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Narrowing the Uncertainties: A Scientific Action Plan for Improved Prediction of Global Climate Change

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EXECUTIVE SUMMARY

The IPCC has the responsibility for assessing both the state of scientific knowledge of climate and climatic changes due to human influences. The World Climate Research Programme (WCRP), sponsored by the World Meteorological Organization (WMO) and the International Council for Scientific Unions (ICSU), and the International Geosphere Biosphere Programme (IGBP), sponsored by ICSU, together constitute the international framework of the quest for scientific understanding of climate and global change.

The scientific strategy to achieve effective prediction of the behaviour of the climate system must be based on a combination of process studies, observation and modelling. Sections 1 to 10 of this report identified several areas of scientific uncertainty and shortcomings. To narrow these uncertainties, substantial scientific activities need to be undertaken. The following 5 areas are considered the most critical:

- 1) control of the greenhouse gases by the Earth system,
- 2) control of radiation by clouds,
- 3) precipitation and evaporation,
- 4) ocean transport and storage of heat, and
- 5) ecosystem processes.

Within the WCRP, the Global Energy and Water Cycle Experiment (GEWEX) is addressing (2) and (3), while the World Ocean Circulation Experiment (WOCE) is concerned with (4) and parts of (1). Two core activities of the IGBP, the Joint Global Ocean Flux Study (JGOFS) and the International Global Atmospheric Chemistry Programme (IGAC) are designed to investigate the control of greenhouse gases by the oceanic and terrestrial biospheres, while the Biospheric Aspects of the Hydrological Cycle (BAHC) is a complement to GEWEX that also addresses (3). An additional core project of the IGBP focuses on Global Change and Terrestrial Ecosystems (GCTE). Both the WCRP and IGBP have other essential core activities, such as the Tropical Oceans - Global Atmosphere (TOGA) Programme and the study of Past Global Changes (PAGES), that contribute to these efforts to reduce uncertainties in climate predictions.

Narrowing the uncertainties in future climate change predictions requires strongly enhanced national participation in these internationally coordinated programmes.

This will require increased commitments to the endeavours of the WCRP and the IGBP. These programmes are the result of many years of planning and they represent consensus statements of the international science community regarding the maturity of

the fundamentals that underpin these projects and the readiness of the community to commit to these timely endeavours.

In order to proceed with this agenda, all nations must reaffirm their commitment to observe and document the fundamental aspects of the climate system and the changes occurring within it, including:

- 1) improvement of the global atmosphere and land surfaces observing system. The World Weather Watch and Global Atmospheric Watch need to be fully implemented and augmented by improved atmospheric sounders, radiometers and wind observations, active sensors for wind and rain, vegetation sensors, and an improved commitment to quality control and archival of all data,
- 2) development of a global ocean and ice observing system. Satellite observations of ocean surface temperature, wind and topography, sea-ice concentration and colour, operational upper-ocean heat and freshwater monitoring and systematic sea-level and deep-ocean measurements are required,
- 3) establishment of a comprehensive system for climate monitoring. It is essential that existing networks (WWW, GAW, IGOSS, GEMS, GSLS) be maintained and, where appropriate, enhanced. Special attention needs to be given to calibration and quality control, documentation and international coordination and data exchange.

The analysis and interpretation of the observational data will require the understanding arising from the projects of the WCRP and the IGBP, and will involve the use of more refined climate models. The next generation of predictive models will require additional computing resources in order to incorporate the more sophisticated understanding of the climate system arising from this research effort. This effort will lead to predictions that have higher spatial resolution than can be attained at this time.

The time scales for narrowing the uncertainties must be measured in terms of several years to more than a decade. Advances must await the conduct of several major experiments, many of which will be about a decade in duration, and the development of new technologies for space based observation and numerical computation. It is essential that government funding agencies recognize the magnitude of both the financial and human resources needed to undertake these research programmes and make the necessary commitments.

11.1 Introduction

In order to deal with the issues posed by increased atmospheric greenhouse gas concentrations and to prepare human societies for the impacts of climate change, climate predictions must become more reliable and precise. Present shortcomings include

- Significant uncertainty, by a range of three, regarding the sensitivity of the global average temperature and mean sea-level to the increase in greenhouse gases,
- Even larger uncertainties regarding regional climatic impacts, such that current climate change predictions have little meaning for any particular location,
- Uncertainty in the timing of the expected climate change,
- Uncertainty in the natural variations

To overcome these shortcomings, substantial improvements are required in scientific understanding which will depend on the creative efforts of individual scientists and groups. Nevertheless the scale of the task demands international coordination and strong national participation.

The IPCC has responsibility for assessing the current state of scientific knowledge of climate and climatic changes due to human influences. The World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU) established in 1980 the World Climate Research Programme (1) to promote scientific research on physical climate processes and to develop a capability for predicting climate variations. Several major internationally coordinated climate research projects organized by the WCRP are now underway. The Intergovernmental Oceanographic Commission (IOC) assists with the oceanographic component. Furthermore ICSU established in 1986 the International Geosphere-Biosphere Programme (2) to study the interactive physical, chemical and biological processes responsible for change in the Earth system especially those which are most susceptible to change on time scales of decades to centuries. The IGBP with its emphasis on biogeochemical aspects and the WCRP with its emphasis on physical aspects, together constitute the international framework of the quest for the scientific understanding of global change. This report deals with climate change but it must be stressed that climate change is but one of a wide range of environmental issues that are confronting the world. Many of these issues are linked and scientific study of one issue will frequently aid in understanding others.

(1) The World Climate Research Programme (WCRP) is jointly sponsored by the World Meteorological Organization and the International Council of Scientific Unions. The main goals of the WCRP are to determine to what extent transient climatic variations are predictable and to lay the scientific foundation for predicting the response of the Earth's climate to natural or man made influences. The main components of the WCRP are the numerical experimentation programme to develop improved models of the Earth's climate, the Global Energy and Water Cycle Experiment (GEWEX), the Tropical Ocean and the Global Atmosphere (TOGA) Programme and the World Ocean Circulation Experiment (WOCE). Each programme includes a range of projects to study specific aspects or physical processes of the Earth system. An example is the International Satellite Cloud Climatology Project to determine the quantitative effect of clouds on the Earth radiation balance and climate.

(2) The International Geosphere-Biosphere Programme (IGBP) is an inter disciplinary research initiative of the International Council of Scientific Unions to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring and the manner in which changes are influenced by human actions. A central objective of the IGBP is to establish the scientific basis for quantitative assessments of changes in the Earth's biogeochemical cycles including those which control the concentration of carbon dioxide and other chemicals in the atmosphere.

