one of these gases specifically. It is, however, necessary to study the effects of these greenhouse gases separately in order to estimate their relative contributions to the warming at any given time and, consequently, to develop strategies for reducing their possible harmful effects.

A review of previous assessments of the CO₂ problem shows that there are agreements on some basic issues. The net emissions of CO₂ from the biota (due to deforestation and land use changes) in themselves will be insufficient to cause a significant change of climate, while fossil fuel reserves are large enough that climatic changes would occur if these reserves continue to be exploited at a high rate in the future.

Generally it has also been agreed that regional patterns of climatic change cannot yet be predicted. Thus, the ways in which higher CO₂ concentrations and given changes in climate would affect ecosystems and human activities cannot be predicted either. This is presumably one of the main reasons why there has been substantial disagreement among previous studies regarding recommendations for future action.

Emission of CO₂

- The observations that began in 1958 have clearly shown that the atmospheric CO₂ concentration has increased from about 315 ppmv in 1958 to about 343 ppmv in 1984. We know the amount of CO₂ that has been emitted into the atmosphere by fossil fuel combustion and changing land use and can relate approximately the observed increase of atmospheric CO₂ to these human activities.

- An evaluation of the "pre-industrial level" of atmospheric CO₂ (concentrations occurring in the middle of the last century), based on direct measurements and analyses of air trapped in glacier ice, yields a value of 275 ± 10 ppmv.

* The complete text of the IMI report will be published by Wiley in 1986.
Combustion of fossil fuels—primarily oil, gas and coal—currently meets about 80% of the global energy demand. Future emissions of CO₂ will depend on how this global demand changes and what role fossil fuels play in the future supply. However, even short-term (a few decades) projections of energy use are very uncertain.

The present assessment places an upper bound on possible CO₂ emissions of about 20 Gt C/year in the year 2050, i.e. about a fourfold increase of the present emission (5Gt C/year). Higher values seem unlikely in view of environmental, social and logistic constraints.

The lower bound on CO₂ emissions is placed at 2 Gt C/year in 2050. This value could possibly be achieved by sustained global efforts to limit the future use of fossil fuel energy by decreasing energy demands and by increasing the use of non-fossil energy sources.

Policy decisions concerning fossil fuel use should take into account the negative effects of CO₂ emissions with regard to changes in climate while simultaneously considering their other environmental effects (e.g. air pollution, increasing ozone concentrations, acid rains).

**Increases of atmospheric CO₂**

Understanding of the global carbon cycle has improved in recent years. Despite these advances, it is still not possible to balance the global carbon budget completely. However, the remaining uncertainties do not seriously influence the conclusions regarding the future levels of atmospheric CO₂ concentrations.

Constant or very slowly increasing (0.5% per year) emissions of CO₂ during the next four decades, with slowly increasing emissions thereafter, would give an atmospheric CO₂ concentration of less than 440 ppmv at the end of the next century (i.e. less than 60% above the pre-industrial level).

If the present increase of CO₂ emission (an average of 1–2% per year since 1973) continues over the next four decades with a slackening of the rate of increase thereafter, a doubling of the pre-industrial CO₂ concentration would be reached towards the end of the next century.

The upper bound scenario implies that the CO₂ concentration might double by the middle of the next century, while the lower bound scenario implies that doubling of CO₂ concentration will not be reached until after 2100.
Other greenhouse gases and aerosols

- The equilibrium temperature change due to the increasing concentrations of other greenhouse gases (in particular, nitrous oxide, methane, ozone and chlorofluorocarbons) up to the present is estimated to be about half of the temperature change attributed to the increase of atmospheric \( \text{CO}_2 \) alone. The concentrations of some of these gases, and hence their relative importance in changing the climate, are increasing more rapidly than that of \( \text{CO}_2 \).

- If present trends continue, the role of non-\( \text{CO}_2 \) greenhouse gases in changing the climate will become at least as important as that of \( \text{CO}_2 \) within the next few decades. The combined concentrations of atmospheric \( \text{CO}_2 \) and other greenhouse gases would be equivalent to a doubling of \( \text{CO}_2 \) possibly as early as the third decade of the next century.

- Chlorofluorocarbons may, within decades, become the greenhouse gas that next to \( \text{CO}_2 \) is increasing its importance for changing the radiative properties of the atmosphere most rapidly, if no preventive measures are taken. On the other hand, their regulation would be easier to achieve than the limitation or reduction of \( \text{CO}_2 \) emissions.

- Our knowledge of the global biogeochemical cycles that determine atmospheric concentrations of methane, nitrous oxide and ozone is still inadequate as a basis for policy decisions on how to reduce or limit the future growth of their concentrations.

- Although changes in global climate due to increasing concentrations of aerosols in the atmosphere probably have not been significant in the past, the possibility that they may become of importance in the future, particularly regionally, cannot be excluded. Future changes in aerosol concentrations cannot be projected with any certainty.

Changes in climate

- An evaluation of results from climate models leads to the conclusion that the increase in global mean equilibrium surface temperature due to increases of \( \text{CO}_2 \) and other greenhouse gases equivalent to a doubling of the atmospheric \( \text{CO}_2 \) concentration is likely to be in the range of 1.5 - 5.5°C. Although no value within this wide range of uncertainty can be excluded, it is plausible that the increase may be found in the lower half of this range.

- The observed increase in mean temperature during the last 100 years (0.3 - 0.7°C) cannot be ascribed in a statistically rigorous manner to the increasing concentration of \( \text{CO}_2 \) and other greenhouse gases, although the magnitude is within the range of predictions (0.3 - 1.1°C).
The expected global mean temperature due to a doubling of CO₂ is of about the same magnitude as the change of global temperature from the last glacial period to the present interglacial.

Continental or regional scale changes in climate cannot yet be modelled confidently, except that there are indications that warming will be enhanced in high latitudes and that summer dryness may become more frequent over the continents at middle latitudes in the Northern Hemisphere.

Changes in sea level

The global average sea level has risen 12 ± 5 cm during the twentieth century.

It is estimated empirically, on the basis of observed changes since the beginning of this century, that a global warming of 1.5°C to 5.5°C would lead to a sea-level rise of 20 to 165 cm. The major contributing factor to such a rise would be the thermal expansion of ocean water.

A catastrophic collapse of the West Antarctic ice sheet is not judged to be imminent, although many glaciologists consider that further research is necessary before a reliable assessment of this possibility can be made.

Assessing the impact on ecosystems

Based on evidence from climatic changes of the distant past, there is little doubt that a future change in climate of the order of magnitude obtained from climate models for a doubling of the atmospheric CO₂ concentration could have profound effects on global ecosystems.

Prediction of the future impacts on ecosystems is precluded by the lack of reliable estimates of climatic changes at regional scales, and by the lack of knowledge concerning the interactive effects of CO₂ and climate variables on vegetation. Despite the inability to make predictions, sensitivity analyses can produce useful information for judging the possible direction and magnitude of effects for given changes in CO₂ levels or climate variables, and thus for identifying specific regions and environmental changes which may warrant policy attention in the future.

Consequences for agriculture

In general, the direct effects of enhanced CO₂ concentrations on crop yield are beneficial. It is estimated from laboratory experiments on individual plants that, in the absence of climatic change, a doubling of the CO₂ concentration would cause a 0-10% increase in growth and yield of C₄ crops (e.g. maize, sorghum, sugar cane) and a 10 to 50% increase for C₃ crops (e.g. wheat, soyabean, rice), depending on the specific crop and growing conditions.
In analysing the sensitivity of crop yields to possible changes in climate without including the direct effects due to higher CO₂ concentrations, most research has focused on average yields of cereal grains in core crop regions of the temperate latitudes. Less attention has been paid to the tropics and subtropics, to the climate-sensitive margins of production, and to possible changes in year-to-year climatic extremes.

Crop impact analyses show consistently that warmer average temperatures are detrimental to both wheat and maize yields in the mid-latitude core crop regions of North America and Western Europe. Given current technology and crop varieties, a sudden warming of 2°C with no change in precipitation might reduce average yields by 10 ± 7%. Increases in precipitation could partially offset these effects, while drier conditions could exacerbate them. Changes in the length of the growing season or in the frequencies of extreme climatic events could also have important effects.

At the margins of crop areas, spatial shifts in cropping patterns might occur as a result of changes in climate. A limited number of marginal-spatial analyses suggest that, in the mid- to high-latitude cereal growing regions, horizontal shifts of several hundred kilometres per °C change are possible, assuming unchanged technology and economic constraints. In North America, these are comparable in magnitude to shifts in crop patterns that have taken place over this century. At the cool, high altitude limits of production, altitudinal shifts of more than a hundred metres per °C may be possible.

Models of agricultural production and trade suggest that numerous feedback mechanisms exist in many regions through which agriculture can adjust and adapt to environmental change. Over the long term, food production in such areas appears more sensitive to technology, price or policy changes than to climatic changes, and these factors are largely controllable, whereas climate is not.

However, for some regions, particularly the lands marginal for food production in the developing world, agriculture may be acutely sensitive to climatic change, as evidenced by the tolls taken by year-to-year variations in climate. If these regions can adopt measures to reduce further the ill-effects of current, short-term climatic variability, it is likely that they will be better prepared to adapt to any adverse effects of future changes in climate, should they occur.

Consequences for forests

At present, firm conclusions cannot be reached regarding the direct effects of elevated CO₂ concentrations on the productivity, species competition, or size and areal extent of the world's forests. This is because of the paucity of experimental evidence for relevant tree species, particularly over one or more growing cycles, and the large uncertainties involved in "scaling up" from the short-term responses of individual leaves or plants to complex forest systems.
If, indeed, elevated CO₂ concentrations do result in increased growth of individual trees over the long term, increases in productivity would be most likely to occur in commercial forest plantations, and would be less likely to occur in mature natural forests, although biomass turnover rates would increase.

The sensitivity of forests to climatic change has been analysed using forest simulation models. These studies suggest that temperature increases of the size indicated by current climate models for a doubling of atmospheric CO₂ are potentially sufficient to produce substantial intermediate and long-term responses in the composition, size and location of forest ecosystems.

These climate models predict the largest warming to occur at high latitudes as a result of increased concentrations of greenhouse gases, with smaller rises in temperature in the lower latitudes. The natural forests of the high latitudes in general, and the boreal forests in particular, may be most sensitive to temperature changes. Warmer conditions could thus possibly lead to large reductions in the areal extent of boreal forests and a poleward shift in their boundaries.

The forests of the tropical and sub-tropical zones probably would be more sensitive to changes in precipitation than in temperature. However, because of the high uncertainty regarding future changes in precipitation in the tropics, and because of the lack of models that can be used to simulate the effects on tropical ecosystems caused by changes in climate variables, it is virtually impossible to make informed prediction of the responses of tropical forests to future climatic changes at present.

The problem of a possibly changing climate due to the emissions of greenhouse gases should be considered as one of today's most important long-term environmental problems. It should be considered in the context of other ongoing changes of our environment also caused by human activities, such as air pollution, acid rains, and deforestation. Only in this way can an integral view of the mutual interplay between the environment as a whole and the global society be considered satisfactorily.
ON THE PRACTICAL IMPLICATIONS OF THE GREENHOUSE QUESTION*

BY

WILLIAM C. CLARK

Questions raised by the increasing atmospheric concentration of radiatively active "greenhouse" gases 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.

