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Advancing Our Understanding

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Executive Summary

Further work is required to improve the ability to detect, attribute, and understand climate change, to reduce uncertainties, and to project future climate changes. In particular, there is a need for additional systematic observations, modelling and process studies. A serious concern is the decline of observational networks. Further work is needed in eight broad areas:

- *Reverse the decline of observational networks in many parts of the world.* Unless networks are significantly improved, it may be difficult or impossible to detect climate change over large parts of the globe.

- *Sustain and expand the observational foundation for climate studies by providing accurate, long-term, consistent data including implementation of a strategy for integrated global observations.* Given the complexity of the climate system and the inherent multi-decadal time-scale, there is a need for long-term consistent data to support climate and environmental change investigations and projections. Data from the present and recent past, climate-relevant data for the last few centuries, and for the last several millennia are all needed. There is a particular shortage of data in polar regions and data for the quantitative assessment of extremes on the global scale.

- *Understand better the mechanisms and factors leading to changes in radiative forcing; in particular, improve the observations of the spatial distribution of greenhouse gases and aerosols.* It is particularly important that improvements are realised in deriving concentrations from emissions of gases and particularly aerosols, and in addressing biogeochemical sequestration and cycling, and specifically, in determining the spatial-temporal distribution of carbon dioxide (CO_2) sources and sinks, currently and in the future. Observations are needed that would decisively improve our ability to model the carbon cycle; in addition, a dense and well-calibrated network of stations for monitoring CO_2 and oxygen (O_2) concentrations will also be required for international verification of carbon sinks. Improvements in deriving concentrations from emissions of gases and in the prediction and assessment of direct and indirect aerosol forcing will require an integrated effort involving *in situ* observations, satellite remote sensing, field campaigns and modelling.

- *Understand and characterise the important unresolved processes and feedbacks, both physical and biogeochemical, in the climate system.* Increased understanding is needed to improve prognostic capabilities generally. The interplay of observation and models will be the key for progress. The rapid forcing of a non-linear system has a high prospect of producing surprises.

- *Address more completely patterns of long-term climate variability including the occurrence of extreme events.* This topic arises both in model calculations and in the climate system. In simulations, the issue of climate drift within model calculations needs to be clarified better in part because it compounds the difficulty of distinguishing signal and noise. With respect to the long-term natural variability in the climate system *per se*, it is important to understand this variability and to expand the emerging capability of predicting patterns of organised variability such as El Niño-Southern Oscillation (ENSO). This predictive capability is both a valuable test of model performance and a useful contribution in natural resource and economic management.

- *Improve methods to quantify uncertainties of climate projections and scenarios, including development and exploration of long-term ensemble simulations using complex models.* The climate system is a coupled non-linear chaotic system, and therefore the long-term prediction of future climate states is not possible. Rather the focus must be upon the prediction of the probability distribution of the system's future possible states by the generation of ensembles of model solutions. Addressing adequately the statistical nature of climate is computationally intensive and requires the application of new methods of model diagnosis, but such statistical information is essential.

- *Improve the integrated hierarchy of global and regional climate models with a focus on the simulation of climate variability, regional climate changes, and extreme events.* There is the potential for increased understanding of extremes events by employing regional climate models; however, there are also challenges in realising this potential. It will require improvements in the understanding of the coupling between the major atmospheric, oceanic, and terrestrial systems, and extensive diagnostic modelling and observational studies that evaluate and improve simulation performance. A particularly important issue is the adequacy of data needed to attack the question of changes in extreme events.

- *Link models of the physical climate and the biogeochemical system more effectively, and in turn improve coupling with descriptions of human activities.* At present, human influences generally are treated only through emission scenarios that provide external forcings to the climate system. In future more comprehensive models, human activities need to begin to interact with the dynamics of physical, chemical, and biological sub-systems through a diverse set of contributing activities, feedbacks, and responses.

Cutting across these foci are crucial needs associated with strengthening international co-operation and co-ordination in order to utilise better scientific, computational, and observational resources. This should also promote the free exchange of data among scientists. A special need is to increase the observational and research capacities in many regions, particularly in developing countries. Finally, as is the goal of this assessment, there is a continuing imperative to communicate research advances in terms that are relevant to decision making.

The challenges to understanding the Earth system, including the human component, are daunting, but these challenges simply must be met.

14.1 Introduction

There has been encouraging progress over this first decade of the IPCC process. We understand better the coupling of the atmosphere and ocean. Significant steps have been taken in linking the atmosphere and the terrestrial systems although the focus tends to be on water-energy and the biosphere with fixed vegetation patterns. Even so, revealing and unexpected teleconnections are being discovered; moreover, progress is being made towards model structures and data sets that will allow implementation of coupled atmosphere-ocean-terrestrial models that include key biological-biogeochemical feedbacks. There is also encouraging progress in developing integrated assessment models that couple economic activity, with associated emissions and impacts, with models of the biogeochemical and climate systems. This work has yielded preliminary insights into system behaviour and key policy-relevant uncertainties.