11.2 Problem Areas and Scientific Responses

To achieve effective prediction of the behaviour of the climate system we must recognize that this system is influenced by a complex array of interacting physical, chemical and biological processes. The scientific strategy to address these processes must include both observation and modelling. We must be able to understand the mechanisms responsible for past and present variations and to incorporate these mechanisms into suitable models of the natural system. The models can then be run forward in time to simulate the evolution of the climate system. Such a programme includes three essential steps:

Analysis of observational data, often obtained from incomplete and indirect measurements, to produce coherent information and understanding,

Application of observational information and understanding to construct and validate time-dependent mathematical models of natural processes,

Running such models forward to produce predictions that can (and must) be tested against observations to determine their "skill" or reliability over relatively short time-periods

Sections 1 to 10 of this assessment have identified several areas of scientific uncertainty. The following 5 areas are considered the most critical

11.2.1 Control of the Greenhouse Gases by the Earth System

Greenhouse gases in the atmosphere such as carbon dioxide and methane, are part of vast natural cycles. For some greenhouse gases, the current rates of release which are directly attributable to human activities are small percentages of large natural fluxes between the atmosphere, the ocean and terrestrial ecosystems while for others human activities result in dominant emissions. The atmospheric carbon content is a very small fraction of existing reservoirs of carbon in ocean waters and sediments. Relatively minor adjustments in the world ocean circulation and chemistry, or in the life cycle of terrestrial vegetation, could significantly affect the amount of CO₂ or CH₄ in the atmosphere, even were anthropogenic emissions to be stabilized. In particular, global warming is likely to decrease the absorption of carbon dioxide by sea water and lead to widespread melting of methane gas hydrates in and under the permafrost and also release CH₄. Conversely, positive changes in the biogenic storage of carbon in the ocean could increase the oceanic CO₂ uptake and ameliorate the greenhouse effect.

Current knowledge of oceanic and terrestrial biogeochemical processes is not yet sufficient to account quantitatively for exchanges between the atmosphere, ocean and land vegetation (Section 1). The international Joint Global Ocean Flux Study (JGOFS), a core project of IGBP, has been designed to investigate the oceanic biogeochemical processes relating to the cycle of carbon in the ocean and to assess the capacity of the ocean for absorbing CO₂. (3) A central question being addressed relates to the role of the ocean and its circulation (see description of the World Ocean Circulation Experiment in Section 11.2.4) in the uptake of CO₂ produced from the burning of fossil fuels. This uptake occurs via both physical and biological processes. Neither is well quantified on a global scale, and the regulation of the biological processes is at present only poorly understood. In particular, the biogeochemical processes responsible for the long-term

storage of a portion of the total primary production cannot at this time be resolved sufficiently in time and space to say how they might be affected by climate change. The first component of JGOFS, relating to process studies, began with a pilot study in the North Atlantic in 1989. Two time-series of measurements have been initiated at stations in the vicinity of Bermuda and Hawaii. JGOFS will result in an order of magnitude improvement in the precision of the assessment of the ocean's role in sequestering CO₂ from the atmosphere.

(3) *The Joint Global Flux Study (JGOFS), a core project of the IGBP is organized by ICSU's Scientific Committee on Oceanic Research. Its major goal is to determine and understand on a global scale the time varying fluxes of carbon and associated biogenic elements in the ocean and to evaluate the related exchanges with the atmosphere, the sea floor and continental boundaries. This project has three major components: 1) a sequence of studies to elucidate the connections between various biogeochemical processes and distributions; 2) a global-scale survey and long time series of measurements to improve the basic description of the carbon cycle; and 3) a modelling effort to identify critical processes and variables, to construct basin and global-scale fields from observed parameters and to predict future states of the ocean. The next generation of satellites will provide ocean colour data for the global assessment of temporal and spatial patterns in primary productivity and the WOCE hydrographic survey will provide the ship opportunities and ancillary physical and chemical data required to generate the first global inventory of ocean carbon.*

Another core project, the International Global Atmospheric Chemistry Programme (IGAC), is being designed to investigate the interactions between atmospheric chemistry and the terrestrial biosphere, particularly fluxes of carbon dioxide, methane and nitrogen oxides (4).

11.2.2 Control of Radiation by Clouds

Radiation is the primary energy source of the climate system and the principal heat input to the oceans (Section 2). These fluxes are very sensitive to the amount, distribution and optical properties of water and ice clouds (Sections 3 and 5) and are central to the problem of greenhouse heating. Aerosols also influence the net radiative flux at the surface. The net heat flux to the ocean determines the rate of ocean warming and volume expansion which is likely to be the largest contribution to the global rise of the mean sea-level during the next century if the Greenland and Antarctic ice sheets are neither gaining nor losing mass (Section 9).

(4) The International Global Atmospheric Chemistry Programme (IGAC), a core project of the IGBP, is jointly organized with ICSU's Commission on Atmospheric Chemistry and Global Pollution. Its goal is to document and understand the processes regulating biogeochemical interactions between the terrestrial and marine components of the biosphere and the atmosphere and their role in climate. It consists of several research projects, which address natural variability and anthropogenic perturbations in the composition of the atmosphere over terrestrial tropical, polar, and mid-latitude regions as well as over the oceans. Other research efforts will address through observations and modelling the global distribution of chemically and radiatively important species (including emission rates and other processes governing their abundances) and the role of these substances in cloud condensation. The results will yield a marked improvement in our understanding of the processes responsible for regulating the abundance of atmospheric constituents that are of relevance to climate.

(5) The Global Energy and Water Cycle Experiment (GEWEX) is a programme launched by the WCRP to observe, understand and model the hydrological cycle and energy fluxes in the atmosphere, on the land surface and in the upper ocean. The Programme will investigate the variations of the global hydrological regime and their impact on atmospheric and oceanic dynamics, as well as variations in regional hydrological processes and water resources, and their response to change in the environment such as the increase of greenhouse gases. The GEWEX Programme has several components. It incorporates a major atmospheric modelling and analysis component requiring a substantial increase in computer capabilities because climate models with high spatial resolution are needed to achieve realistic simulations of regional climates. GEWEX will provide an order of magnitude improvement in the ability to model global precipitation and evaporation, as well as accurate assessment of the sensitivity of the atmospheric radiation and clouds to climate changes. Because of the complex interactions of clouds and radiation, the GEWEX Programme will cooperate with the TOGA Programme and other projects in studies of cloud processes. In addition, there will be studies to improve the extraction of atmospheric and land-surface information from satellite data. The GEWEX Programme also includes a series of land surface experiments to develop understanding and parameterizations of evaporation and heat exchanges from inhomogeneous vegetated surfaces. Advancement of hydrological models and their integration into climate models is another objective of the GEWEX Programme. The IGBP Core Project on the Biospheric Aspects of the Hydrological Cycle (BAHC) will deal with the complementary problem of resolving the role of the biosphere and land-surface processes in this context and develop methods to implement the interaction of the biosphere with the physical Earth system in global models.