My approach is based on four fundamental characteristics:

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

o The environmental changes related to greenhouse gases 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 greenhouse gas-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 greenhouse gas question must contend with those long-term background changes.

o Possible causes and effects of greenhouse gas-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 greenhouse gas question; actions taken on greenhouse gases will affect those other problems in turn. The practical implications of the greenhouse gas question cannot usefully be addressed without accounting for linkages to related problems and their solutions.

o Finally, uncertainty dominates every aspect of the greenhouse gas 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 greenhouse gases.

* The complete text will be published in the World Climate Programme series in 1986.
"The" greenhouse gas 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". In real world messes 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 greenhouse gas question might hold for them. 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 greenhouse gas 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 greenhouse gas debate would better comprehend each others' concerns and preferred actions.

Despite some gratifying progress, the tool kit needed for societies to cope effectively with the greenhouse gas question is far from complete. Missing are the broader perspectives that could help to locate the greenhouse gas question within the context of related economic trends, political agendas, and environmental problems. It is these contextual issues that will both shape impacts of greenhouse gas-related environmental changes on societies, and provide societies with their options for dealing with those impacts. This analysis has attempted to characterize some of the missing perspectives and the tools needed for working with them. Three of the more important areas in which recent studies have suggested real prospects for progress are risk assessment, frequency of extremes, and policy exercises.

1. **Risk assessment.** The greatest single blunder in contemporary efforts to understand the practical implications of the greenhouse gas question is the continuing focus on "most likely" rather than "possible" impacts and consequences. In the short run, the greatest single addition to usable knowledge about the greenhouse gas 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 how thoroughly uncertainties pervade the greenhouse gas question. Both the policy makers and the scientists who write the assessments are concerned that continued releases of greenhouse gases 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 greenhouse gas 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 halfway between the extremes.
The methods of risk assessment are relatively well developed, and a healthy critical dialogue now exists regarding their strengths and weaknesses. Several examples of good practice with useful results do exist which could serve as models for useful work on the greenhouse gas question. The major obstacle to their application is the absence of usable uncertainty estimates from the scientific research community. Until very recently, little effort had been made to provide systematic, quantitative estimates of the scientific uncertainties relevant to the greenhouse gas question.

Dickinson recently 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". 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 greenhouse gases and other gases 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 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 greenhouse gases be compared with probable drastic impacts of measures that might be taken in response to increasing concentrations of greenhouse gases. The necessary analysis has not been done.

Large hydropower dams that are one alternative to greenhouse gas-producing fossil fuels have a probability of failure of about $10^{-4}$ per dam-year. A single 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. Nuclear power is another alternative to the continued emission of greenhouse gases. 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 fall, i.e. with a chance of $10^{-4}$ or less per reactor-year, or $10^{-2}$ per reactor by the year 2100. 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). This worst-case 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 (i.e. 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 $10^{-5}$. The chance that the world of 2100 will have witnessed a single local nuclear power catastrophe is thus 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 greenhouse gas 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 greenhouse gas question.

2. Changing frequencies of extreme environments. 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. 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. This is not, however, a useful distinction. The overwhelming message of the data is that the environment varies at all scales, and societies can respond to such variations at all scales. If greenhouse gas 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.

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 has been summarized by Wigley* 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. 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. Wigley 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." 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. 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.

An additional dimension of the nonlinear response argument is fundamental to (but often only implicit in) the "extreme events" view of climate impacts. The key nonlinearity or threshold 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. The properties of multiple equilibria and bifurcation are found in many nonlinear social, ecological, and physical systems, especially those operating at multiple time scales. 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. The time is ripe for the "extreme event" element of the greenhouse gas 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 greenhouse gas-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 greenhouse gas and related emissions.

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. The first step in addressing the problem of extreme in space 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. Such impact analysis would then provide a focus for continuing work in climatic teleconnections.

3. Policy Exercises: learning to cope with the greenhouse gas question. 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. In the program on "Sustainable Development of the Biosphere" at the International Institute for Applied Systems Analysis, we are 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. Policy exercises are derived from approaches developed in support of political-military strategic planning during the late 1950's and early 1960's. The method sought to write "future histories" through "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.
Four "difficult questions that eluded or exceed the capacity of alternative analytic tools" were explored by the original political exercises:

1. What political options could be imagined in light of the conflict situations portrayed? What likely consequences would each have?
2. Could political inventiveness be fostered by having those actually 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?
3. 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?
4. Could the game sensitize responsible officials to make potential decisions more realistic, especially with respect to likely political and policy consequences?

Experience with the exercises and previous military gaming shows that they can be very useful in providing an orderly framework for analysis and discussion. 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 greenhouse gas 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. 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. In the final analysis, it is only by working through specific future histories of the greenhouse gas questions and social responses to it that we will 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. A systematic effort to develop appropriate regional policy exercises for learning to cope with the greenhouse gas question should therefore begin immediately.
STRUCTURED RESPONSE I

THE CO₂-CLIMATE PROBLEM REVISITED

BY

THOMAS F. MALONE*©

INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS

It is a pleasure to provide a "structured response" to the two splendid papers by Professor Bolin and Dr. Clark. The authors are to be congratulated on thoughtful analyses and incisive summaries of what is appropriately described in the Executive Summary in these words: "...changing climate due to the emission of greenhouse gases should be considered as one of today's most important long-term environmental problems."

A decade ago, I was privileged to represent ICSU on the Panel on Climate of the WMO Executive Committee. Chaired by Dr. William Gibbs of Australia, the Panel included Professor Bolin, J. Murray Mitchell, C.C. Wallen, Herman Flohn and several other distinguished scientists from the world scientific community. We spent considerable time focussing on the CO₂-climate issue and ended up by recommending that WMO organise a programme to address this intrinsically global problem. Little immediate action resulted, but in the course of time, the matter moved higher and higher on the WMO agenda.

In a sense, then, this response is a revisitation for me of a problem that a small group of us examined over a decade ago.

Two questions provide a structure for this response:

1. What has changed over the past decade?
2. In the light of these changes what "action imperatives" appear to be in order?

Five developments merit attention:

1. Perhaps the most important development is the finding that increases in the "other" greenhouse gases (nitrous oxide, methane chlorofluorocarbons and tropospheric ozone) have contributed about one half of any equilibrium temperature change that might be ascribed to the increase in CO₂. Moreover, the rate of increase in the impact of these "other" gases appears to be greater than the increase in the effects of CO₂ itself. To those of us who met in Geneva a decade ago, this may be categorized as a "surprise". The significance of this "surprise" is that the date of a possible significant global environmental impact is earlier by several decades than previous estimates had suggested.

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What other "surprises" lie ahead? The history of scientific progress leads us to anticipate that there will be surprises. One can only speculate what they will be. The role of the oceans and of chemical processes in the troposphere would seem to be possible candidates, but one cannot even speculate that they will add to or subtract from the urgency of scientific research and policy analysis.

2. With the completion of FGGE, the development of more sophisticated and realistic models of the general circulation of the global atmosphere, with vastly increased computational power, we have been able to demonstrate unequivocally, through enhanced predictive capability, that these models are beginning to reflect finite progress toward understanding the physical processes that determine climate change. Of special significance is the enhanced capacity to incorporate the influence of radiatively active gases in interactive, three-dimensional, multi-layered models. This new capability has emerged from the need for a scholarly investigation of the environmental consequences of the elemental amorphous carbon particles injected into the atmosphere by a hostile exchange of nuclear weapons.

Within a decade, observations and understanding will bring us within reach of models coupling the atmosphere and the oceans. This will provide us with a quantum jump in our capacity to assess the impact of "greenhouse gases" - and possibly permit us to illuminate the murky issue of differential regional effects. (In the material before us, I did not note sufficient attention to what we do know about the latitudinal gradient of CO₂-induced temperature change.)

3. A serious attack has finally been launched on the exceedingly complex problem of the impact of climatic change on ecosystems - both natural and cultivated systems. New ground has been broken by Professor R. Kates and by Dr. Martin Parry and his colleagues. These advances have a strong relationship to the need to develop what has been called "stress ecology" by Mark Harwell and his colleagues, who have been addressing ecological and agricultural consequences of a nuclear war in the project SCOPE-ENUWAR which has produced a 500 page volume of direct relevance to the deliberations of this conference. It turns out that cultivated ecosystems are especially vulnerable to relatively small perturbations in temperature, precipitation, sunlight and other environmental elements.

4. To me, one of the most promising -- and I would even say exciting -- developments of the past decade is represented by the attention sharply focussed by Dr. Clark on the attractive possibilities of initiating a scholarly and pragmatic examination of the policy considerations of the issue before us. Clark's paper is an important milestone in the deliberations within the International Institute for Applied Systems Analysis and its national members over the past two years addressed to the crucial issue of "Sustainable Development of the Biosphere". I applaud
his emphasis on the need to search for the "bottom line" of an assessment of the practical implications of "greenhouse gas/climate problem". This attention is most timely, if we are to generate a meaningful dialogue between scientists and decision makers. His distinction between what is "most likely" and what is "possible" might well become an important agenda item for this Conference. Exploring the intertwined scientific, economic, and political considerations — all linked to problems of energy, population, agriculture and environment — within the context of uncertainty, risk assessment and management, means and higher moments, thresholds and nonlinear impacts hold promise of providing us with the "kit of tools" Clark stresses is helping us to cross the threshold of a new era of international assessment. The proposal for "policy exercises" is decidedly attractive! To put the Clark paper in proper perspective, it constitutes only a small but important development in that "long series of small but correct decisions" that Johnny von Neuman advised us a quarter of a century ago would be required if "civilization is to survive technology".

5. Last — but not least — of developments over the last decade has been the maturing in the perception of the problem before us. This has been true in both the governmental sector and the scientific community. By this I mean that both groups now recognize that the issue before this Conference is but one example of a generic set of issues arising from the circumstance that growth in population and the potential increase in the capacity of each individual to transform natural resources into the goods and services that sustain life, and give it meaning, have brought us well into an era within which human activity can produce changes on a global scale, comparable to those within a geologic time frame — and to do so within the lifetime of a single member of the human species.

An example of this new perception on the part of sovereign national governments is the Vienna Convention for the Protection of the Ozone Layer endorsed by 20 countries on March 23, 1983. This modest, but very important, anticipatory response to a potential global threat followed a decade of discussion and debate. It provides for an exchange of information, research and data and monitoring of possible adverse health effects. The "protocols" that will be necessary to transform the convention into an effective mechanism will probably require more years of discussion. However, a start has been made!!

An example of the new perception on the part of scientists was the action taken by the scientific community (ICSU) to initiate a feasibility study of the concept of systematically exploring "Global Change". This will involve a number of ongoing programmes, and will include an initiative linking the biota in the biosphere with the physical characteristics of the biosphere by an examination of the physical, chemical, and biological processes that regulate the total earth system, the unique environment for life, the changes that are occurring in that system and the manner in which these changes are influenced by
human action. Closely related to this activity is the proposal for examining the emission, transport, transformation, temporal and spatial distribution, and deposition of chemicals in the troposphere. This enterprise has the potential for transforming the "crisis of the month" syndrome into a systematic effort to erect the intellectual framework necessary to cope with those crises. Progress is presently so rapid in atmospheric chemistry that only last weekend, I learned from Professor I. Rasool of ICSU/COSPAR that it may be possible to measure the elusive, but crucial, hydroxyl radical, OH, by remote-sensing techniques.

And so we come to the "imperatives" that would constitute the Agenda for Action that Dr. Tolba urge we develop over the next week here at Villach.

As a scientist, I expect - and would welcome - a plea for "more research". I do hope that our analysis will not stop with that general recommendation. A perceptive "research agenda" with priorities, however, could be quite useful.