The challenges are significant, but the record of progress suggests that within the next decade the scientific community will develop fully coupled dynamical (prognostic) models of the full Earth system (e.g., the coupled physical climate, biogeochemical, human sub-systems) that can be employed on multi-decadal time-scales and at spatial scales relevant to strategic impact assessment. Future models should certainly advance in completeness and sophistication; however, the key will be to demonstrate some degree of prognostic skill. The strategy will be to couple the biogeochemical-physical climate system to representations of key aspects of the human system, and then to develop more coherent scenarios of human actions in the context of feedbacks from the biogeochemical-physical climate system.

Developing these coupled models is an important step. From the perspective of understanding the Earth system, determining the nature of the link between the biogeochemical system and the physical climate system represents a fundamental scientific goal. Present understanding is incomplete, and a successful attack will require extensive interdisciplinary collaboration. It will also require global data that clearly document the state of the system and how that state is changing as well as observations to illuminate important processes more clearly.

14.2 The Climate System

14.2.1 Overview

Models of physical processes in the ocean and atmosphere provide much of our current understanding of future climate change. They incorporate the contributions of atmospheric dynamics and thermodynamics through the methods of computational fluid dynamics. This approach was initially developed in the 1950s to provide an objective numerical approach to weather prediction. It is sometimes forgotten that the early development of "supercomputers" at that time was motivated in large part by the need to solve this problem. In the 1960s, versions of these weather prediction models were developed to study the "general circulation" of the atmosphere, i.e., the physical statistics of weather systems satisfying requirements of conservation of mass, momentum, and energy. To obtain realistic simulations, it was found necessary to include additional energy sources and sinks: in particular, energy exchanges with the surface and moist atmospheric processes with the attendant latent heat release and radiative heat inputs.

Development of models for the general circulation of the ocean started later, but has proceeded in a similar manner. Models that deal with the physics of the oceans have been developed and linked to models of the atmospheric system. Within ocean models, the inclusion of geochemical and biological interactions has begun, with a focus upon the carbon cycle. Since the late 1960s, the geochemical aspects of the carbon cycle have been included in low-dimensional box models. More recently, including the carbon chemistry system in general circulation models has simply been a question of allocation of computing resources. Modelling of the biological system, however, has been more challenging, and it has only been recently that primitive ecosystem models have been incorporated in global general circulation ocean models. Even though progress has been significant, much remains to be done. Eddy-resolving ocean models with chemistry and biology need to be tested and validated in a transient mode, and the prognostic aspects of marine ecosystems including nutrient dynamics need greater attention at basin and global scales.

Model development for the ocean and atmosphere has had a fundamental theoretical advantage: it is based on firmly established hydrodynamic equations. At present there is less theoretical basis for a "first principles" development of the dynamical behaviour of the terrestrial system. There is a need to develop a fundamental methodology to describe this very heterogeneous and complex system. For the moment, it is necessary to rely heavily upon parametrizations and empirical relationships. Such reliance is data intensive and hence independent validation of terrestrial system models is problematical. In spite of these difficulties, a co-ordinated strategy has been developed to improve estimates of terrestrial primary productivity and respiration by means of measurement and modelling. The strategy has begun to yield dividends. Techniques from statistical mechanics have been wedded to biogeochemistry and population ecology, yielding new vegetation dynamic models. Global terrestrial models at meso-spatial scales (roughly 50 km grids) now exist which capture complex ecophysiological processes and ecosystem dynamics.

Expanded efforts are needed in these domain-specific models. In the ocean, we need to consider better the controls on thermohaline circulation, on potential changes in biological productivity, and on the overall stability of the ocean circulation system. Within terrestrial systems the question of the carbon sink-source pattern is central: what is it and how might it change? Connected to this question is the continued development of dynamic vegetation models, which treat competitive processes within terrestrial ecosystems and their response to multiple stresses. And for the atmosphere, a central question has been, is, and likely will be the role of clouds. Also, there is a corresponding non-linearity associated with change in the distribution and extent of sea ice. Further increased efforts will be needed in linking terrestrial ecosystems with the atmosphere, the land with the ocean, the ocean (and its ecosystems) with the atmosphere, the chemistry of the atmosphere with the physics of the atmosphere, and finally linking the human system to them all. Such models will also need to be able to highlight different regions with increased spatial and temporal detail.