For the past two decades, the Earth radiation budget at the top of the atmosphere has been measured from satellites. The most recent radiometric measurement (Earth Radiation Budget Experiment) discriminates between cloudy and cloud-free areas, thus providing direct determination of the net energetic effect of clouds in the present climate. This information is not enough, however, to distinguish between the effect of different types of clouds at different altitudes. The ongoing International Satellite Cloud Climatology Project of WCRP (started in 1983) is working to assemble global statistics of the distribution and properties of different cloud types. In order to quantify the interannual variability of cloud systems, ten or more years of data are required. Because of the importance of changes in cloudiness in the radiation budget, these measurements must be continued. Process studies will be important in the study of feedbacks such as cloud-radiation interaction and its dependence on cloud water content, particle size and altitude.

Further modelling and observational research will nevertheless be necessary to achieve accurate representation in climate models of the role of clouds and radiation. The WCRP's Global Energy and Water Cycle Experiment (GEWEX), discussed more fully in Section 11.2.3, has as one of its objectives the more precise quantitative deduction of all energy fluxes within the atmosphere and at the air-sea and air-land interfaces (5).

Achieving the objectives of GEWEX will require the development of major new instruments to be flown on the next generation of multi-disciplinary satellite platforms in polar orbit or on the International Space Station and co-orbiting platforms (Earth Observing System, EOS). For this reason, the main GEWEX observing period must be timed to start with the launch of these satellite systems (expected in 1997 to 2000). The Experiment will last approximately five years and scientific interpretation and application of the results will take several further years.

11.2.3 Precipitation and Evaporation

The condensation of water is the main energy source of the atmospheric heat engine and the transport of water vapour by the atmospheric circulation is a key process in the redistribution of the sun's energy in the Earth system. Water vapour is also an important greenhouse gas. The vertical distribution of latent heating in precipitating clouds has a large effect on the large-scale circulation of the atmosphere. Precipitating clouds also play an important role in the general circulation through their effect on vertical transport of heat, moisture and momentum. The inflow of fresh water at high latitudes is a major factor in determining sea water buoyancy which forces the ocean circulation. The rates of accumulation of snow and the ablation of ice in the Antarctic and Greenland ice sheets are important sources of uncertainty for sea level rise during the next century (Section 9). Changes in the hydrological regime, precipitation and evaporation and consequent change in soil moisture and the availability of fresh water resources, are the most serious potential consequences of impending climate change in terms of its effect on man.

Unfortunately, present quantitative knowledge of the large-scale water budget is still very poor. For example, it has not yet been possible to measure or deduce from existing measurements either global precipitation or global evaporation (Section 7). About one third of the water runoff from continents to the ocean takes place as flow in small ungauged coastal rivers or underground aquifers. Much improved quantitative assessments of these components of the global water cycle are essential to achieve accurate predictions of future water resources in a changed climate. Values of precipitation and evaporation at sea can be inferred only roughly from general circulation models or satellite observations.

To address these and the other problems mentioned in Section 11.2.2 WCRP has launched the GEWEX programme (5) and specific projects aimed at the collection and analysis of observations available at present, such as the Global Precipitation Climatology Project (started in 1988) and the Global Run off Data Project (1980). The Global Precipitation Climatology Project has undertaken to combine all available rain gauge measurements and meteorological data with satellite observations of rain-clouds to produce the first global climatological record of monthly-mean total precipitation, including over the oceans. These projects require increased support by operational meteorological and hydrological agencies to upgrade the worldwide collection and exchange of essential ground-based measurements of rain, snow and river flow.

An ensemble of modelling and field studies of atmospheric and hydrological processes has already been initiated. The most significant achievements towards this objective are hydrological atmospheric field studies aiming to close the energy and water budget of a land parcel of

size commensurate with the spatial resolution of a general circulation model. A series of regional-scale (10 to 100 km) field studies (Hydrological Atmospheric Pilot Experiments, HAPEX, First ISLSCP Field Experiment and others) in different major ecosystems was started in 1986 and future experiments will continue to the end of the century. Cooperation between WCRP and IGBP is being pursued to take into account the role of biological processes in evapotranspiration from terrestrial vegetation and, conversely, the effect of climate change on terrestrial ecosystems. Hydrological models of a continent-size river basin driven by daily precipitation and evaporation estimated from analysed meteorological fields, are now being developed and will be applied during a continental-scale project in the mid-1990s. Other programmes, such as the Coupled Ocean-Atmosphere Response Experiment of the TOGA Programme, are important for determining the physical processes within mesoscale convective cloud systems.

11.2.4 Ocean Transport and Storage of Heat

The ocean plays a major role in the climate system through its storage and transport of heat. The response time of the upper ocean is relatively short (months to years) compared to the deeper ocean. It is now recognized that the largest portion of the interannual variability of the climate system is linked to the tropical oceans. For this reason, the Tropical Ocean - Global Atmosphere (TOGA) Programme (6) was originated and it is maintaining an intensive observational programme from 1985 to 1995. In addition, the TOGA Coupled Ocean-Atmosphere Response Experiment (COARE) is planned for the mid-1990s, to investigate the coupling between the warm western tropical Pacific Ocean through cloud dynamics, with the high atmosphere. With the TOGA observational array of buoys, current meters, and ships, it has been possible to investigate the evolution of the tropical ocean and to initiate experimental forecasts of the El Niño phenomenon.

(6) The WCRP's Tropical Ocean - Global Atmosphere (TOGA) Programme is aimed at understanding and eventually predicting how the evolution of the tropical oceans interacts with and causes global-scale variability of the atmosphere. The El Niño - Southern Oscillation (ENSO) is the major cause of interannual variability of the climate system. TOGA began its observing period in 1985 and will continue until 1995. A large array of special oceanographic and atmospheric measurements have been deployed. The TOGA Programme also includes process studies and model development. One special activity is the investigation of monsoon dynamics.

If the atmosphere and upper-ocean alone were responding to the increase in greenhouse heating and the cloud-radiation feedback operated according to current knowledge, then the surface of the Earth would already be 1 to 2°C warmer than the temperatures of the nineteenth century. The response of the Earth's climate to increased greenhouse heating is being reduced by the thermal inertia of the ocean, determined by the largely unknown rate of penetration of heat into the upper 1000 metres. Deep ocean warming results mainly from water sinking at high latitudes, frequently in the presence of sea ice, and subsequent circulation in the ocean. Quantitative modelling of the global ocean circulation is essential to determine the timing of global warming. The WCRP World Ocean Circulation Experiment (7) will provide the understanding and observations of the global ocean to enable the development of these ocean models.