As an inveterate committee member, I welcome the proposal for the "Coordinating Board" mentioned by Dr. Tolba. However, if this conference focuses on institutional quick-fixes, it will have been of questionable value. Institutional innovations must be specific and justified by filling needs not now met.

Three areas have emerged in my mind from the advance documentation. Other items may arise during the course of our deliberations. Moreover, there is an institutional instrumentality in place to address each of these items:

A half-century of observing international science and institutional instrumentalities leave me persuaded that a careful match of tasks and responsible institutions is an imperative for progress.

With respect to RESEARCH, ICSU is capable of enlisting the best minds in the world scientific community. Its programmes of cooperation with WHO, UNEP and Unesco provide us with an attractive pattern for action.

With respect to POLICY, IIASA provides us both with the intellectual strength and the outreach into both the world of intellect and the world of decision makers. By illuminating the policy issues and options, IIASA could lay the groundwork for addressing in a deliberate manner the third domain I identify as being of importance to our deliberations.

As a reversal of a position I held a year or so ago, I believe it is timely to start on the long, tedious and sensitive task of framing a CONVENTION on greenhouse gases, climate change and energy. The task will likely take longer than the decade of discussion needed to draft an ozone convention.
Finally, a word about the broad philosophical framework within which we might proceed. I think that might be found in Immanuel Kant's "Critique of Pure Reason", published more than two centuries ago. He remarked that human reason addresses three basic questions:

- What can I know? - (i.e., what is certain, uncertain, or ambiguous?)
- What ought I to do? - (i.e., what are the moral imperatives?)
- What may I hope? - (My hope is that we will address the tasks of this conference by first reaffirming a robust faith in the destiny of humankind).
In addition to the general questions and problems discussed by previous speakers, I will inform you of the concrete research efforts aimed to elucidate or narrow many uncertainties in our knowledge about our climate system mentioned earlier. These efforts are organized by the World Climate Research Programme (WCRP). This Programme is organized and coordinated by the Joint Scientific Committee (JCS), established by WMO and ICSU. The ocean part of the Programme is coordinated together with the IOC-ICSU Committee on Climate Change and Oceans (CCCO). During last week, from October 2-4, the Officers of both committees, JSC and CCCO, discussed the Implementation Plan for WCRP, in this country near Vienna. This Implementation Plan will be proposed for the consideration of the first informal meeting of governmental representatives who will meet in Geneva in the middle of May 1986.

WCRP in its Implementation Plan has undergone some restructuring but it is essentially intended to fulfil the aims of its Scientific Plan published at the end of 1984. It now comprises five major projects each of which consists of modelling and diagnostic efforts, process studies, observations, obtaining and compiling various data sets mostly of a global character.

The first is the Atmospheric Climate Prediction Project which aims at fulfilling the goals of the first stream of research within WCRP, i.e. to assess the predictability of climate on monthly or seasonal time scales. It consists of developing general circulation models, diagnosis by using observations of meteorological variables, studies and parametrizations of diabatic processes. The last includes the International Satellite Cloud Climatology Project under which are several regional experiments to obtain the ground truth for satellite data. There are two major data projects: Global Precipitation Climatology Data Project and Radiation Data Climatology Project. There will be serious efforts to specify the boundary conditions at the underlying surface. They include studies and interrelations between land surface processes and climate. To obtain the data for this UNEP, COSPAR and IAMAP have jointly developed the International Satellite Land Surface Climatology Project. To link the land hydrology and atmospheric processes, two experiments - HAPEX I and HAPEX II - will be organized, one in south-western France in 1986 and the other in the late eighties in the U.S. Great Plains. The Global Sea Surface Temperature Project will take care of the oceans for these shorter time scale studies.

The second project is TOGA, Tropical Oceans and Global Atmosphere. Scientists now believe that the key for interannual variability lies in the tropical oceans and in mechanisms of their interactions with the global atmosphere. Studies of the interannual variability of climate have great practical value per se and they also would constitute a base to study the climatic noise from which the climate signal, i.e. the climate change
should be discerned. TOGA will consist of obtaining data on the mean sea level, heat profiles in the upper ocean and circulation in it. There are two data projects - the Upper Tropical Wind Data Project which will show how the troposphere reacts on the changing tropical ocean, or lives by itself, and the Ocean-Atmosphere Interface Data Project which will collect data on the heat, moisture and momentum fluxes between the atmosphere and ocean. Of course, TOGA implies the development of numerical models and corresponding parametrizations.

The third project is WOCE, World Ocean Circulation Experiment. The Scientific Plan for WOCE is not yet complete but it will consist of three major observational experiments: Global Description of the World Ocean, South Ocean Experiment and Gyre Dynamics Experiment: the last is aimed at obtaining data on oceanic gyres occupying the northern and southern parts of the Atlantic and Pacific Oceans. WOCE like TOGA, critically needs satellite observations, especially those which could supply information on large scale topography of the ocean surface. It also needs a specialized ship for regular measurements within the ocean in the upper kilometer or more to verify satellite observations of the topography from which ocean currents could be deduced.

The fourth project has only just started its development and encompasses cryosphere research, mostly sea ice. It will be developed with the same methodology as previous projects.

The last is the Climate Sensitivity Assessment Project, which is aimed to assess the sensitivity of climate at first hand to changes in atmospheric concentrations of the radiatively active gases including CO₂. It consists of modelling activities, monitoring these gases, etc.

We realize that not everything related to climate change is covered by WCRP or is within the responsibilities of its governing bodies. Such things as monitoring are conducted by WMO stations. The studies of biogeochemical cycles of carbon, CO₂, or other greenhouse gases are carried out under different auspices - under ICSU or SCOPE - and close coordination between these activities and WCRP is vitally needed. But what is beyond question is that we need first of all strong and material support from funding agencies, from agencies possessing satellites and from governments. We scientists must make our case convincing enough to these organizations and obtain their strong and continuing support. Only then we may hope that in combining all these efforts, we can narrow the range of uncertainties of our climate projections for the future.

In conclusion, I cannot restrain myself from drawing parallels between the subject we are discussing here and that of an activity which covered another environmental issue. Several people attending this Conference, including myself, recently participated in a project unparalleled in the history of science. I mean the SCOPE ENUWAR Project, which was aimed at an assessment of the environmental consequences of nuclear war, including climatic consequences. Because of the goodwill and concentration of the participants and with the adequate funding provided the Project was completed in one and half years with a two-volume report in which the consequences for climate, ecology, agriculture, just like the problems we are discussing here, were given detailed, authoritative and convincing treatment. At the beginning, only a year ago or so, there were many talks on uncertainties of the first predictions, or projections, using the terminology adopted here.
Sceptics, and others, implied that these uncertainties may save us. In this respect, for me the situation with our problem here, though it is of a different nature and time scale, is similar. We should start hard, consistent and coordinated work without expecting that something will save us even if we do not take any measures against the aggravating environmental threat.
The statement that we still know too little about the structure and functioning of tropical systems: forests, savannas, crops, rivers, lakes, etc., let alone the climate, is already commonplace. The fact is that we know still less about those systems' responses to man-induced changes. The role of tropical systems in many important processes in the biosphere is at best beginning to emerge. Whether the changes we impose on tropical systems be drastic and catastrophic like nuclear winter, or gradual like the increase in CO₂ and other radiatively active gases, our answers to the likely consequences are only based on educated guesses.

There are however several good reasons and a few important constraints in trying to find the right answers and hopefully act accordingly.

One good reason is that of total land area; tropical rain forests, tropical seasonal forests and savannas occupy about one fourth to one third. According to different authors, they represent anything between one third and four fifths of total terrestrial biomass C and around one half of total productivity. Their impact on the global C cycle can therefore be considerable. It is interesting to note that soil and debris C represent a smaller proportion: only one fifth of total C in those compartments is worldwide. This is evidence of the accelerated pace of C cycling at higher temperature.

One could expect both agricultural and natural systems in the tropics to be severely affected by changes in climate, perhaps in a larger proportion if there are changes in the hydrological régime accompanying the temperature rise.

The contribution of the tropics - usually developing countries - to the increase of CO₂, is a minor proportion of the total emissions, but it is worthwhile stressing that their share is increasing at a faster rate than any other sector, due to some or all of the following reasons: a) population increase rates; b) relative reduction of emission rates in the developed, industrialized countries; c) industrialization with a growing tendency toward heavy industries, while developed nations go for high-tech fields; d) inefficient use of fuels.

Another important factor that I want to bring to the attention of the conference is the way the problem is perceived in the tropics. If in the industrialized nations politicians and technical decision-makers are wary of ecological problems posed by scientists with their usual load of uncertainties, problems that are global rather than national, long-term in scope and which cannot be perceived easily by their constituencies, they are even more so in developing nations where there are many more pressing issues. Acidification, greenhouse effect, nuclear winter or even deforestation are viewed as academic exercises in which developed nations can indulge but we
cannot afford. The ever-widening gap between the industrialized world and our countries tends to produce a feeling of frustration, a negative response or at best a lack of response to these issues. I personally think that the reasons are valid but the lack of response is dangerous because it might take planners unawares. The general public is even less informed and understandingly less interested in such long-term global issues. More than a situation of "winners and losers" it can be perceived as a play in which others have written the script and are the actors while we are forced to be passive, captive audiences. When these problems are aired publicly they are often labelled as luxury items in the wish-lists of scientists who deviate their efforts from more productive areas of science and technology for development.

Provided the scientific community can reach decision makers in tropical countries, two courses of action should be taken:

(a) re-assess crop zonation and practices for the possible changes in climate,

(b) help reduce emissions by improving efficiency rather than cutting down on development.

However, both points deserve a few words of caution. First, societal conservatism can be a serious hindrance in changing food habits. The cases of adaptation of New World crops to the Old World come in handy. It took nearly two centuries for potatoes to become adapted and acceptable. The process of expansion and adoption of maize (corn) is still in a stage where it is only used with pigs and cows as inefficient intermediaries. Another serious problem arises from the displacement of inefficient, often obsolete technologies as the industrialized world progresses, with the transfer of those to Third World countries. A major improvement in food availability in tropical countries can only come from increased yields and improved food conservation practices. Both imply an increase of CO₂ emissions and the latter the use of chloro-fluorocarbons for refrigeration.

Now let me mention a few salient points that in my opinion merit some attention during the working group sessions of this Conference:

1) Most of what is forest land in the wet tropics is very limiting for conventional agriculture, both because of soil quality and hydrological regime. They could become even less amenable to productive conversion if the climate becomes hotter and possibly wetter.

2) Many important tropical crops are C₄ grasses, e.g. sugar cane, maize, sorghum. It is generally accepted that these would be less responsive to increases in atmospheric CO₂ as compared with C₃ cereals which can only be marginally grown in the tropics. This would accentuate the present dependency on food imports.

3) A very important factor I have not seen mentioned in connection with the greenhouse gases problem, is that, if temperature increases, nighttime respiration could also be enhanced, thus possibly offsetting the beneficial effects of high productivity during the day.
Last but not least, a number of possible interacting loops between processes should be carefully taken into account in the greenhouse effect studies. Among them are the decrease in transpiration rate of some plants at high pCO$_2$; changes in decomposition rate due to litter quality, temperature and humidity changes, etc., possible increases in the rate of CH$_4$ productions in wetlands. Even some minor changes in parts of the cycles, which are considered as minor problems for the modelling of the warming effects of CO$_2$ and other greenhouse gases, can have disproportionate effects if conditions change. Research work by our group in the Amazon has shown that even minor climatic changes in the past, probably within stochastic variability, have produced widespread fires in what is normally considered a fire-proof biome. Cascading effects, synergisms and thresholds cannot be ignored.