Models, however, depend upon high quality data. Data allow hypotheses about processes and their linkages to be rejected or to be given increased consideration. Giving formal (e.g., quantitative) expression to processes is at the heart of the scientific enterprise. Such expressions reflect our knowledge and form the basis for models. Models are simply formal expressions of processes and how they fit together. And all rest upon data. Models are of limited use without observations; the value of observations increases by interaction with models. Systematic global observations are an essential underpinning of research to improve understanding of the climate system. For numerous applications in climate-impact research, information about the complex nature of the system is needed. Unfortunately, there continue to be justifiable concerns about the loss of some monitoring of climate parameters and deterioration of coverage. There is a basic need for more observations with better coverage, higher accuracy, and with increased availability. This overriding importance of data has been recognised repeatedly in the past and in this volume (e.g., Chapter 2, Section 2.8; Chapter 3, Section 3.5; Chapter 4, Section 4.2; Chapter 6, Section 6.14; Chapter 11, Section 11.6.1 and Chapter 12, Section 12.4), and there are reasons for guarded optimism on the issue of data even though there are also significant reasons for concern. One such reason for tempered optimism is the plan for and beginning implementation of global observing systems such as the Global Climate Observing System (GCOS), Global Ocean Observing System (GOOS), and Global Terrestrial Observing System (GTOS). However plans in themselves do not produce data, and data that are not accessible are of limited value. The issue of data remains central for progress.

14.2.2 Predictability in a Chaotic System

The climate system is particularly challenging since it is known that components in the system are inherently chaotic; there are feedbacks that could potentially switch sign, and there are central processes that affect the system in a complicated, non-linear manner. These complex, chaotic, non-linear dynamics are an inherent aspect of the climate system. As the IPCC WGI Second Assessment Report (IPCC, 1996) (hereafter SAR) has previously noted, "future unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve 'surprises'. In particular, these arise from the non-linear, chaotic nature of the climate system … Progress can be made by investigating non-linear processes and sub-components of the climatic system." These thoughts are expanded upon in this report: "Reducing uncertainty in climate projections also requires a better understanding of these non-linear processes which give rise to thresholds that are present in the climate system. Observations, palaeoclimatic data, and models suggest that such thresholds exist and that transitions have occurred in the past … Comprehensive climate models in conjunction with sustained observational systems, both *in situ* and remote, are the only tool to decide whether the evolving climate system is approaching such thresholds. Our knowledge about the processes, and feedback mechanisms determining them, must be significantly improved in order to extract early signs of such changes from model simulations and observations." (See Chapter 7, Section 7.7).

14.2.2.1 Initialisation and flux adjustments

Integrations of models over long time-spans are prone to error as small discrepancies from reality compound. Models, by definition, are reduced descriptions of reality and hence incomplete and with error. Missing pieces and small errors can pose difficulties when models of sub-systems such as the ocean and the atmosphere are coupled. As noted in Chapter 8, Section 8.4.2, at the time of the SAR most coupled models had difficulty in reproducing a stable climate with current atmospheric concentrations of greenhouse gases, and therefore non-physical "flux adjustment terms" were added. In the past few years significant progress has been achieved, but difficulties posed by the problem of flux adjustment, while reduced, remain problematic and continued investigations are needed to reach the objective of avoiding dependence on flux adjustment (see Chapter 8, Section 8.4.2; see also Section 8.5.1.1).

Another important (and related) challenge is the initialisation of the models so that the entire system is in balance, i.e., in statistical equilibrium with respect to the fluxes of heat, water, and momentum between the various components of the system. The problem of determining appropriate initial conditions in which fluxes are dynamically and thermodynamically balanced throughout a coupled stiff system, such as the ocean-atmosphere system, is particularly difficult because of the wide range of adjustment times ranging from days to thousands of years. This can lead to a "climate drift", making interpretation of transient climate calculations difficult (see Chapter 8, Section 8.4.1).

The initialisation of coupled models is important because it produces the climate base state or "starting point" for climate change experiments. Climate model initialisation continues to be an area of active research and refinement of techniques (see Chapter 8, Section 8.4). Most groups use long integrations of the sub-component models to provide a dynamically and thermodynamically balanced initial state for the coupled model integration. However, there are at least as many different methods used to initialise coupled models as there are modelling groups. See Stouffer and Dixon (1998) for a more complete discussion of the various issues and methods used to initialise coupled models.

Since the SAR, improvements in developing better initialisation techniques for coupled models have been realised. For instance, starting with observed oceanic conditions has yielded improved simulations with reduced climate drift (Gordon *et al.*, 1999). Earlier attempts with this technique usually resulted in relatively large trends in the surface variables (Meehl and Washington, 1995; Washington and Meehl, 1996). Successfully starting long coupled integrations from observations is important for a number of reasons: it simplifies the initialisation procedure, saves time and effort, and reduces the overhead for starting new coupled model integrations.

Such progress is important, but again further work is needed. We simply do not fully understand the causes of climate drift in coupled models (see Chapter 8, Section 8.4.2).