(7) The World Ocean Circulation Experiment (WOCE) of the WCRP is a worldwide oceanographic programme to describe the oceanic circulation at all depths and on the global domain during a five year period (1990-1995). The primary goal of WOCE is to develop global ocean models for the prediction of climate change and to collect data sets necessary to test those models. Over the five years of the programme there will be an intensification of the effort to determine air-sea fluxes globally by combining marine meteorological and satellite data, an upper ocean measurements programme to determine the annual and inter-annual oceanic response to atmospheric forcing and a programme of high quality hydrographic and chemical tracer observations, surface and under water drifters, current meter arrays, tide gauges and satellite altimetry to determine the basic features of the deep-ocean circulation. WOCE will provide adequate determination of global heat and fresh water fluxes in the bulk and at the surface of the ocean.

Three new satellite missions in support of WOCE are in the final stages of preparation or being planned.

The US-French TOPEX-POSEIDON precision altimetry mission, to measure the ocean surface topography with unprecedented accuracy for the purpose of determining ocean circulation (to be launched in 1992),

The European Space Agency ERS-1 and ERS-2 missions to measure wave height and ocean surface topography, wind stress and temperature at the surface of the ocean (to be launched in 1991 and 1994),

The US-Japanese ADEOS project to provide, in particular, more complete observations of the wind stress over the global ocean (to be launched in 1994)

Oceanographic agencies and institutions are joining forces to deploy the research vessel fleet needed to implement the WOCE hydrographic and geochemical surveys at sea, which call for 25 ship years. The concentration of a number of chemicals and isotopes will be measured throughout the ocean. By studying the distribution of substances that entered the environment at different times over the last century, geochemists and ocean modellers can estimate the time scales associated with the slow renewal and circulation of the ocean's deep water masses.

WOCE systems are to be activated for five years only. Maintaining systematic observations of essential oceanographic quantities after WOCE, to monitor the changes taking place in the ocean and to define the state of the global ocean circulation from which further dynamical predictions could be made, is a requirement which remains to be put into effect (Section 11.3.2).

11.2.5 Ecosystem Processes

As indicated above, both terrestrial and marine ecosystems are important as sources and sinks of biogenic gases that have radiative properties in the atmosphere. In addition, terrestrial ecosystems play an important role in the exchange of moisture and therefore energy between the land surface and overlying atmosphere. Thus predictions of climate, driven by anthropogenic increases in the atmospheric content of greenhouse gases, must take into consideration the likelihood that feedback from ecosystems will be altered by climate change itself. Temporal and spatial patterns in temperature, precipitation and nutrient deposition (including extreme events) will directly affect soils, plant productivity, vegetation structure and community composition. This influence is not limited to natural ecosystems, it also imposes regional constraints on agriculture and forestry. Large scale displacement of particular ecosystems will affect the climate system by altering local surface roughness and albedo.

A more quantitative understanding of the function of ecosystems in climate is important. In particular, research is needed to provide better global observations of the nature and extent of vegetation and soils. In addition, *in situ* studies must be scaled up to investigate the physiological and ecological processes that configure an ecosystem response to climate change. The interpretation of such data requires a modelling approach that also includes the ability of community constituents to migrate away from a unsuitable climate regime. The full use of this information in climate predictions requires higher resolution models (50 km) capable of simulating extreme conditions.

and the full range of the seasonal cycle. The IGBP is engaged in planning new studies of climate and land use changes on ecosystems, and their attendant feedbacks on climate. Partly to address these ecosystem dimensions of climate regulation, the IGBP has established a core project on Global Change and Terrestrial Ecosystems (GCTE) (8)

(8) *Global Change and Terrestrial Ecosystems (GCTE)* is a core project of the IGBP, aimed at developing the capacity to predict the effects of changes in climate, atmospheric composition and land-use practices on terrestrial ecosystems. This capacity is required both because the ecosystem changes are of direct importance to humans, and because they will have a feedback effect on further evapotranspiration, albedo and surface roughness. The project has two main foci: Ecosystem "Physiology" - the exchanges of energy and materials, and their distribution and storage - and Ecosystem Structure - the changes in species (functional type) composition and physiognomic structure, on the patch, landscape and regional (continental) scales. The project is based on close integration of experimentation and modelling. It consists of seven core activities, each of which is made up of a number of particular tasks, which include such topics as elevated CO₂ effects on ecosystem functioning, changes in the biogeochemical cycling of C, N, P and S, soil dynamics, vegetation dynamics and changes in spatial patterns.

11.3 Requirements for Narrowing Uncertainties in Future Climate Change

Climate research can provide a valuable service to society by providing the means for detection of future climate change, quantitative prediction of the timing and rate of the expected global changes and assessments of probable regional effects. In order to achieve these goals, it is necessary to develop a comprehensive Global Earth Observing System, to develop improved climate models and to acquire new scientific knowledge. As shown in Figure 11.1, there is an essential symbiosis between observations and modelling. Observations are required for long-term climate monitoring, especially for detection of climate change, and for local process studies. Modelling is required to support process studies as well as to provide the vehicle for climate predictions. Observations and modelling are brought together to develop an understanding of the components of the climate system. At present, modelling and data assimilation studies are limited by availability of computer time; large increases in computer resources are a major requirement. A second major limitation on the advancement of climate research is the shortage of highly trained scientists.

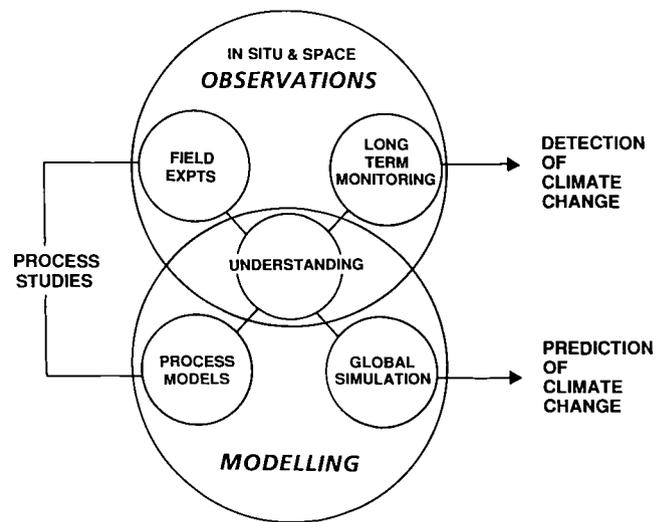


Figure 11.1: The symbiosis between observations and modelling

11.3.1 Improvement of the Global Atmosphere and Land Surfaces Observing System

Basic information on climatic processes, climate variations and systematic trends originates from the operational meteorological observing systems of the World Weather Watch, complemented by various operational hydrological networks and environmental measurements of the Global Atmospheric Watch (9). In addition to the **maintenance** of the basic meteorological systems, specific **improvements** are needed, in particular:

- improved infrared and microwave atmospheric sounding instruments on meteorological satellites, to obtain more accurate temperature/moisture information with better vertical resolution in the troposphere (e.g., high spectral resolution infrared spectrometer/radiometer),
- improved tropospheric wind observations from geostationary satellites (cloud-drift winds) and platforms in low Earth-orbit (Doppler wind lidar),
- rain-radars and passive multiple-frequency imaging radiometers in the microwave spectrum, to estimate rainfall over the whole globe, and
- radiometers to determine more accurately the Earth's radiation budget.