The changes in precipitation which accompany changes in temperature in more refined models could be the clue to attracting the attention of governments in tropical countries regarding these subjects. From these models a better projection to integrate the results of experiments carried out by organizations, individuals and even communities or regions, could be a great help in promoting responses at the national level.

I would like to finish with a good lesson from the tropical world. In Brazil, presumably motivated by economic or geopolitical reasons, the first example of a massive recycled CO$_2$ fuel system has been developed in a short time. At present some 50% of new motor vehicles are fueled by pure ethanol from sugar cane, and a growing number of old gasoline vehicles are being converted. Additionally, all gasoline is mixed with 20% alcohol.
WORKING GROUP I - EMISSIONS OF CO₂ INTO THE ATMOSPHERE

Chairman: G. Goodman

Members:
B. Bolin
H. de Boois
B. Döös
G. Dorin
G. Edmonds
J. Jäger
W. Keepin
F. Koomanoff
J.M. Ndombi
K.C. di Primio
G.W. Yohe

Rapporteur: S. Unninayar

The Problem

Carbon dioxide (CO₂) is a radiatively active atmospheric constituent. CO₂ concentration has increased from about 315 ppmv in 1958 to about 345 ppmv in 1984, compared to a pre-industrial level of 275 +/- 10 ppmv. The most significant contributions to this increase are anthropogenic, fossil fuel burning and changing land use (e.g. deforestation). The recoverable fossil fuel reserves are so large (c. 4000 Gt) that they present no constraint to the future buildup of atmospheric CO₂ concentration. The current rate of emission of CO₂ from fossil fuel burning is approximately 5 Gt of carbon per year (Gt C/yr), and has remained relatively stable over the last five years.

Future emissions of CO₂ will depend on how global energy demand changes, about 80% of which is met by fossil fuel burning, and the role fossil fuels play in the future energy supply. These are the primary uncertainties in future emissions of CO₂. A decade of research has shown a decline in the expectations for the annual growth of CO₂ emissions.

A range of concentration for CO₂ between 390 and 580 ppmv is currently projected for 2050. Disagreement exists on a precise upper bound for future CO₂ emissions. The present assessment places the upper bound at about 20 Gt C/yr in the year 2050, about a four-fold increase from the present emission rate of 5 Gt C/yr. Higher values seem unlikely in view of
environmental, social, and logistic constraints on fossil fuel use, although in the extreme case some researchers argue that as much as a 25% chance exists that emissions could exceed 26 Gt C/yr. There is general agreement that CO₂ emission rates are unlikely to fall below 2 Gt C/yr in 2050.

Research to reduce uncertainty in future projections of CO₂ emissions should focus on energy end-use analyses, the determinants of economic growth and development, factors affecting the composition of economic activity, and to identify specific factors which are leading indicators of future emissions and potential targets for policy analysis. This latter approach has already proved its worth in economics.

The literature on future emissions of other greenhouse gases is in a primitive state, with most analysts relying mainly on time trend analyses of past atmospheric concentrations. Sources and sinks need to be clearly identified and more sophisticated tools of analysis applied to build a consistent, integrated set of scenarios.

The current state of knowledge leads to the conclusion that international policy analysis for greenhouse gas (GHG) abatement should begin immediately, although at this time, the implementation of policy options to modify or control the use of fossil fuels is not warranted on the basis of the climate change problem alone.

A Proposal for Contingency Planning

Given the uncertainty which dominates both the estimates of future emissions and the possible consequences of increased concentrations of greenhouse gases the development of a carefully structured set of contingency plans is recommended. This would involve a graduated series of response measures designed to meet increasing GHG levels and any consequent climatic, environmental and socio-economic impacts with increasingly comprehensive abatement actions, although under a favorable unfolding of future events these measures may never need to be implemented. The development of globally agreed policies designed to abate emissions will take many years of international effort to formulate and negotiate.

It is therefore proposed to recognize three phases or zones of graduated response. (See attached schematic diagram).

PHASE 1: SURVEILLANCE PHASE (FLASHING GREEN ZONE) where rising greenhouse gas levels stimulate contingency planning (approximately the current situation).

PHASE 2: ACTION ALERT PHASE (YELLOW ZONE) where strongly elevated greenhouse gas levels make the implementation of the previously planned abatement policies mandatory.

PHASE 3: CRISIS ACTION PHASE (RED ZONE) where drastic abatement actions (already planned) are paramount and urgent.
Under this escalating response concept, it is hoped that policy developments in the Surveillance (Flashing Green) Phase will avoid or at least dramatically slow down and delay the onset of the Action Alert (Yellow) Phase, thus "buying time" for any needed technological and societal adjustment to any ultimate climatic or environmental changes. Likewise, further policy implementation in the Action Alert (Yellow) Phase will avoid the onset of the Crisis Action (Red) Phase altogether.

Key Recommendations

Primary recommendations are: (a) to encourage the formation of a coordinating committee to promote and coordinate research in both basic and applied science as well as policy analysis relevant to the greenhouse issue, (b) to set up mechanisms for contingency planning as described in items 1-4; and (c) to begin exploring the potential for a global convention on greenhouse gases. Great importance is also attached to the need for programs to heighten public awareness of the greenhouse problem and continued support by national governments for research to reduce uncertainty on greenhouse gas emissions.

Recommendations are categorized under the three phases identified in Section (2) above: the Surveillance (Flashing Green) Phase, the Action Alert (Yellow) Phase, and the Crisis Action (Red) Phase. A schematic diagram with summarized information is contained in Figure 1.

"GREEN" SURVEILLANCE PHASE: we recommend the formation of an International Greenhouse Gas Coordinating Committee (IGCC) to

* promote and coordinate research, monitoring and assessment activities (including both scientific and policy research);
* promote the exchange of information related to climate warming between countries;
* prepare and disseminate educational material to improve public awareness.

The IGCC should also explore the possible advantages of an intergovernmental agreement or global convention. The closer the earth comes to crossing into the "yellow" action alert zone of strongly elevated GHG levels, the more active should the Committee become in designing and implementing constructive interventions into energy, climate, and socio-economic areas. Preparation for the potential extreme futures can begin now by studying and identifying the widest possible range of response options to them for governments and international agencies.

To maximize the flexibility of response to circumstances that the world may some day confront, but with which we are currently unfamiliar, a strong effort should be directed towards:

1) the analysis of decision-making rules under the specific kinds of risks that will accompany a greenhouse warming under these extreme cases;

2) the determination of (a) the cost of damages from a greenhouse warming, (b) the costs, benefits, and risks of interventions at
different points in time, (c) the decision-making behaviour of policy makers in high-risk circumstances, and (d) the lead times between identification of serious risks and the implementation of specific responses;

3) the development of an efficient set of leading indicators to maximize the time available between recognition and response and establishment of comprehensive arrangements for monitoring them over time;

4) public education.

Regarding energy, there are a wide range of technically feasible end-use opportunities to reduce substantially the primary energy requirements needed to deliver a given measure of goods and services. Many of these are already available and in use or will soon become so at lower life-cycle costs than the traditional technologies they replace. Examples of some of these developments include new manufacturing processes less consumptive of energy or more efficient plants to produce fertilizer, paper and chemicals as well as light-weight, high-efficiency vehicles, improved control systems for electric motors and advanced cookstoves. Development adaptation of these systems to local circumstances and their widespread adoption will take years but can be accomplished without necessarily constraining national rates of GDP growth. The market penetration of promising new technologies not yet in the advanced development and testing phases will take even longer.

Good prospects also exist for moving away from fossil fuels e.g. the use of ethanol for motor vehicles and charcoal for industrial process heat. In both these instances recycled carbon from biomass is utilized. Widespread reliance on solar energy and renewable nuclear and other non-fossil energy systems is also highly feasible in the future.

"YELLOW" ACTION ALERT PHASE: when this phase is signalled by the leading indicators, the IGCC should move to implement abatement policy alternatives, some of which will probably require a span of years to produce results. During this phase, there will be a need to: further refine decision-making rules and analyse the whole range of response options maintaining full flexibility in their implementation.

A number of policy instruments are available to national governments to stimulate a smooth transition to energy strategies that reduce the rate of growth or limit the build-up of greenhouse gases. The attractiveness of specific measures will vary over time and among countries. Policies that might have this effect include but are not limited to those that (1) eliminate subsidies for energy supply and allow prices for energy to approach long-run marginal costs; (2) provide economic incentives for the rapid development and deployment of energy efficient and non-fossil fuel technologies; (3) deliver improved information to investors, lenders, and consumers about cost-effective opportunities for investments in energy efficiency; and (4) set performance standards for end-use devices.

Policies that preserve flexibility and diversity in supplying energy and that as far as possible avoid irreversible commitments to large-scale, long-term use of coal or oil shale may also be appropriate. Over the
intermediate term, policies to encourage the substitution of less carbon-intensive fuels are appropriate for consideration by governments. Such policies might include (1) a "carbon tax" on fossil fuel use; (2) a system of marketable permits for CO$_2$ or greenhouse gas emissions, tradeable on a regional basis or (3) incentives for the use of alternative non-fossil technologies.

"RED" CRISIS ACTION PHASE: if the situation becomes unmanageable, enforcement and/or intervention by international agreement would be essential.
SCHEMATIC TABLE OF CONTINGENCY PLANNING ACTIVITIES
(See Fig. 1)

<table>
<thead>
<tr>
<th>Zone III</th>
<th>Perception level of problem</th>
<th>Policy development and actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crisis Action Phase &quot;RED&quot;</td>
<td>Severe public anxiety</td>
<td>Only crisis remedial measures contemplated-drastic enforcement of abatement</td>
</tr>
<tr>
<td>Zone II Action Alert Phase &quot;YELLOW&quot;</td>
<td>High priority for additional actions by decision-makers to optimize benefits and minimize disbenefits</td>
<td>Graduated Abatement Policy Implementation under new Convention (depending upon attitudes adopted by various governments; inter-governmental agency and private sector actions, etc); Monitoring and Assessment for efficacy of abatement measures</td>
</tr>
<tr>
<td>Zone I Surveillance Phase &quot;GREEN&quot;</td>
<td>Increasing priority assigned by more perceptive decision-makers</td>
<td>Formation of International GHG Co-ordinating Committee (IGCC); Accelerated Monitoring and Assessment; R &amp; D on key determinants of CO₂ emissions; R &amp; D on leading indicators; Development of International Convention on GHG policies; Abatement policy development; Abatement policy implementation; under existing Conventions (acid-rain; ozone etc.); Public awareness building strategies</td>
</tr>
<tr>
<td>Surveillance Phase &quot;GREEN&quot;</td>
<td>Public awareness growing in some regions</td>
<td></td>
</tr>
</tbody>
</table>

- Perception level of problem
- Policy development and actions

- Zone III Crisis Action Phase "RED": Severe public anxiety
- Zone II Action Alert Phase "YELLOW": High priority for additional actions by decision-makers to optimize benefits and minimize disbenefits
- Zone I Surveillance Phase "GREEN": Increasing priority assigned by more perceptive decision-makers
Note 1: Trace-gas levels demarcating zone thresholds to be defined.

"2: Scale of time-axis to be defined.

"3: Successive abatement of GHGs and CO$_2$ delays onset of Yellow and Red phases ('buys time').
Background

Since the beginning of high precision measurements of atmospheric CO₂ in 1957, the attention of scientists and laymen alike has been drawn to the potential of climatic impact due to the rise of the CO₂ concentrations. In addition, there has been recent concern about radiatively active trace gases other than CO₂. Radiatively active trace gases in the atmosphere such as CO₂ allow incoming shortwave solar radiation to penetrate to the earth's surface while absorbing and re-emitting the outgoing long-wave radiation from the earth. (This is the greenhouse effect). Such gases are called the greenhouse gases.