14.2.2.2 Balancing the need for finer scales and the need for ensembles

There is a natural tendency to produce models at finer spatial scales that include both a wider array of processes and more refined descriptions. Higher resolution can lead to better simulations of atmospheric dynamics and hydrology (Chapter 8, Section 8.9.1), less diffusive oceanic simulations, and improved representation of topography. In the atmosphere, fine-scale topography is particularly important for resolving small-scale precipitation patterns (see Chapter 8, Section 8.9.1). In the ocean, bottom topography is very important for the various boundary flows (see Chapter 7, Section 7.3.4). The use of higher oceanic resolution also improves the simulation of internal variability such as ENSO (see Chapter 8, Section 8.7.1). However, in spite of the use of higher resolution, important climatic processes are still not resolved by the model's grid, necessitating the continued use of sub-grid scale parametrizations.

It is anticipated that the grids used in the ocean subcomponents of the coupled climate models will begin to resolve eddies by the next report. As the oceanic eddies become resolved by the grid, the need for large diffusion coefficients and various mixing schemes should be reduced (see Chapter 8, Section 8.9.3; see also, however, the discussion in Section 8.9.2). In addition, the amount of diapycnal mixing, which is used for numerical stability in this class of ocean models, will also be reduced as the grid spacing becomes smaller. This reduction in the sub-grid scale oceanic mixing should reduce the uncertainty associated with the mixing schemes and coefficients currently being used.

Underlying this issue of scale and detail is an important tension. As the spatial and process detail in a model is increased, the required computing resources increase, often significantly; models with less detail may miss important non-linear dynamics and feedbacks that affect model results significantly, and yet simpler models may be more appropriate to generating the needed statistics. The issue of spatial detail is intertwined with the representation of the physical (and other) processes, and hence the need for a balance between level of process detail and spatial detail. These tensions must be recognised forthrightly, and strategies must be devised to use the available computing resources wisely. Analyses to determine the benefits of finer scale and increased resolution need to be carefully considered. These considerations must also recognise that the potential predictive capability will be unavoidably statistical, and hence it must be produced with statistically relevant information. This implies that a variety of integrations (and models) must be used to produce an ensemble of climate states. Climate states are defined in terms of averages and statistical quantities applying over a period typically of decades (see Chapter 7, Section 7.1.3 and Chapter 9, Section 9.2.2).

Fortunately, many groups have performed ensemble integrations, that is, multiple integrations with a single model using identical radiative forcing scenarios but different initial conditions. Ensemble integrations yield estimates of the variability of the response for a given model. They are also useful in determining to what extent the initial conditions affect the magnitude and pattern of the response. Furthermore, many groups have now performed model integrations using similar radiative forcings. This allows ensembles of model results to be constructed (see Chapter 9, Section 9.3; see also the end of Chapter 7, Section 7.1.3 for an interesting question about ensemble formation).

In sum, a strategy must recognise what is possible. In climate research and modelling, we should recognise that we are dealing with a coupled non-linear chaotic system, and therefore that the long-term prediction of future climate states is not possible. The most we can expect to achieve is the prediction of the probability distribution of the system's future possible states by the generation of ensembles of model solutions. This reduces climate change to the discernment of significant differences in the statistics of such ensembles. The generation of such model ensembles will require the dedication of greatly increased computer resources and the application of new methods of model diagnosis. Addressing adequately the statistical nature of climate is computationally intensive, but such statistical information is essential.

14.2.2.3 Extreme events

Extreme events are, almost by definition, of particular importance to human society. Consequently, the importance of understanding potential extreme events is first order. The evidence is mixed, and data continue to be lacking to make conclusive cases. Chapter 9, Sections 9.3.5 and 9.3.6 consider projections of changes in patterns of variability (discussed in the next section) and changes in extreme events (see also Chapters 2 and 10). Though the conclusions are mixed in both of these topical areas, certain results begin to appear robust. There appear to be some consistent patterns with increased CO_2 with respect to changes in variability: (a) the Pacific climate base state could be a more El Niño-like state and (b) an enhanced variability in the daily precipitation in the Asian summer monsoon with increased precipitation intensity (Chapter 9, Section 9.3.5). More generally, the intensification of the hydrological cycle with increased CO_2 is a robust conclusion. For possible changes in extreme weather and climate events, the most robust conclusions appear to be: (a) an increased probability of extreme warm days and decreased probability of extreme cold days and (b) an increased chance of drought for mid-continental areas during summer with increasing CO_2 (see Chapter 9, Section 9.3.6).

The evaluation of many types of extreme events is made difficult because of issues of scale. Damaging extreme events are often at small temporal and spatial scales. Intense, short-duration events are not well-represented (or not represented at all) in model-simulated climates. In addition, there is often a basic mismatch between the scales resolved in models and those of the validating data. A promising approach is to use multi-fractal models of rainfall events in that they naturally generate extreme events. Reanalysis has also helped in this regard, but reanalysis *per se* is not the sole answer because the models used for reanalysis rely on sub-grid scale parametrizations almost as heavily as climate models do.