Temporal and spatial patterns in key vegetation properties can, when calibrated and interpreted in the context of ground-truth data, be efficiently studied with satellite sensors. These data are critical in detecting regional shifts in ecosystem form and function in response to climate and land use changes. Sustaining these activities at levels appropriate to the study of climate change requires

(9) Several international organizations operate major observational networks that provide information that needs to be included in a comprehensive system for climate monitoring. For climate monitoring purposes it is essential that each of these networks be maintained and where appropriate, enhanced. The important characteristics of climate monitoring systems include long-term continuity, consistency of calibration, quality control, documentation of techniques, and international availability of data. The major networks are the World Weather Watch and Global Atmosphere Watch of WMO, the Integrated Global Ocean Services System of WMO and the Intergovernmental Oceanographic Commission, the Global Environmental Monitoring System of UNEP, and the Global Sea-Level Service of IOC.

- e) improved commitment to the acquisition and archival of AVHRR data for determining rates of change (for example, those arising from desertification and land clearing), shifts in seasonal vegetation cycles, and rates of plant production needed for carbon cycling modelling, and
- f) improved high spectral resolution sensors, like those being defined for EOS, to determine vegetation characteristics (including physical and chemical properties) needed as input for global biogeochemical models.

11.3.2 Development of a Global Ocean and Ice Observing System

From the perspective of global climate change, systematic ongoing observations of the global ocean are needed for several purposes. The key to predicting the rate of change of the global system is to be found in observations of the ocean circulation and heat storage. Predictions of future climate change will eventually be carried out starting from the observed state of the combined atmosphere and ocean system. An example of this approach is the forecast of El Niño and other tropical climate disturbances by the WCRP Tropical Ocean and Global Atmosphere (TOGA) Programme.

A comprehensive ocean and ice observing system requires

- a) satellite observations of the ocean surface temperature, wind and topography, sea ice concentration and chlorophyll content (ocean colour), and of the topography of the Antarctic and Greenland ice sheets, by an international array of space platforms in suitable orbits around the Earth.

- b) an international operational upper-ocean monitoring programme, to determine the time and space dependent distribution of heat and fresh water in upper ocean layers, seasonal variations and long-term trends, and
- c) an international programme of systematic sea-level and deep-ocean measurements, at suitable time and space intervals, to determine the state of the ocean circulation, ocean volume and transport of heat.

11.3.3 Establishment of a Comprehensive System for Climate Monitoring

In the previous two sections (11.3.1 and 11.3.2) improvements to the global atmosphere and land surface observing system and development of a global ocean and ice observing system were discussed. These observing systems must be coupled with existing observing systems to establish a comprehensive system for climate monitoring. It must be recognized that the requirements for climate monitoring are different from those for weather prediction. Failure to recognize this in the past means that there are a number of uncertainties which have been introduced into long-term climatological time series. A long-term commitment is now needed by the world's national weather services to monitor climate variations and change. Changes and improvements in observational networks should be introduced in a way which will lead to continuous, consistent long-term data sets sufficiently accurate to document changes and variations in climate (9). Some observing systems have and will be established for research purposes. These research systems are usually of limited duration and area and may have different emphases from a climate monitoring system (Figure 11.1). However, it is important that these observations also be integrated with the information from long-term monitoring systems.

Satellite observations are not yet of long enough duration to document climate variations. In order for these data to be most useful, it is very important that they be analysed and interpreted with existing *in situ* data. High priority should be given to the blending or integration of spaced-based and *in situ* data sets in such a way as to build upon the strengths of each type of data. Examples of ongoing projects that have used mixed satellite data sets, careful cross calibration and coordinated data processing to produce global data sets are the WCRP's International Satellite Cloud Climatology Project (ISCCP) and the Global Precipitation Climatology Project (GPCP). For some applications it is necessary to assimilate the observations into operational numerical weather prediction models for which purpose the observations need to be available in near real time. All satellite instruments should be calibrated both prior to launch and in flight. For those instruments now in operation, techniques should be developed to prevent or detect instrument drift. In planning

new satellite observations for long-term monitoring, special attention should be paid to continuity of calibration and processing, archival and access to the data

It is, further, imperative that there be strengthened international agreements and procedures for international exchange of existing basic climatological data (e.g., rain-gauge measurements and/or meteorological satellite data). National data centres must make available, through free exchange, to the world climate community, data sets collected in their countries. Existing CLIMAT and international data exchange (World Weather Records) must include essential variables which are absent at present. For most climate variables, the spatial and temporal resolution of the exchanged data is inadequate, precluding world-wide analyses of extremes. New methods of international exchange may be needed. For a worldwide ocean monitoring system there are requirements for strengthening international agreements to facilitate standard temperature, salinity and velocity measurements by all vessels and oceanographic drifting platforms within national Exclusive Economic Zones. Agreements among scientists and research institutions for international sharing of oceanographic data need to be strengthened.

There remains considerable data in manuscript form, which will prove valuable in producing more definitive analyses of climate change and variability. These data should be documented in computer compatible form. These and proxy data, including palaeo climate data, are needed to reconstruct variations in past climates. In many cases, spatial and temporal resolution needs to be improved. Palaeodata can be particularly valuable in testing hypotheses regarding the mechanisms that have in the past linked physical and biogeochemical aspects of climate change. The IGBP has established a core project specifically for studying Past Global Changes (PAGES) (10).

The WMO has undertaken to strengthen its activities to monitor the chemical composition and other characteristics of the atmosphere, away from pollution sources, and to incorporate these activities into a coordinated Global Atmosphere Watch (GAW) programme. The main objective of GAW is to establish a global monitoring network of about 20 observatories complemented by regional stations whenever possible.

In addition to the above-mentioned needs to improve available instruments and methods to observe various climate parameters the development of a comprehensive system for monitoring climate change around the world is likely to be required under a convention on climate change. There are many international bodies involved in already existing monitoring activities such as the World Climate Research Programme, the World Climate Programme, the WMO Commission for Climatology, the Global Atmosphere Watch, the UNESCO Man and Biosphere, the Intergovernmental Oceanographic Commission and the

(10) *The IGBP core project on Past Global Changes (PAGES) coordinates and integrates existing national and international palaeo projects and implements new activities in order to obtain information on the pre-industrial variations of the Earth system and the baseline on which human impacts are superimposed. Typical research tasks are the separation of anthropogenic and corresponding responses and the documentation of possible internally forced processes. Of particular interest are the deconvolution of long-term climatic changes over a glacial cycle of ecosystems to the warming at the end of the last glaciation and changes in the atmospheric content of CO₂ and CH₄ throughout the last glacial cycle and during periods of abrupt climatic change. All this information will help to evaluate both climatic and biogeochemical cycle models.*

UNEP Global Environmental Monitoring System. The future overall system for monitoring climate change and its effects requires coordination of activities of these and other organizations.