Because of the clear cut separation in the subject matters dealt with by this working group, its report is in two parts: part (a) dealing with cycling of carbon, and part (b) on other non-CO₂ radiatively active constituents.

a. Cycling of Carbon

Atmosphere

High precision atmospheric CO₂ measurements since 1957 are a cornerstone of current carbon cycle knowledge. During the past ten years, several nations have become active in regular CO₂ monitoring, both continuously at fixed sites and with low frequency using flasks at either fixed sites or mobile platforms. The data reveal latitudinal and seasonal variability and also year to year variations.
Recent breakthroughs in ice core research have enabled the extension of the CO₂ record back to 150,000 years before present (BP), corresponding to more than a full glacial cycle. Proxy data, including Carbon 13 (13C) in tree rings and oceanic sediments, provide important complementary data. Major results are the following:

- During the last two pre-industrial millennia mean-CO₂ concentration was in the range of 275+/−10 ppmv.

- In the first half of the 19th century the CO₂ concentration started to rise to levels which, for the period 1960–1970, correspond satisfactorily to the atmospheric CO₂ measurements at Mauna Loa, Hawaii.

These observations strongly suggest that the observed CO₂ excursion is the result of human perturbations. These have resulted from changing land use in the course of the past centuries and, during the last decades, primarily from fossil fuel burning.

Ice core data show that over the last 150,000 years the atmospheric CO₂ concentration was strongly correlated with major climatic changes. Namely, during the coldest periods of the two last glacialations CO₂ concentrations were about 200 ppmv rising almost simultaneously with the climatic shift to values of 270–280 ppmv in the interglacial periods. Consequently CO₂ changes could have significantly contributed to past climatic changes. These natural variations are comparable in magnitude to the anthropogenic increase during the last 150 years.

Large-scale and climatically coherent CO₂ variations helped in the understanding of the mechanisms controlling the natural atmospheric CO₂ content. In principle, changes between glacial and interglacial stages are forced by changes in oceanic circulation and/or marine biological activity. Independent 13C measurements on oceanic sediments indicate fluctuations in marine biology, oceanic circulation and atmospheric CO₂ content.

Other Reservoirs

The atmospheric CO₂ is in exchange with the inorganic and organic carbon in the ocean and the carbon in the terrestrial biosphere. Part of the CO₂ released into the atmosphere is taken up by these other reservoirs. The fraction of the emission remaining in the atmosphere is called the airborne fraction.

Carbon cycle models have been developed allowing simulation of anthropogenic and natural carbon cycle perturbations, such as the uptake of 14C from nuclear weapons tests, the dilution of atmospheric 14C from 14C-free fossil fuel CO₂, and the 14C variations due to solar modulation of cosmic radiations. These models enabled reconstruction of the time history of the anthropogenic CO₂ input into the atmosphere based on ice core data. The total integrated CO₂ input agrees with lower independent estimates of CO₂ emissions caused by changing land use and fossil fuel burning. This leads to a reasonably consistent picture of the integrated human impact on the carbon system, unless one accepts the possibility that the higher estimates of terrestrial flux values are more probable. Thus, carbon cycle simulation models are useful in projecting future atmospheric CO₂ concentrations for given CO₂ emission scenarios. The use of dynamic carbon cycle models which
include the dependence of the air-borne fraction on the time history of the CO₂ input for future projections is greatly preferable to the often used concept of a constant airborne fraction.

The group also identified significant gaps in present knowledge of the carbon cycle dynamics concerning important terrestrial and oceanic physical, chemical and biological processes, such as climate feedbacks on the oceans and the terrestrial biosphere and the possibly missing sink.

There appear to be several possible, perhaps complementary, explanations for the inconsistency in modeling if higher estimates of terrestrial CO₂ fluxes are considered, as follows: (1) errors in the time sequence of terrestrial land-use changes; (2) existence of additional contemporary carbon sinks not represented in current models; and (3) masking of existing sinks by oversimplified terrestrial and ocean models. This possible inconsistency implies that significant errors in projections with current carbon cycle models are possible, particularly if the objective is to ensure that future CO₂ levels do not exceed a given target CO₂ concentration.

To resolve these uncertainties, it appears that we must place the CO₂ question in the context of a global picture which involves understanding the linkages of carbon to the biogeochemical cycles of nutrients, and treats these cycles in the context of climate feedbacks rather than as isolated, independent systems.

Oceans

The group endorsed conclusions drawn from observations that the ocean is the ultimate sink for anthropogenic CO₂, and that atmospheric CO₂ exchanges with dissolved CO₂ in the ocean surface. The principal rate-controlling step in ocean CO₂ uptake is the transfer via vertical mixing and circulation processes, from the mixed layer to the deep ocean. The polar ocean regions may be of special importance for the uptake of excess CO₂ since there vertical mixing is relatively fast and the efficiency of the biological pump (i.e. biological depletion of total CO₂ in surface waters) is not limited. Mineral nutrient runoff from anthropogenic sources, including agricultural fertilization and erosion, could potentially enhance primary productivity in the estuarine and shallow marine environments. The transport of carbon and minerals from land to sea (via rivers) is another potentially significant phenomenon. These fluxes have not previously been considered in models because uncertainties have been large. Other important aspects of the marine "biological pump" significant in carbon transport have been documented, but not considered in current models: these include macrofloc formation and fecal pellet transfer mechanisms which rapidly sequester nutrients and minerals. In the light of emerging data on carbon transfer in the air - water - earth - life system, previous models should be revised.

Studies of climate and CO₂ fluctuations in ice cores and in lake and marine sediments indicate the influence of changes in ocean circulation patterns on the atmospheric CO₂ regulation. If the anticipated climatic changes alter ocean circulation, the uptake of CO₂ by the ocean will be affected.
Terrestrial Biosphere

Current estimates of terrestrial carbon losses (0.6 - 2.6 Gt yr\(^{-1}\)) in 1980 are lower than earlier estimates, but are still quite uncertain. The stated ranges in the literature do not represent the potential uncertainties. These loss rates have been calculated indirectly through models, from the estimated transformation rates of nature to human-influenced ecosystems, on the basis of changes in the relative stocks of carbon in those two types of systems. The stated uncertainties in these loss estimates result from different assumptions about types of vegetation converted to cropland or pasture, extent of historical degradation of forest carbon stocks, and current carbon stocks and deforestation rates in tropical regions. Additional uncertainties are contributed by the modeling assumptions and data bases. Thus, there is considerable doubt and speculation about whether the current terrestrial CO\(_2\) release estimates represent the net flux of carbon between terrestrial systems and the atmosphere or whether there are other sources or sinks from changes in currently undisturbed areas, for example, from climate or CO\(_2\) fertilization effects. Currently, there is indirect evidence for such changes, and although no consensus exists on estimates of likely future changes, it is recognized that these uncertainties represent major unresolved issues in carbon cycle research.

Future carbon cycle research should be keyed to removing earlier oversimplifications in carbon cycle models and to pursuing obvious areas of uncertainties.

Taking into account potential changes in future ocean CO\(_2\) uptake and without a better perception of the causes for a possible imbalance in the global carbon budget, CO\(_2\) projections are afflicted with important uncertainties.

Recommendations

The working group concludes that a significant warming trend during the next decades to centuries is highly probable. This requires more intensive research efforts on the responses of natural systems to anthropogenic perturbations expressed in initiatives such as: The Global Change Program (ICSU), the Biogeochemical Cycling Project (SCOPE), and the various Global Tropospheric Chemistry (GTC) and initiatives.

The Working Group made the following specific recommendations:

1. Monitoring Today and in the Future

   **Atmosphere**

   Continue to operate the current baseline monitoring stations. Special attention should be given to the establishment of new stations in areas of major oceanic or terrestrial influence.

   **Water**

   The Transient Tracers in the Ocean Program (TTO) should be revived in
coordination with planned satellite remote sensing programmes, such as the World Ocean Circulation Experiment (WOCE).

Higher priority should be given to measurements of pCO₂, total CO₂, alkalinity and other relevant tracers in regions of large inter-annual variation of CO₂ exchange between the ocean and the atmosphere and where changes in ocean circulation might be induced.

The ongoing Scientific Committee on Problems of the Environment/United Nations Environment Programme (SCOPE-UNEP) project on transport of carbon and minerals in aquatic systems should be continued. High priority should be given to estuaries and open sea.

**Land**

Time series measurements should be made of:

(i) regional and global changes in the standing biomass (including use of changes in tree ring characteristics); and

(ii) carbon and nutrient losses from soil erosion in areas of intensive human interference.

**2. Events and Processes; Past and Present**

**Atmosphere**

Clarify the pre-industrial CO₂ concentration.

Study the impact of El Niño events on atmospheric CO₂ and other radiative gases.

Study the natural variability of CO₂ during climatic events like Little Ice Age and Mediaeval Optimum within the last 1000 years, based on ice cores, tree rings, lake and ocean sediments. Obtain detailed CO₂ record for the mid-Holocene warm period (6000-8000 BP).

Conduct detailed study of glacial-interglacial transitions during the Quaternary based on ice cores and sea sediments.

Search for confirmatory evidence of rapid CO₂ fluctuations (of the order of 1 ppmv/year) during the past 150,000 years.

**Water**

Conduct further research on the interrelation between oceanic circulation and marine biological activity in order to quantify the oceanic sink and understand CO₂ temporal variations.

Study mobilization and storage of carbon and nutrients in rivers, lakes and estuaries.

Study paleoceanic circulation using marine sediments information.
Land

Conduct measurements of carbon fluxes in major terrestrial ecosystems.

Continue detailed studies of the terrestrial land use history for understanding past sources of CO₂, CH₄ and N₂O.

Reconstruct effects on ecosystems during past periods of climatic change.

3. Modelling

Atmosphere

Improve three-dimensional tracer models for assessing sources and sinks of radiatively active atmospheric constituents.

Water

Develop dynamic ocean general circulation models that incorporate biogeochemical processes for carbon and other key elements.

Conduct additional model experiments to study the ocean response to climatic perturbations.

Develop models of carbon and nutrient transport for coupling land with the sea via rivers and estuaries.

Land

Develop models that provide more accurate assessments of human modification of carbon storage (land use, atmospheric CO₂, climate changes, etc.).

4. General

The complexity of the topic requires a holistic approach. Emphasis should be placed on the cycling of relevant elements and their interaction with one another and with the climate system.

Natural records provide critical information on the carbon cycle, past climate, and on various parameters driving the climate. There is a unique opportunity to compare directly the changes occurring in the climate with those of the atmospheric composition and the ocean.

b. Non-CO₂ Greenhouse Gases and Aerosols

It has now become clear that greenhouse warming resulting from human activities is no longer attributable to increasing CO₂ alone. A number of other gases, some of them exclusively man-made and released by man into the atmosphere, need to be included in any current and future assessments of climate change.
These non-CO₂ greenhouse gases are far less abundant than CO₂. However, some of them are much more effective, molecule for molecule, than CO₂ in inducing a climate warming. They do so in one or both of the following two ways: (1) by themselves with their high absorption in a part of the earth's radiation spectrum in which the atmosphere is otherwise transparent, and (2) by participating in atmospheric chemical reactions forming secondary products which themselves have greenhouse properties. There is also the possibility that human activities reduce the oxidizing capacity of the atmosphere, thereby increasing the levels of the non CO₂ greenhouse gases.