One area that is possibly ripe for a direct attack on improving the modelling of extreme events is tropical cyclones (see Section Chapter 2, 2.7.3.1; Chapter 8, Section 8.8.4; Chapter 9, Section 9.3.6.4, and Chapter 10, Box 10.2). Also, there is the potential for increased understanding of extreme events by employing regional climate models (RCMs); however, there are also challenges to realising this potential (see Chapter 10). It must be established that RCMs produce more realistic extremes than general circulation models (GCMs). Most RCM simulations to date are not long enough (typically 5 or 10 years for nested climate change simulations) to evaluate extremes well (see Chapter 10, Section 10.5.2).

Another area in which developments are needed is that of extremes associated with the land surface (flood and drought). There is still a mismatch between the scale of climate models and the finer scales appropriate for surface hydrology. This is particularly problematical for impact studies. For droughts there is a basic issue of predictability; drought prediction is difficult regardless of scale.

A particularly important issue is the adequacy of data needed to attack the question of changes in extreme events. There have been recent advances in our understanding of extremes in simulated climates (see, for example, Meehl *et al*., 2000), but thus far the approach has not been very systematic. Atmospheric Model Intercomparison Project 2 (AMIP2) provides an opportunity for a more systematic approach: AMIP2 will be collecting and organising some of the high-frequency data that are needed to study extremes. However, it must be recognised that we are still unfortunately short of data for the quantitative assessment of extremes on the global scale in the observed climate.

Finally, it is often stated that the impacts of climate change will be felt through changes in extremes because they stress our present day adaptations to climate variability. What does this imply for the research agenda for the human dimension side of climate studies?

14.2.2.4 Organised variability

An overriding challenge to modelling and to the IPCC is prediction. This challenge is particularly acute when predictive capability is sought for a system that is chaotic, that has significant non-linearities, and that is inherently stiff (i.e., widely varying time constants). And within prognostic investigations of such a complex system, the issue of predicting extreme events presents a particularly vexing yet important problem. However, there appear to be coherent modes of behaviour that not only support a sense of optimism in attacking the prediction problem, but also these modes may offer measurable prediction targets that can be used as benchmarks for evaluating our understanding of the climate system. In addition, predictions of these modes represent valuable contributions in themselves.

Evaluating the prognostic skill of a model and understanding the characteristics of this skill are clearly important objectives. In the case of weather prediction, one can estimate the range of predictability by evaluating the change of the system from groups of initial states that are close to each other. The differences in these time-evolving states give a measure of the predictive utility of the model. In addition, one has the near-term reality of the evolving weather as a constant source of performance metrics. For the climate issue, the question of predictability is wrapped up with understanding the physics behind the low-frequency variability of climate and distinguishing the signal of climate change (see Chapter 9, Section 9.2.2.1). In other words, there are the paired challenges of capturing (predicting) “natural” variability of climate as well as the emerging anthropogenically forced climate signal. This dual challenge is distinctively climatic in nature, and whereas the longer-term character of climate projections is unavoidable and problematic, the intra-seasonal to inter-decadal modes of climate variability (e.g., ENSO, Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO) – see also Chapter 7, Box 7.2) offer opportunities to test prognostic climate skill. Here, some predictive skill for the climate system appears to exist on longer time-scales. One example is the ocean-atmosphere phenomenon of ENSO. This skill has been advanced and more clearly demonstrated since the SAR, and this progress and demonstration are important (see Chapter 7, Section 7.6; Chapter 8, Section 8.7 and Chapter 9, Section 9.3.5). Such demonstrations and the insights gained in developing and making prognostic statements on climate modes frame an important area for further work.

This opportunity is well summarised in Chapter 8 (in particular, Section 8.7), “The atmosphere-ocean coupled system shows various modes of variability that range widely from intra-seasonal to inter-decadal time-scales (see Chapters 2 and 7). Since the SAR, considerable progress has been achieved in characterising the decadal to inter-decadal variability of the ocean-atmosphere system. Successful evaluation of models over a wide range of phenomena increases our confidence.”

14.2.3 Key Sub-systems and Phenomena in the Physical-Climate System

Central to the climate system are the coupled dynamics of the atmosphere-ocean-terrestrial system, the physical processes associated with the energy and water cycles and the associated biological and chemical processes controlling the biogeochemical cycles, particularly carbon, nitrogen, phosphorus, sulphur, iron, and silicon. The atmosphere plays a unique role in the climate system since on a zeroth order basis it sets the radiative forcing. Specific sub-systems that are important and yet still poorly understood are clouds and sea ice; the thermohaline ocean circulation is a fundamentally important phenomenon that needs to be known better, and underlying these sub-systems and phenomena are the still ill-understood non-linear processes of advection (large-scale) and convection (small-scale) of dynamical and thermodynamical oceanic and atmospheric quantities. These sub-systems, phenomena, and processes are important and merit increased attention to improve prognostic capabilities generally.