11.3.4 Development of Climate Models

Improved prediction of climate change depends on the development of climate models, which is the objective of the climate modelling programme of the WCRP. Atmospheric general circulation models are based on numerical models used with considerable success by the national weather services to predict weather several days ahead. However, when adapted for climate prediction, these models need to be extended in several ways, all of which place heavy demands on computer resources. Extending the period of integration from days to decades has already been achieved, but so far only at the expense of poor spatial resolution and/or inadequate representation of the interaction between the atmosphere and the oceans. In addition, some feedback mechanisms in the climate system depend on biological chemical interactions, the proper understanding of which are key tasks for the IGBP.

The oceans are represented in most climate models in a very simplified way that does not properly simulate the ocean's ability to absorb heat and hence retard (and to some extent alter the pattern of) global warming. These (so-called equilibrium) models provide an estimate of eventual climate changes but not the rate at which these will take place. In order to predict the evolution of climate realistically, it is necessary to develop further a new generation of models in which the atmosphere and oceans (and sea-ice) are fully coupled and in which the circulation of the oceans as well as the atmosphere is explicitly

computed. The oceans have important eddies occurring on small scales and fine spatial resolution is essential for their explicit representation in a realistic manner.

Finer resolution than used at present is also required for the atmospheric component if regional variations of climate are to be predicted. Present day climate models do not have sufficient resolution to represent in a meaningful way the climate of specific regions as small as, for example, the majority of individual nations. The implementation of finer resolution models will require significant advances in computer capability such as can be expected within the next 5 to 10 years. Improved parameterization of cloud and other processes will also need to be incorporated. To develop these parameterizations, very-fine mesh models will need to be developed, covering domains large enough to embrace entire mesoscale convective cloud systems, and appropriate field experiments will need to be carried out in different regions to provide input data and validation.

Models are required not only for prediction and process studies, but also for analysing the inevitably incomplete observational data sets to reconstruct and monitor climate change. Appropriate 4-dimensional data assimilation techniques exist for observations of atmospheric temperature and wind, but substantial improvements over the course of the next decade are needed to extend these methods for assimilating other parameters such as precipitation. Similar techniques will also be required for the analysis of ocean observations.

The development of advanced geosphere-biosphere models will be an important task for the IGBP. Such models are needed to introduce, as dynamic variables, the biological source and sink terms into descriptions of the way in which greenhouse gases will vary with climate change. That will become feasible with supercomputers available early in the 21st century. Such models will simulate detailed events with sufficient spatial and temporal resolution to permit explicit treatment of the strong non-linear interactions between physics, chemistry and biology that occur on small scales.

Model validation is a prerequisite to reducing uncertainties. The interaction between observational data and numerical modelling is a continuing process. It is essential for the development and testing of these models, for their operation and for their validation and eventual application to prediction. Confidence in models depend on comparisons with observations. Modellers must identify data sets needed, their temporal and spatial scales of measurement and the required accuracy and simultaneity of observations. The observational system must be designed to provide such measurements and the data analysis and information system must be able to transform these measurements into usable parameters.

11.3.5 International Research on Climate and Global Change

Carrying out this global multi-disciplinary programme requires unprecedented co-operation of the world scientific community and task sharing by research institutions and responsible national administrations with long-term commitments of support. Inasmuch as global climate change is recognized as a problem concerning all nations, establishing an effective global climate monitoring and prediction system must also be recognized as a responsibility to be shared by all nations. For the physical aspects of the climate system, research on the clouds and radiation, the global water cycle and the oceans should be given highest priority at this time. Within the World Climate Research Programme, this includes the Global Energy and Water Cycle Experiment (GEWEX) and World Ocean Circulation Experiment (WOCE). Resource commitments are required as a matter of urgency. Regarding biogeochemical aspects of the climate system, research on the role of the ocean and the terrestrial biosphere as sources and sinks of greenhouse gases should be given highest priority. Within the International Geosphere-Biosphere Programme, this includes the Joint Global Ocean Flux Study (JGOFS) and the International Global Atmospheric Chemistry Programme (IGAC). Internationally coordinated research on the role of ecosystems in climate, including a biospheric contribution to GEWEX through an IGBP core project on BAHC, is now being organized. These studies will be an obvious complement to climate studies and be important in laying the sound foundation for assessing the effects of climate change on ecosystem functions and subsequent feedbacks to the climate system.

As noted earlier, there are strong interactions between climate change and other global environmental issues. A research programme on climate change will provide valuable insight into these issues and as we gain understanding of the functioning of the total Earth system, research programmes will need to be modified and reframed in terms of a research programme aimed at supporting global environmental management in all its aspects.

It is recognized that there are important scientific questions that are being addressed by national and other research programmes independently of these international programmes. The emphasis in this report has been given to those scientific questions that require large experimental and observing systems, and therefore require international coordination of efforts.

11.3.6 Time-scales for Narrowing the Uncertainty

New concepts and scientific methods cannot mature overnight and the lead time for significant progress in knowledge must be estimated in terms of years or even a decade, as for any major new technical development.

Although progress will occur incrementally in all fields, it is instructive to identify times when the pace of progress will be intensified as a result of specific activities some of which are shown for illustrative purposes in Figure 11.2. Where the oceans are concerned, substantial advances can be expected after the mid-1990s as a result of the WOCE and JGOFS field programmes. On the same time scale, model developments will lead to better treatment of the oceans in coupled atmosphere-ocean general circulation models and hence to more realistic predictions of the rate of change of climate. For the atmosphere, clouds introduce the greatest uncertainty: some progress will occur during the 1990s as a result of the ISCCP and continued Earth radiation measurements from space. The Global Energy and Water Cycle Experiment, to start in the late 1990s, will provide the first comprehensive data set for marked improvement in the treatment of clouds and radiation in climate models. A proper treatment of clouds may require the development of more powerful satellite instruments such as three-dimensional cloud radars after the turn of the century. A similar time scale applies to the representation of precipitation and evaporation, and associated transport processes. The series of HAPEXs will continue through the mid-1990s and the Continental Scale Study of a large

river basin will follow. Advanced space instruments (Figure 11.3) involving a heavy investment in active sensors (lasers and radars) will begin producing important results at the end of the 1990s as part of the GEWEX. This is also the time when we shall begin to see global models incorporating chemical and biospheric aspects and advanced four-dimensional data assimilation techniques. Improved understanding of the sources and sinks of the major greenhouse gases will only come following completion of JGOFS (for the marine component) and IGAC (for the terrestrial component and the atmospheric transformations) at the end of the century. Although still lacking some of these improvements, a major advance in the ability to predict the regional differences in climate change is expected to take place in the late 1990s, with the implementation of higher resolution models of the atmosphere. A broad summary of the time-scales for narrowing the uncertainties is given in Figure 11.4.