At least twenty of the non-CO₂ greenhouse gases have been observed in significant concentrations and their list is growing. At present, however, five are considered to be of primary concern. There are CFC-11, CFC-12, methane (CH₄), nitrous oxide (N₂O) and tropospheric ozone (O₃).

CFC-11 and CFC-12 are exclusively anthropogenic, CH₄ and N₂O are both anthropogenic and natural, while tropospheric O₃ can partly result from the chemistry of some of the non-CO₂ gases (e.g. CH₄ and other hydrocarbons, CO, NO, NO₂). The airborne fraction for some of these gases is close to unity, considerably greater than that for CO₂. Gases such as CFC-11, CFC-12 and N₂O can also lead to destruction of ozone molecules in the stratosphere.

Model calculations based upon best available emissions projections show that the importance of the non-CO₂ greenhouse gases in changing the climate may become comparable to that of CO₂ in the next 50 years.

The prediction of trends in the concentrations of CFC-11 and CFC-12 depends nearly exclusively upon their emission rates. Such is not the case for CH₄, N₂O and tropospheric ozone and to that extent trend predictions for these are still speculative. It needs to be emphasized that the pre-industrial CH₄ concentration could also be determined on air samples from ice cores. The rate of increase of CH₄ observed in the ice cores during the last four decades is in agreement with that determined in the atmosphere during the last ten years, being within the error limits of the measurements.

In addition to the greenhouse gases, aerosol particles in the atmosphere also influence radiation transfer either directly by extinction (e.g. carbonaceous particles) or indirectly by modifying cloud formation and cloud microstructure (e.g. sulphate particles). Their role may be particularly important in the continental and regional scales. Since their concentrations, chemical composition and hence the radiative characteristics are highly variable in space and time, future projections of these parameters cannot be made with confidence.

Recommendations

1. Promote a strong programme of (a) long-term monitoring of the non-CO₂ radiatively active species, including aerosols, and (b) research on the sources, sinks and chemistry of important trace species.

A global monitoring network suitable for trend determinations and study of regional/continental scale sources of the greenhouse species is partially in place. Five to ten sites for background measurements of CFC-11, CFC-12 and N₂O will very soon be in operation. This should be sufficient
for long-term trends and other research needs. Global measurements of CH\(_4\), which has a lifetime of 5-10 years, are being made at more than 20 locations. While this is sufficient for long-term trend studies, the network will undergo modifications as needed to identify the critically important CH\(_4\) sources and sinks.

In addition to the five non-CO\(_2\) greenhouse gases identified above, several others (e.g. methyl chloroform (CH\(_3\)CCl\(_3\)), CFC-22, CFC-13) with significant radiative effects, long life times and increasing atmospheric concentrations have been observed. At current concentrations, these do not contribute in any major way to greenhouse warming. However, the potential for them to become important exists should their concentrations continue to rise. Thus occasional (e.g. once a year) surveys of the background concentrations of these species should be made.

Tropospheric ozone (O\(_3\)), because of its short lifetime, must be measured with high frequency at many locations to determine its trend accurately. Because of uncertain knowledge of the variability of tropospheric ozone, a specific network design cannot be recommended. However, basic research into the formation and destruction of tropospheric ozone should be undertaken in order to design a proper monitoring network.

Absolute comparability of trace species measurements by different international institutions requires an active programme of data quality control. Programmes of standards development and data intercomparisons directed toward a high data precision among various measurement programmes should be encouraged and continued.

Reliable predictions of future concentrations of CH\(_4\), N\(_2\)O, and tropospheric O\(_3\) demand better understanding of the sources, sinks, and chemistry of these species and their precursors and products (e.g. CO, NO, NO\(_2\)). Much of this work is proposed under the various Global Tropospheric Chemistry Project (GTC) initiatives. Very strong support for these programmes is urged.

Beside CO\(_2\) and CH\(_4\), the study of the pre-industrial concentrations of atmospheric trace gases and constituents, their natural variability and their increase during industrial time should be reconstructed by ice core studies.

2. The elaboration of a Protocol on chloro-fluorocarbons in the framework of the Vienna Convention for the Protection of the Ozone Layer should be supported. (Such a Protocol is assumed to include information on production, emissions and use patterns as well as the chemical and radiative properties of these substances). The chloro-fluorocarbons are synthetic chemicals; their control is possible and has a double benefit of helping in preserving the ozone shield and in limiting the extent of climate change.

3. Measurements of the concentrations of carbonaceous materials and sulphate ions on aerosol particles with a size below one micron should be encouraged.
Impact of Greenhouse Gases on Climate

Climate modelling studies continue to indicate that increasing concentrations of the greenhouse gases in the atmosphere will lead to significant changes in a number of climate parameters, including temperature. Specific estimates of the magnitude of the change in global mean equilibrium temperature necessarily involve subjective interpretation of a limited number of model experiments. The SCOPE Report on the Role of Carbon Dioxide and Other Radiatively Active Constituents in Climate Variation and Associated Impacts gives a range of possible temperature increases for doubling of CO₂. Because of the model imperfections these numbers should for the time being not be interpreted as a prediction for the range of the eventual impact on climate. Rather they can be considered as a measure for the agreement among the different model approaches. Furthermore, some of these calculations of globally averaged temperature change seem to be influenced strongly by predicted large changes in high-latitude regions near the sea-ice margin. Examination of predicted changes averaged over land areas in mid-latitudes may reveal a smaller range of uncertainty, and would moreover provide an index of climatic change more meaningful to decision-makers for these areas.

With the future projections used throughout the SCOPE report no collapse of the West Antarctic ice shield and no dramatic rise of the sea level can be envisaged in the time scale this assessment is dealing with. Nevertheless it seems worth noting that consistent use in impact studies of
the upper limits for an eventual temperature increase would lead to far more alarming consequences than stated in the SCOPE Executive Summary. In summary: Although quantitative uncertainty in model results persists it is highly probable that increasing concentration of the greenhouse gases will produce significant climatic change.

Sources of Uncertainty

1. General

Partly these uncertainties exist because there are fundamental scientific problems that remain to be solved, partly because the grid lengths and parameterizations used by models are not optimal but are influenced by the computational power available, and partly because the physical situation usually considered is the longer-term equilibrium climate, which is a significant idealization. The present phase of research should be seen as one in which important physical processes are being identified and accurate descriptions within models developed.

Among the principal sources of uncertainty are:

- cloudiness-radiation interactions
- ocean and sea-ice behaviour and
- land surface processes, including hydrology.

2. Time-dependent Effects

Most model integrations to date have been concerned with determining the equilibrium climate resulting from a postulated increase in the concentrations of carbon dioxide, i.e. the asymptotic response if the enhanced concentration were maintained indefinitely. The computations are therefore, in some measure, unrealistic, and the situation they represent simplified. Despite this simplification, there are substantial differences among the equilibrium response of the models. It is essential that the causes of these differences be fully explored and understood before computations with comprehensive coupled ocean/atmosphere models are used, in order to estimate the magnitude and spatial details of the transient response. In the longer term, estimates based on a consideration of the fully varying situation will be required. Meantime, the use of simpler models to investigate some of the main features of the transient response is encouraged.

3. Treatment of Greenhouse Gases other than CO₂

The radiative effects of trace gases other than CO₂, including ozone, can be treated quite accurately in radiative-convective models. In 3-D models, these gases are considered in terms of CO₂ equivalents, and it is still to be proven that this approach provides the same results within acceptable accuracy even if temporal, vertical, and eventually geographical distributions of these gases differ from those of the CO₂, especially in the stratosphere.
4. Treatment of Aerosols

(i) Stratospheric Aerosol has been monitored for some years by satellites and ground based light intensity detecting and ranging instruments (LIDAR). Significant changes, including multiannual trends, were observed. Such changes are one possible cause of decadal variations found in the climate record. Since changes in stratospheric aerosol concentrations are likely to occur in the future, improved monitoring and the incorporation of aerosol radiative characteristics into climate models should aid understanding of such variations which may mask the effect of the greenhouse gases.

(ii) Tropospheric Aerosol has different impact on the radiation budget depending on its composition. It can be expected that due to industry, droughts and desertification the amount of tropospheric aerosol will increase at least in some regions of the world. It seems, therefore, necessary and timely to considerably improve the monitoring — including advanced space techniques — and the modelling of this component. A better understanding of the climatic effects of aerosol is also desired to explain the relation between aerosol deposits presently inferred from ice cores and historical climate events.

5. Application of Model Results

At present, and certainly for a number of years to come, climate change studies by means of models provide possible scenarios, not predictions of future climate.

The results of the climate modelling efforts should at present, serve scientists doing impact studies mainly in developing scientific tools, helping them to understand and to use model results, and giving them at the same time a list of affected parameters as well as a range of possible values. During this period, communication between modellers and impact analysts is of primary importance. It will take many more years of research in climate modelling before reliable regional climate predictions can be expected.

The state of current modelling capabilities is such that more confidence can be placed in large-scale (not smaller than $10^6$ km$^2$) and time-integrated (e.g. half annual) projections of various climatic parameters than in small-scale, short-term, and high-frequency perturbations. Projections of detailed and localized variations in temperature, precipitation and other parameters sought by those attempting to study the impact of climate change on agriculture, for example, will not be very accurate and may not even be available. It may, therefore, be advantageous for impact analysts to make use of the perturbations in which one may have more confidence. Examples include the following:

- The major climatic effect in mid-latitude land areas is a lengthening of the warm season and shortening of the cold season. Snow accumulation will occur later and snow melt earlier; the snowline in mountain areas will rise. Summer dryness may become more frequent.
The major climatic effects in high sub-polar latitudes are a shortening of the winter season; a shrinking of the sea ice extent; and an increase in precipitation that may substantially increase runoff.

The major climatic effects in low latitudes are probably an increase in both precipitation and evaporation over the tropical rainbelt and maybe a strengthening of the monsoon over some land areas.

The effects of such shifts in climatic parameters on water resources, agricultural planting schedules, and other activities should be considered.

6. Future Development of Models

It is important to consider the extent to which the present uncertainties in model computation described can be reduced or eliminated within the next decade or so. It has to be noted that the carbon dioxide issue includes all the problems that the World Climate Research Programme (WCRP) is designed to solve. Even at the end of a decade of research in this Programme, many uncertainties undoubtedly will remain. In particular, it is likely that estimates of the response of the ocean circulation to enhanced carbon dioxide concentrations will be tentative. However, substantial progress may be expected within a decade on the use of combined ocean/atmosphere models and on problems of short-term climatic variability.

Modellers need to be aware of and pay attention to the requirements for the specification of climate changes on scales small enough to be useful to those trying to estimate the impact of climate changes on agriculture, water resources, etc. Almost certainly this will require finer grid resolutions than have been used for the carbon dioxide problem until now. It is an open question as to when the use of substantially higher resolutions will be justified, but, in view of the practical importance, it should be undertaken at the earliest reasonable time. Several approaches are possible following the experience of modellers in numerical weather predictions: thus additional computer power which should become available may be used either to increase the resolution everywhere, or to increase the resolution selectively in areas of special interest by employing nesting or gradually decreasing mesh size techniques already used for shorter time-scales.

It may be necessary to consider whether additional approaches may be helpful for bridging the gap between Global Climate Monitoring (GCM) projections (predictions of perturbations) and the changes in important weather features that may be expected on a local and regional scale. This problem has, to date, been addressed by several means, including nesting of models, use of regional models, and by purely statistical relations. An alternative, deserving consideration, may be to extract from GCM's information about large-scale circulation changes and to relate such changes to smaller scales based on experience gained from regional climatology. Although injecting a skilled interpreter between the modeller and impact analyst lengthens the chain, it may actually accelerate the process of relating perturbations to impacts.
There is an important final consideration. The rate of progress towards firmer estimates of the probable climate change will be dependent on the size of the effort devoted to climate modelling and allied matters, and, no less important on the existence of adequate international co-ordination. On neither of these considerations does the present situation justify complacency.