14.2.3.1 Clouds

The role of clouds in the climate system continues to challenge the modelling of climate (e.g., Chapter 7, Section 7.2.2). It is generally accepted that the net effect of clouds on the radiative balance of the planet is negative and has an average magnitude of about 10 to 20 Wm^{-2}. This balance consists of a short-wave cooling (the albedo effect) of about 40 to 50 Wm^{-2} and a long-wave warming of about 30 Wm^{-2}. Unfortunately, the size of the uncertainties in this budget is large when compared to the expected anthropogenic greenhouse forcing. Although we know that the overall net effect of clouds on the radiative balance is slightly negative, we do not know the sign of cloud feedback with respect to the increase of greenhouse gases, and it may vary with the region. In fact, the basic issue of the nature of the future cloud feedback is not clear. Will it remain negative? If the planet warms, then it is plausible that evaporation will increase, which probably implies that liquid water content will increase but the volume of clouds may not. What will be the effect and how will the effects be distributed in time and space? Finally, the issue of cloud feedbacks is also coupled to the very difficult issue of indirect aerosol forcing (see Chapter 5, Section 5.3).

The importance of clouds was summarised in the SAR: "The single largest uncertainty in determining the climate sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation and their role in the hydrological cycle" (Kattenberg *et al.*, 1996, p.345). And yet, the single greatest source of uncertainty in the estimates of the climate sensitivity continues to be clouds (see also Chapter 7, Section 7.2). Since the SAR, there have been a number of improvements in the simulation of both the cloud distribution and in the radiative properties of clouds (Chapter 7, Section 7.2.2). The simulation of cloud distribution has improved as the overall simulation of the atmospheric models has improved. In addition, the cloud subcomponent models used in the coupled models have become more realistic. Also, our understanding of the radiative properties of clouds and their effects on climate sensitivity have improved. And yet in Chapter 7, Section 7.2.2 we find that, "In spite of these improvements, there has been no apparent narrowing of the uncertainty range associated with cloud feedbacks in current climate change simulations."

Handling the physics and/or the parametrization of clouds in climate models remains a central difficulty. There is a need for increased observations. J. Mitchell highlighted the challenge in a recent paper at the World Climate Research Programme (WCRP) Workshop on Cloud Properties and Cloud Feedbacks in Large-scale Models where he stated that "Reducing the uncertainty in cloud-climate feedbacks is one of the toughest challenges facing atmospheric physicists" (Mitchell, 2000).

Cloud modelling is a particularly challenging scientific problem because it involves processes covering a very wide range of space- and time-scales. For example, cloud systems extending over thousands of kilometres to cloud droplets and aerosols of microscopic size are all important components of the climate system. The time-scales of interest can range from hundreds of years (e.g., future equilibrium climates) to fractions of a second (e.g., droplet collisions). This is not to say that all cloud microphysics must be included in modelling cloud formation and cloud properties, but the demarcation between what must be included and what can be parametrized remains unclear. Clarifying this demarcation and improving both the resulting phenomenological characterisations and parametrizations will depend critically on improved global observations of clouds (see Chapter 2, Section 2.5.5; see also Senior, 1999). Of particular importance are observations of cloud structure and distribution against natural patterns of climate variability (e.g., ENSO). Complementing the broad climatologies will be important observations of cloud ice-water and liquid-water content, radiative heating and optical depth profiles, and precipitation occurrence and cloud geometry.

The recently approved CloudSat and PICASSO missions, which will fly in formation with the National Aeronautics and Space Administration (USA) (NASA) Earth Observing System (EOS) PM (the Aqua Mission), will provide valuable profiles of cloud ice and liquid content, optical depth, cloud type, and aerosol properties. These observations, combined with wider swath radiometric data from EOS PM sensors, will provide a rich new source of information about the properties of clouds (Stephens *et al.*, 2000).

And yet, this question of cloud feedback remains open, and it is not clear how it will be answered. Given that the current generation of global climate models represents the Earth in terms of grid-points spaced roughly 200 km apart, many features observed on smaller scales, such as individual cloud systems and cloud geometry, are not explicitly resolved. Without question, the strategy for attacking the feedback question will involve comparison of model simulations with appropriate observations on global or local scales. The interplay of observation and models, again, will be the key for progress. Mitchell (Mitchell, 2000) states this clearly, "Unless there are stronger links between those making observations and those using climate models, then there is little chance of a reduction in the uncertainty in cloud feedback in the next twenty years." This is echoed in this report (see Chapter 7, Section 7.2.2), "A straightforward approach of model validation is not sufficient to constrain efficiently the models and a more dedicated approach is needed. It should be favoured by a larger availability of satellite measurements."