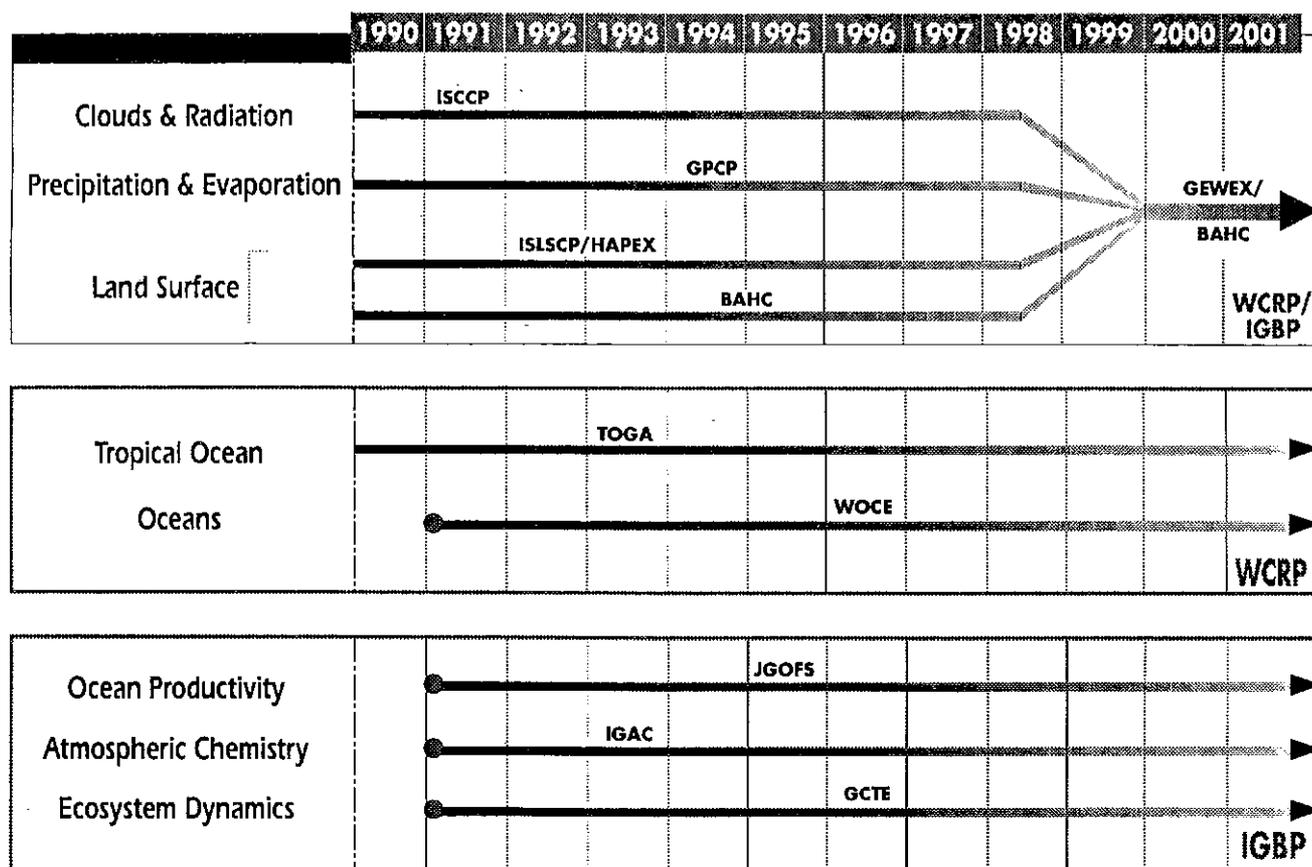


Figure 11.2: Schematic time schedules of major scientific programmes, as referred to in text.