7. Detection of Climate Change

Because of the heat capacity of the oceans, the full global climate response to increasing greenhouse gas concentrations is delayed. In waiting for stronger evidence of greenhouse warming to consider policy action, it is therefore essential to recognize that commitment is being made for further warming as the oceans have time to warm. Early detection of climate change is therefore essential.

The present temperature change signal predicted by climate sensitivity studies cannot yet be discriminated in a scientifically rigorous way from the noise due to natural fluctuations. If the model results are reliable, it is expected that the signal may be detectable with confidence in 10-20 years, when both the signal and the length of record have increased.

According to the results of sensitivity studies, it seems promising to continue the search for temperature trends inter alia in the stratosphere, where the signal-to-noise ratio may be fairly large. A priority list of single variables which should react to climate change is given in the SCOPE report (Chapter 6), where also the problems involved to detect the signal are discussed. Investigation is also needed of other, more qualitative indicators which may in their totality, reflect climate change, e.g. droughts, desertification, changes in weather patterns, length and distribution of snow cover, length or shift of vegetation period, change of stratospheric water vapour, cloudiness, changes in the strength of the Southern Oscillation, monsoon, and ocean circulations. Further diagnostic and model studies are clearly needed to investigate whether a change in such complex phenomena can be quantified and could be in accordance with the present views on climate change.

8. Research Needs and Recommendations

For the future improvement of climate models, it seems not only necessary to update the parameterizations of processes as new experimental results become available but also to compare the model outputs with empirical data sets or time series of climate indices, which can be derived from monitoring activities.

(i) The research necessary to conduct climate change studies with increasing credibility is specified in some detail and completeness within the Scientific Plan for the WCRP. This plan also addresses the contribution which satellites have to make in order to extend spatial coverage of existing data, and medium as well as large scale experiments necessary for process studies. The WCRP and related national climate programmes merit full support. Additional attention may be needed for the treatment of the hydrological cycle.
(ii) One way to validate a climate model is to simulate the long-term variation of past and contemporary climate. For this purpose it is necessary to assess and monitor not only changes of climate, but also possible causal factors as noted in the reports of other Working Groups. An integrated strategy should be developed covering both monitoring and modelling of long-term climate changes and possible causal factors such as solar irradiance and stratospheric and tropospheric aerosol concentrations. This strategy should also include programmes for improved monitoring of secular changes of global sea level. For this purpose it seems to be necessary to re-examine the measurement possibilities, including careful geodetic measurements of changes of elevation with respect to the centre of the earth, e.g. by satellite altimetry and a network of sea level recording stations. Other factors affecting sea level include oceanic circulation (to be studied within the World Ocean Circulation Experiment (WOCE) and related projects), change in volume of glaciers and ice sheets, and changes of inland and ground water storage. Communication channels existing within the WCP and ICSU should be used and strengthened for this purpose.

(iii) Modern electronic communication and data storage techniques (for example, as proposed in Earth Observing System, NASA, TM 86120) should be used to develop an international data system through the World Climate Data Programme (WCDP) and other national and international institutions. This should provide easy, integrated access to existing data and a framework for incorporating new data sets from satellites and other sources, and should cover the whole range of geosciences. Scientists should be able to locate data of interest, determine their quality and obtain them rapidly and inexpensively through the communication system.

(iv) The activities described in the WCRP Scientific Plan do not yet encompass biogeochemical investigations of the reasons for the growth of certain atmospheric constituent concentrations. Such problems must be studied in special research efforts like the Global Tropospheric Chemistry Programme recently proposed by the Commission of Atmospheric Chemistry and Global Pollution of the International Association for Meteorology and Physics (IAMAP) and similar programmes for the oceanic biomass production in the framework of the International Council of Scientific Union's (ICSU) Global Change Programme. Such a programme should be implemented.
DISCUSSION OF ISSUES

General

Increase of CO₂ in the atmosphere will have direct effects on a number of physiological processes in the plant cells and hence growth and performance of plants, and indirect effects as it causes increase in temperature and consequent climatic changes. Some of these impacts may be positive (enhanced photosynthesis and improved water-use efficiency), some are not. Other atmospheric pollutants will also have some chemical and physical effects.

These impacts could have far-reaching influence on all the bio-productive systems: forests, croplands, rangelands, fisheries, etc.; and some of the climatic consequences may exacerbate environmental hazards of desertification and recurrent droughts; bush and forest fires, insect and disease outbreaks, etc. The geographic extents and magnitudes of the likely climatic changes remain to be clearly defined. They represent environmental risks that need to be considered by national and international scientific institutions. Governments need to keep these issues under continuous monitoring and to ensure that national plans for development of natural resources take into full consideration the likely impacts of CO₂ built up and the consequent climatic changes.

Climatic changes may induce shifts in land-use pattern and cropping belts. Technological advances in plant breeding and husbandry could partially mitigate such effects. The impacts of increased atmospheric CO₂ on ecosystems of coastal waters, including estuaries and wetlands, require more detailed study.
The magnitudes of CO₂-related consequences for ecosystems and agriculture are dependent on the time scale of any changes in climate. For example, rapid change of temperature, its global distribution and frequency of extremes could overwhelm the adaptive capacity and resilience of these complex systems.

It is assumed that the change associated with an equivalent CO₂ doubling will occur in 50 to 100 years. Were this change to occur more rapidly (say within 15 to 20 years), the impacts could potentially be more far-reaching.

**Direct effect of CO₂ on terrestrial plants and plant communities**

Prediction of direct effects of CO₂ on plant physiological processes is more tractable than predicting the likely impact of climate change. At the leaf, plant and micro-crop level, we know that for plants grown as monocultures in controlled laboratory environments, growth and yield respond positively to higher CO₂ concentration up to a saturating concentration of 700 to 1000 ppmv for most species (i.e. C₃ species). Transpiration rate of leaves is reduced by high CO₂. The consequent increase in water use efficiency in plant production enables growth of water-limited vegetation to respond positively to higher CO₂ concentration. Thus in the case of the water–CO₂ interaction, the traditional concept that only one environmental factor at a time can limit growth is untrue. There are theoretical reasons why the interaction between CO₂ and other environmental factors in plant growth might also not obey the traditional notion of single limiting factors. The character of the interaction would be different in each case.

Except for the CO₂-water interaction we have almost no experimental information that allows us to quantify the CO₂ effect on plant growth in the presence of various levels of other growth limiting environmental variables. These other variables include both those climatic ones which are expected to change appreciably with increasing CO₂ (mean temperature, chilling and frosting events, humidity, rainfall, and drought intensity and periodicity) and those which are not expected to change much (e.g. radiation, mineral nutrients).

A second gap in knowledge concerns the methodology to scale up information from leaf, plant and micro-crop studies to field crops ecosystems and to hydrological catchment areas. We lack sufficient knowledge concerning the feed-backs (both positive and negative) that could alter or even invalidate our micro-results when extrapolated to larger areas and longer time periods. Such information is needed for those who work on agricultural and hydrological contingency plans for a high-CO₂ future.

Much less is known about the direct effect of CO₂ increase on natural vegetation, since most laboratory experiments have been conducted on single crops. In the natural environment, the biota of the earth is organized into complex aggregations (ecosystems). These systems are made up of various biota interacting with each other and with the physical–chemical environment. Carbon flows within ecosystems after being fixed into energy-rich organic compounds by photosynthesis. The initial response of ecosystems to atmospheric CO₂ enrichment is primarily due to direct physiological response of plants. Ecological responses would be expected to occur if plants change in growth rates and in the biochemicals they produce. Changes in plant growth
differ qualitatively and quantitatively among species. These differential plant responses affect all subsequent organism interactions including plant-plant competition, plant-animal and microbial interaction. We can only speculate on how these plant changes will affect non-photosynthetic organisms. Will biological productivity be accelerated in complex ecosystems? If plant productivity increases, will a predictable percentage of the increase accumulate as increased standing crop? Or is it possible that increasing CO₂ will increase metabolic activity at all trophic levels resulting in no net increase in standing crop? Will altered plant competition resulting from climatic change interacting with increased CO₂ affect the distribution of C₃ and C₄ plants? How will increased CO₂ and climate change affect dark respiration and loss processes of natural ecosystems, particularly in the tropics?

Considerable research efforts have been expended in compiling continental-scale maps of crop potential (e.g. the F.A.O. Agro-Ecological Zones Project). Most maps, though low in spatial resolution, offer us an assessment of the suitability of soil and climatic zones for the production of the major crops at different technological and management levels. The FAO study has shown that in many regions present agricultural production does not fully exploit the prevailing conditions for potential yield. The possible direct effects of CO₂ as well as climatic change on crop potential zones should be explored. However, little work has been carried out at the regional scale on assessing the likely direct effects of CO₂ on potential crop productivity and limited information exists about the global distribution of nutrient limitations that can influence the effects of CO₂ on crop plants.

It should be noted that doubling atmospheric CO₂ concentration is expected to cause crop yield improvement especially in C₃ species under good nutrient supply. Some of the variation in responses reported in the literature may be due to genetic differences. Cultivars also differ in their environmental requirements.

**Plant community-climate modelling**

Numerous crop-climate models (including regression models, crop-growth simulation models, mechanistic equations or other indices) exist. From a global perspective, model development has not proceeded evenly, however. Heavy emphasis has been placed on cereal crops in mid-latitude regions. Many gaps exist for specific crops and regions in the tropics and subtropics (including grass and rangelands). Existing models cannot be used to develop long range forecasts of crop production.

However, many of the existing models could, potentially, be used for applications related to problems of climatic change. These include analyses and sensitivity studies of the yield effects of changes in climate normals, seasonal crop estimates, analyses of alternative crop management practices, and analyses of regional crop potentials. Care must be taken to assure that all models are built upon a strong mechanistic foundation.

There are several forest simulation models that have been used in climate effects assessments. Models of other natural systems (particularly systems in the tropics and subtropics) are not sufficiently elaborate, and need to be developed.
The demand for crop climate models for policy makers in different countries is increasing. The corresponding use of crop-climate models is expanding quickly and, to a large degree, uncritically. The rapid, world-wide diffusion of computer technologies has made it easier to disseminate and use such models in regions and climates other than those in which they were developed.

Credible applications of crop/natural systems - climate models require that the models are carefully validated, preferably on independent data. Many models have not yet undergone verification; others have been only partially evaluated. In many cases, the demands of the particular problem to which a model is being applied will require re-evaluation.

Climatic extremes in tropical and subtropical regions

One of the important ways in which changes in climate may affect the tropical and sub-tropical regions of the world is through the occurrence of extreme climatic events such as droughts or floods, and through changes in their frequencies. Such events currently exert heavy tolls on crops, rangelands and livestock, and continually frustrate progress in development.

Thus, if strategies can be implemented now at local, national and regional levels to reduce the impacts of climatic extremes, the tropical and sub-tropical areas will be better able to mitigate unfavourable or long-term changes in climate, should they occur.

There are two areas in which our lack of knowledge hinders effective adoption of mitigative strategies. First, for much of the developing world we do not have a clear, comprehensive understanding of the types of climatic events, their magnitudes, and their primary impacts (e.g. vegetation, water, livestock) that pose the greatest threats of economic and social disruption. Second, we have little systematic knowledge of the range of potential options for reducing the impacts of climatic extremes that are appropriate to local social and environmental situations, and that are consistent with developmental objectives.