14.2.3.2 Thermohaline circulation

In the oceanic component of climate models, ocean current patterns are represented significantly better in models of higher resolution in large part because ocean current systems (including mesoscale eddies), ocean variability (including ENSO events), and the thermohaline circulation (and other vertical mixing processes) and topography which greatly influence the ocean circulation, can be better represented. Improved resolution and understanding of the important facets of coupling in both atmosphere and ocean components of global climate models have also been proven to reduce flux imbalance problems arising in the coupling of the oceanic and the atmospheric components. However, it must still be noted that uncertainties associated with clouds still cause problems in the computation of surface fluxes. With the availability of computer power, a central impediment to the gain in model accuracy is being reduced; however, there is still a long way to go before many of the important processes are explicitly resolved by the numerical grid. In addition there continues to be a necessary "concomitant" increase in resources for process studies and for diagnosis as computer power increases. It must still be remembered that the system presents chaotic characteristics that can only be evaluated through an analysis of ensembles statistics, and these ensembles must be generated by running suites of models under varied initial and forcing conditions.

In a few model calculations, a large rate of increase in the radiative forcing of the planet is enough to cause the ocean's global thermohaline circulation almost to disappear, though in some experiments it reappears given sufficiently long integration times (see Chapter 7, Section 7.3.7 and Chapter 9, 9.3.4.3). This circulation is important because in the present climate it is responsible for a large portion of the heat transport from the tropics to higher latitudes, and it plays an important role in the oceanic uptake of CO_2. Palaeo-oceanographic investigations suggest that aspects of longer-term climate change are associated with changes in the ocean's thermohaline circulation. We need appropriate observations of the thermohaline circulation, and its natural variations, to compare with model simulations (see Chapter 9, Section 9.3.4.3; see also Chapter 7, Section 7.6 and Chapter 8, Section 8.5.2.2).

The coming decade will be important for ocean circulation in the context of climate. A particularly exciting development is the potential for assimilating synoptic ocean observations (e.g., the US/French ocean TOPography satellite altimeter EXperiment (TOPEX-POSEIDON) and Argo) into ocean general circulation models. Key questions, such as how well do the ocean models capture the inferred heat flux or tracer distributions, are central to the use of these models in climate studies. The effort of comparing models with data, as the direct path for model rejection and model improvement, is central to increasing our understanding of the system.

14.2.3.3 Arctic sea ice

There is increasing evidence that there is a decline in the extent and thickness of Arctic sea ice in the summer that appears to be connected with the observed recent Arctic warming (see Chapter 2, Section 2.2.5.2; Chapter 7, Box 7.1, and Chapter 8, Section 8.5.3; see also Chapter 7, Section 7.5.2 for a general discussion on the role of sea ice in the climate system as well as recent advances in modelling sea ice).

It is not known whether these changes reflect anthropogenic warming transmitted either from the atmosphere or the ocean or whether they mostly reflect a major mode of multi-decadal variability. Some of this pattern of warming has been attributed to recent trends in the Arctic Oscillation (see Section 2.6); however, how the anthropogenic signal is imprinted on the natural patterns of climate variability remains a central question. What does seem clear is that the changes in Arctic sea ice are significant, and there is a positive feedback that could be triggered by declines in sea-ice extent through changes in the planetary albedo. If the Arctic shifted from being a bright summer object to a less bright summer object, then this would be an important positive feedback on a warming pattern (see the "left loop" in Chapter 7, Figure 7.6).

In addition to these recently available observations, there have been several models (Commonwealth Scientific and Industrial Research Organisation (Australia) (CSIRO) – Gordon and O'Farrell, 1997; Department of Energy (USA) Parallel Climate Model (DOE PCM) – Washington *et al*., 2000; National Center for Atmospheric Research (USA) Climate System Model (NCAR CSM) – Weatherly *et al.*, 1998; see also Chapter 7, Section 7.5.2 and Chapter 8, Section 8.5.3) that have improved their sea ice representation since the SAR. These improvements include simulation of open water within the ice pack, snow cover upon the ice, and sea ice dynamics. The incorporation of sophisticated sea ice components in climate models provides a framework for testing and calibrating these models with observations. Further, as the formulation of sea ice dynamics becomes more realistic, the validity of spatial patterns of the simulated wind stress over the polar oceans is becoming an issue in Atmosphere-Ocean General Circulation Model (AOGCM) simulations. Hence, improvements, such as the above-mentioned data, in the observational database will become increasingly relevant to climate model development. In addition, satellite observations have recently been used to determine sea-ice velocity (Emery *et al.*, 1997) and melt season (Smith, 1998).