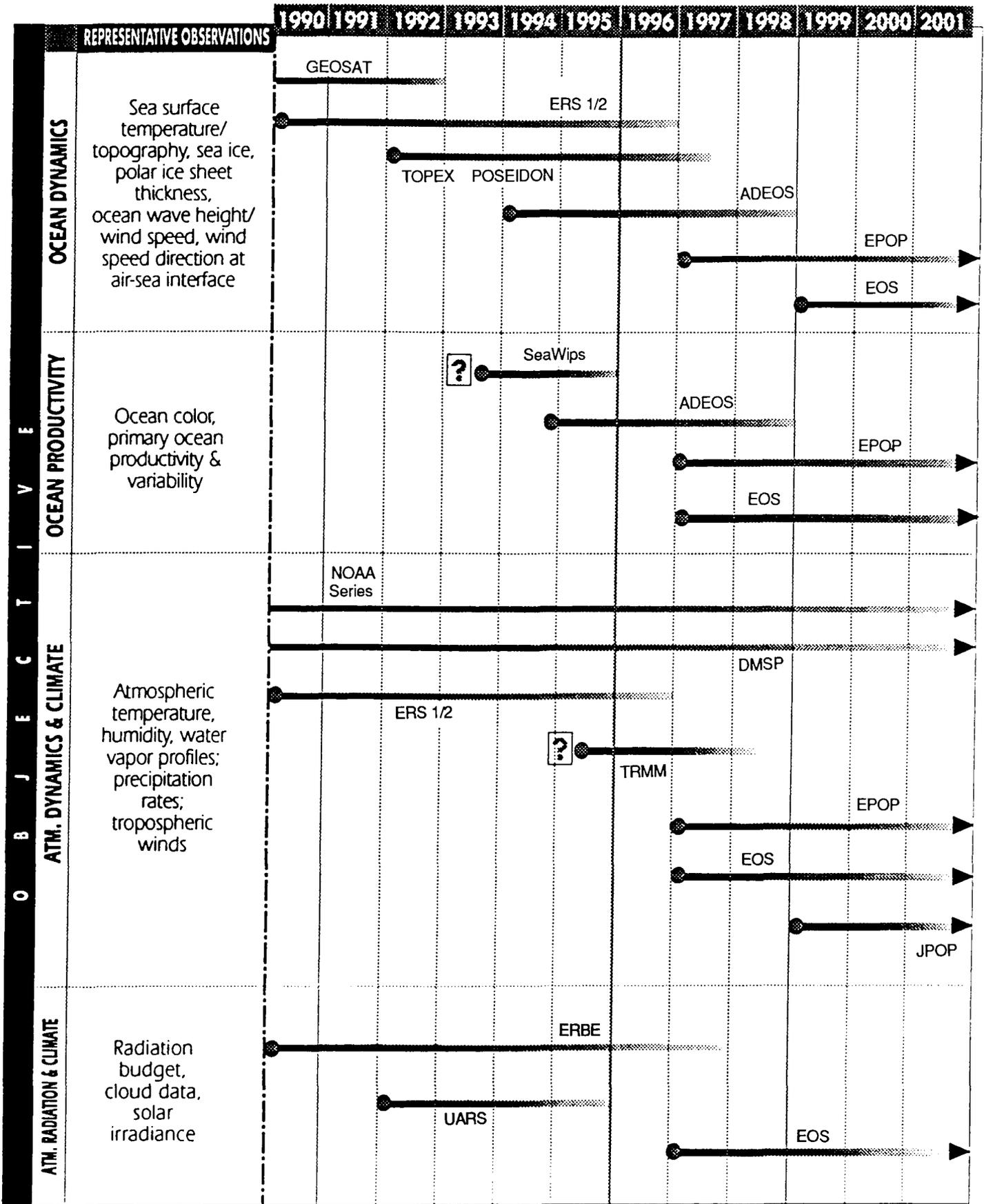


Figure 11.3: Illustrative examples of important satellite measurements.

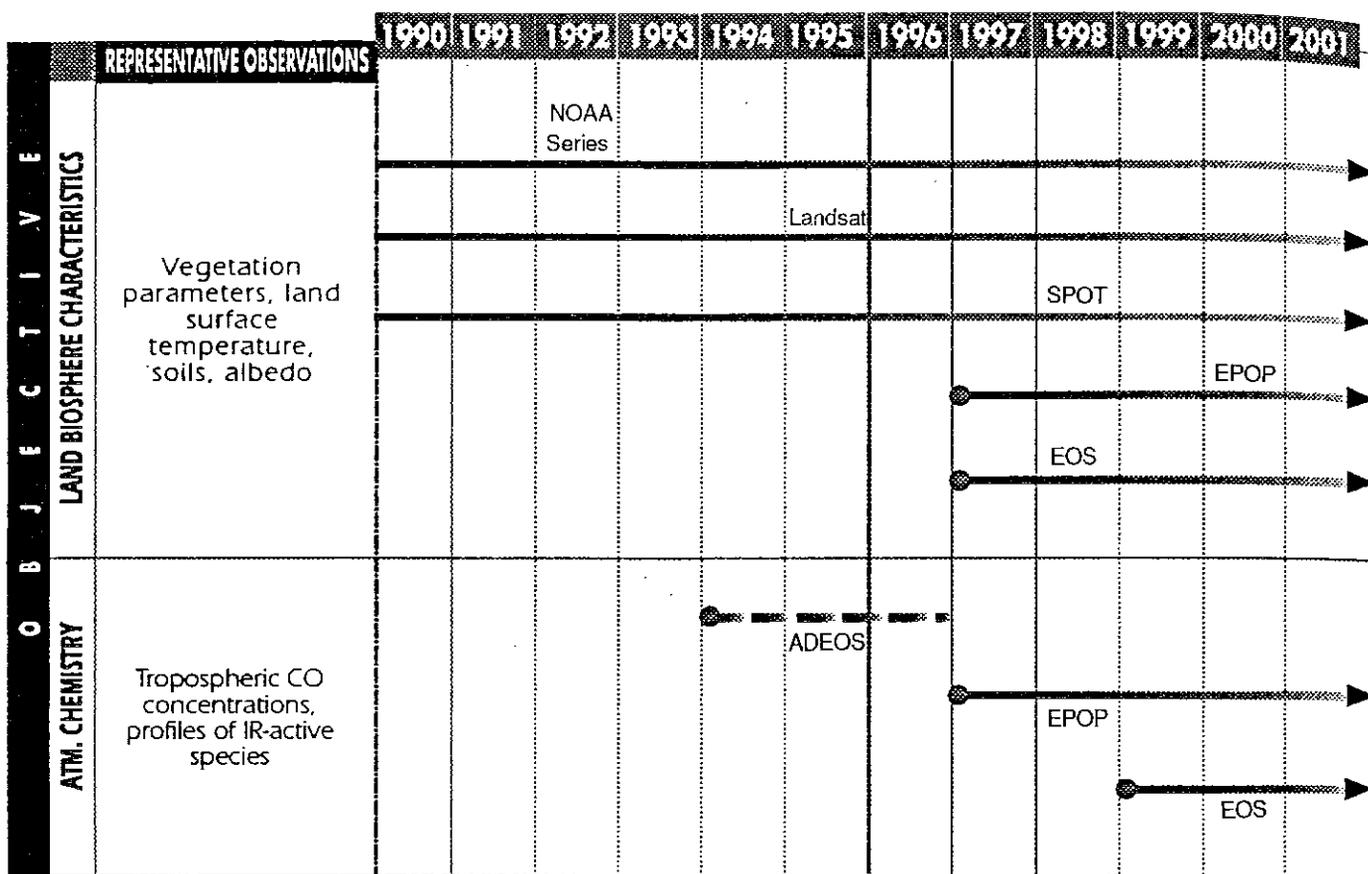
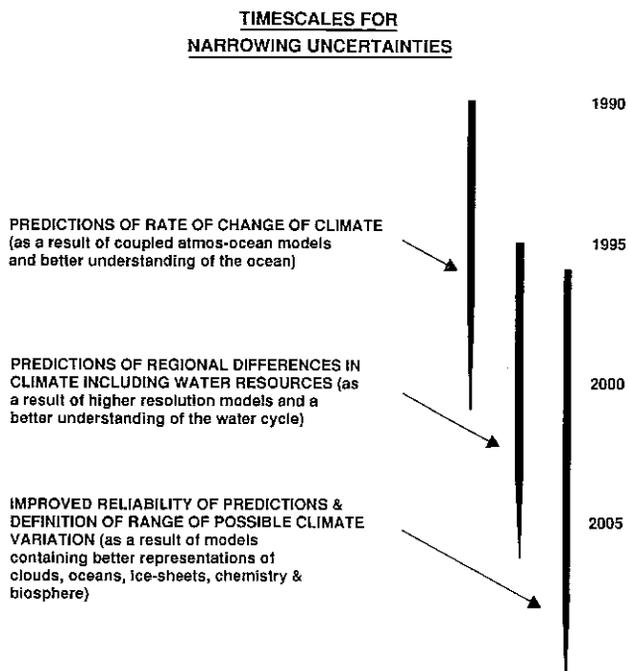


Figure 11.3: (Continued)



For these objectives to be met a long term commitment to observation and modelling activities must be maintained for at least the next decade. It is essential that government funding agencies recognize the magnitude of both the financial and human resources needed to undertake this research programme and the need to plan for appropriately long and sustained scientific efforts. Understanding and predicting the Earth's climate system must surely be the greatest scientific challenge yet to be faced by humankind. It is a worthy banner behind which the nations of the world can unite.

Figure 11.4: Timescales for narrowing uncertainties.