Data and information systems

The environmental impacts of increased CO₂, trace gases, likely climatic changes and recurrent extreme events are likely to influence the present geography of plant cover of the world. Networks for monitoring changes and shifts of the major vegetation types (principal world biomes) are required. Information on conditions of soils, topography, hydrology and cropping patterns is needed world-wide, and especially in the tropics.

Sea level rise

A sea level rise of about 20 to 120 cm is predicted to be associated with an equivalent CO₂-doubling. Estuarine and delta regions are highly productive. There is a potential for sea level rise to change the area, productivity, species and even location of estuarine and delta habitats. In many cases estuarine ecosystems and low-lying agricultural settlements may not be able to migrate inland for various reasons.
RECOMMENDATIONS: ACTION REQUIRED

Considering the observations and noted deficiencies, the Group recommends the following activities.

Direct and indirect effects of CO₂ on plants and terrestrial ecosystems

- Methods, preferably simple, for scaling up such information on interactions to the field, ecosystem, and regional levels should be developed to enable estimates to be made of growth, competition, evapo-transpiration and run-off from catchments, integrated over several seasons.

- Determine quality and quantity of tissue of plants grown at increased atmospheric CO₂ concentration and how observed changes affect animals, decomposers and disease organisms. Study symbiotic relationships to determine their response to plants grown at high CO₂.

- Experimental and theoretical quantification of the interactive effects (on photosynthesis, respiration, growth, yield and water use) between atmospheric CO₂ concentration and other environmental factors (temperature attributes, humidity, radiation, mineral nutrients, salinity, soil pH and atmospheric pollutants), taken alone and in combinations, should be made. A variety of plant species should be so examined.

These activities require controlled environment and field plant growth facilities and plant community modelling expertise. Research laboratories having such facilities and expertise should be encouraged to undertake these studies.

- Effective exploitation of both the beneficial CO₂ effect on crop yield and of any change in climatic attributes, including length of growing season, requires the right choice of crop species and genotype. It is, therefore, necessary to support and strengthen the existing effort to maintain genetic diversity of crops (via seed banks, etc.) for future breeding. Institutions concerned with crop genetic diversity and seed banks should recognise the CO₂-climate issue as an additional reason for maintaining or strengthening their activities. Crop breeders and physiologists should incorporate a search for CO₂-sensitive genotypes into their CO₂ and photosynthesis-related world.

- Develop and refine existing methodology of assessment of geographical distribution of cropping potential (e.g. F.A.O. Agro-Ecological zones maps), through:
  - Development and refinement of the existing methodology of assessment through a number of pilot studies conducted at a regional level.
  - Refinement of global soil data to include information on major limiting nutrients (cf. recommendation I).
- Development of a set of globally consistent scenarios of climatic change (whether recorded changes or possible future changes) and evaluation of the effects induced by such changes.
- Evaluation of the direct impacts of CO$_2$ on potential crop productivity for different crops and in association with changes in climate.

- Assess the sensitivity of the global agricultural resource base with respect to:
- Changes in atmospheric concentrations of carbon dioxide;
- Changes in climate (whether CO$_2$-induced or otherwise);
- A combination of the above.

**Plant community-climate models**

- Organize work at the international level to establish clear standards for model documentation, verification and validation. Establish "benchmark" cases of validated models for a range of ecosystem types.

- It is recommended that an international clearinghouse be established to facilitate activities related to the development, evaluation and dissemination of information on crop and natural biome models. The purpose of the clearinghouse would be threefold:
  - to perform (or arrange) independent verifications and comparisons of the performance of crop-climate models and models of natural biomes;
  - to maintain an up-to-date information on available models and institutions and individuals involved in modelling, and to serve as the information centre for the international network;
  - to identify crops, biomes and regions where further modelling efforts would prove practicable, given the availability of climate and agricultural data, and to stimulate such research activities.

The clearinghouse should be housed in an institution or organisation which is not, itself, involved directly in crop-climate modelling. Nonetheless, the institution should be recognized internationally and be involved in the broader aspects or research on climate, agriculture, impact assessment and modelling. Support should be provided by international organisations concerned with climate, agriculture and environment, on a continuing basis with periodic review.

**Effects of climatic extremes in tropical and subtropical regions**

- Increased research is required on the effects of climatic changes and extremes on ecological systems in subtropical and tropical regions, and the potential strategies for response.
Data collection networks should be established at national and regional levels to provide the required data in-puts for such studies.

Such projects should be supported jointly by international organisations involved in environmental and developmental research. Such projects should be organised and coordinated by a research institution with resources and experience in the fields of climate, climatic impacts and development. For conducting the research and preparing plans of action, this institution should, however, draw upon a research network comprised of research expertise of each country involved in the assessment.

Data and information systems

Appropriate international agencies (FAO/UNEP-GEMS) should sponsor projects aimed at developing world vegetation maps (based on satellite imagery). The maps should be global and should allow intercontinental comparisons. These maps can be used as a baseline and the global vegetation pattern can be regularly resurveyed for change. The data should be stored in data-base systems (e.g. UNEP-GRID) that could provide maps at detailed scales for regions and countries.

International and national institutions should be encouraged to provide support for regional Geographical Information Systems which can be used to store data for a variety of uses, including the development of maps, conduct of analyses and evaluation of potential impacts. While such systems are needed for all reasons, there is a particular need for such systems in the tropical and subtropical areas. The development of Geographical Information Systems should proceed in parallel with the development of improved climate models and improved agriculture, forest, grassland, and ecosystem productivity models.

Sea level rise

A global analysis of the implications of a range of selected sea level rises on agricultural regions and on coastal and estuarine ecosystems, should be conducted. Methodology should be developed using case studies. This work should be coordinated by an international organization, such as UNEP, which could do developmental case studies and should involve national governments from around the world.
WORKING GROUP V - PANEL ON SOCIO-ECONOMIC IMPACTS

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INTRODUCTION

In view of the limited attention so far paid to assessment of the socio-economic impacts of climate change, the panel decided to recommend a number of practical steps which should be taken with the purpose of understanding the implications of climate change for society, minimizing the adverse effects and maximizing the benefits which might occur.

The steps referred to above include the need to obtain information on interactions with other environmental problems (e.g. soil degradation, ocean eutrophication, acidification, ozone layer modification and ground water depletion); to trace pathways of climate impacts between sectors; and to determine points of vulnerability, areas of sensitivity and thresholds of significant dislocations. Follow-on actions require the improvement of technological and policy responses. It was felt that although most methods of impact assessment are in a preliminary stage of development, it was more important to demonstrate the limits of their reliability and, when possible, narrow those limits, than to use up the available lead-time in refining the methods prior to their application.

With special regard to water resource management under climatic stress, it is considered that a major underestimation of the probable impact had been made. Both water supply and demand are susceptible to climate change, and changes in evapotranspiration in many regions would be of greater importance than levels of precipitation in determining future run-off characteristics. Additional research to clarify the issue is considered essential.
In view of the fact that projected life-spans of many long-lived economic investments such as forestry, toxic waste sites, port facilities and water and energy resource development fall within the time horizon of climate change, it is essential that climate considerations be incorporated into the development process at the earliest possible stage.

It is cautioned that solutions contemplated must not neglect the particular needs of developing countries of the low-latitude regions, where very little authoritative research is available on the impact of both present and future tropical climates on health and well-being. Also, attention has to be paid to such countries' legitimate development needs, the satisfaction of which might result in major increase in fossil fuel use and carbon dioxide releases unless efforts are made to improve energy efficiency. Application of regulatory measures under such circumstances could severely hamper development plans and inflict upon such nations additional costs which are beyond their capacity to absorb.

The panel then considered methods for addressing questions relating to the practical implications of increasing concentrations of radiatively active gases and their climatic consequences. It was assumed that the problem has different practical implications for different societies. The approach taken was to characterize the necessary changes needed in research programmes and policy analysis to explore policy makers' questions.

It is necessary to explore the complex linkages between policy actions and environmental response as a whole. It was felt that contemporary efforts to address practical implications of environmental issues considering only single component assessments are generally inadequate.

The purely economic impact of climatic change requires attention, particularly in respect of the efficient use of resources and the equity of their distribution. Rational solutions might be enhanced by the use of economic incentives in addition to regulatory measures to control trace gas emissions and the use of compensation measures to ensure equity for parties with disproportionate vulnerability to climate change.

The panel offered the following guidelines which might be used in addressing current deficiencies in methods and for developing a basis upon which sound political decisions might be made in addressing the issue of socio-economic impacts of climate change.

In the assessment of policy options, the widest possible range of goals for social response should be considered including altering production of greenhouse gases; recovering releases of emissions; initiating social responses capable of modifying the environment; and adapting to change.

The methods for determining which options are most appropriate for coping with the practical implications of climate change have to allow consideration of possible long-term societal, geo-political and technological changes occurring simultaneously with climate change, the timing of social responses relevant to environmental change and the distributional implications of alternative social response options depending on how different societies and geographical regions are differently affected by the change.
In order to use the available knowledge, it is concluded that studies of environmental problems should include risk assessments that emphasise the implications of the possible range of changes, rather than focusing only on the most likely change.

With regard to the steps contemplated, it is considered most important that they are undertaken in a regional context.

On the basis of the above statement, the panel made a number of suggestions for practical steps which should be undertaken in the near future.

RECOMMENDATIONS

Sensitivities

There are likely to be ecological, economic, and social systems which exhibit a special vulnerability to climatic change. Efforts should be made to identify such systems and to characterize the nature of their sensitivity. This would require:

(i) identification of critical thresholds or non-linearities of system responses; and

(ii) specification of climatic extremes that involve a crossing of these thresholds. The research should have a regional focus. The initial focus should be in:

(a) the tropics, with special emphasis on their water budgets, the effect of high evapotranspiration on forests, and the effects of high temperature and relative humidity on health and well being;

(b) artic areas, which are likely to experience the largest temperature changes; and

(c) coastal zones vulnerable to rising sea level.

One particularly promising method involves estimating the spatial shift of boundaries of important ecological, economic and social values. This shift would serve to delimit areas especially vulnerable to climatic change. An example is the shift of agro-ecological zones (such as those mapped by the FAO) that would occur under a changing climate.

Linkages

The greenhouse issue is closely related to other environmental problems: such as acidification and ozone layer modification. Actions, such as limiting fossil fuel use, taken because of these other problems will reshape the greenhouse issue; action taken on the greenhouse issue will affect those other problems in turn. Efforts should be made to characterize these linkages and their implications for policy. Studies should emphasize the net effects of policy responses across the full range of linked environmental problems.
Initial work should focus on large regions \((10^6 \text{ km}^2)\) such as the Great Lakes, Zambesi basin and Amazonia. A comparative approach may be valuable, e.g. a Great Lakes/Baltic study.

**Policies and Adjustments**

The understanding of the greenhouse question, though still incomplete, is sufficiently developed that scientists and policy-makers should begin an active collaboration to explore the effectiveness of alternative policies and adjustments. Efforts should be made to design methods and foci, necessary for such collaboration.

This would involve:

(i) expanding and characterizing the range of technological, management and institutional options;

(ii) characterizing likely time-lags in implementation and the life-time of completed projects; and

(iii) discussing a useful range of scenarios describing plausible patterns of environmental and social change.

Initial studies should be given a regional focus drawing on the sensitivity and linkage studies described above. They would be conducted to explore the utility of alternative social responses to changing climate (e.g. by policy exercises based on free-form gaming).
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