New field programmes are under way with the explicit goal of improving the accuracy of model simulations of sea ice and polar climate (see Randall *et al.*, 1998, for a review). In order to improve model representations and validation, it will be essential to enhance the observations over the Arctic including ocean, atmosphere, and sea ice state variables. This will help provide more reliable projections for a region of the world where significant changes are expected.

The refinement of sea-ice models along with enhanced observations reduces the uncertainty associated with ice processes. (See Chapter 7, Section 7.5 and Chapter 8, Section 8.5.3 for more discussion and evaluation of model performance; for some open issues see Chapter 9, Section 9.4.) This progress is important, and efforts are needed to expand upon it and, as stated, to improve the observational basis significantly.

14.2.4 The Global Carbon Cycle

From measurements of air trapped in ice cores and from direct measurements of the atmosphere, we know that in the past 200 years the abundance of CO_2 in the atmosphere has increased by over 30% (i.e., from a concentration of 280 ppm by volume (pppmv) in 1700 to nearly 370 ppmv in 2000). We also know that the concentration was relatively constant (roughly within ±10 ppmv of 275) for more than 1,000 years prior to the human-induced rapid increase in atmospheric CO_2 (see Chapter 3, Figures 3.2a and 3.2b).

Looking further back in time, we find an extraordinarily regular record of change. The Vostok core (Figure 3.2d) captures a remarkable and intriguing signal of the periodicity of inter-glacial and glacial climate periods in step with the transfer of significant pools of carbon from the land (most likely through the atmosphere) to the ocean and then the recovery of terrestrial carbon back from the ocean. The repeated pattern of a 100 to 120 ppmv decline in atmospheric CO_2 from an inter-glacial value of 280 to 300 ppmv to a 180 ppmv floor and then the rapid recovery as the planet exits glaciation suggests a tightly governed control system. There is a similar methane (CH_4) cycle between 320 to 350 ppbv (parts per billion by volume) and 650 to 770 ppbv. What begs explanation is not just the linked periodicity of carbon and glaciation, but also the apparent consistent limits on the cycles over the period. See Chapter 3, Box 3.4.

Today's atmosphere, imprinted with the fossil fuel CO_2 signal, stands at nearly 90 to 70 ppmv above the previous inter-glacial maximum of 280 to 300 ppmv. The current methane value is even further (percentage-wise) from its previous inter-glacial high values. In essence, carbon has been moved from a relatively immobile pool (in fossil fuel reserves) in the slow carbon cycle to the relatively mobile pool (the atmosphere) in the fast carbon cycle, and the ocean, terrestrial vegetation and soils have yet to equilibrate with this “rapidly” changing concentration of CO_2 in the atmosphere.

Given this remarkable and unprecedented history one cannot help but wonder about the characteristics of the carbon cycle in the future (Chapter 3). To understand better the global carbon cycle, two themes are clear: (1) there is a need for global observations that can contribute significantly to determining the sources and sinks of carbon and (2) there is a need for fundamental work on critical biological processes and their interaction with the physical system. Two observational needs must be highlighted:

- Observations that would decisively improve our ability to model the carbon cycle. For example, a dense and well-calibrated network for monitoring CO_2 and O_2 concentrations that will also be required for international verification of carbon sources and sinks is central.

- “Benchmarks” data sets that allow model intercomparison activities to move in the direction of becoming data-model comparisons and not just model-model comparisons.

We note that the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the United Nations Framework Convention on Climate Change (UNFCCC) recognised the importance of an Integrated Global Observing Strategy Partnership in developing observing systems for the oceans and terrestrial carbon sources and sinks in the global carbon cycle and in promoting systematic observations.

There is also a range of areas where present day biogeochemistry modelling is not only in need of additional data, but is also crucially limited by insufficient understanding at the level of physical or biological processes. Clarifying these processes and their controls is central to a better understanding of the global carbon cycle.

14.2.4.1 The marine carbon system

The marine carbon cycle plays an important role in the partitioning of CO_2 between the atmosphere and the ocean (Chapter 3, Section 3.2.3). The primary controls are the circulation of the ocean (a function of the climate system), and two important biogeochemical processes: the solubility pump and the biological pump, both of which act to create a global mean increase of dissolved inorganic carbon with depth.

The physical circulation and the interplay of the circulation and the biogeochemical processes are central to understanding the ocean carbon system and future concentrations of CO_2 in the atmosphere. In the ocean, the prevailing focus on surface conditions and heat transport has led to a comparative neglect of transport processes below about 800 m depth. For carbon cycle modelling, however, vertical transports and deep horizontal transports assume fundamental importance. The importance of the thermohaline circulation is obviously important (and insufficiently well understood; see Section 14.2.3.2) in moving carbon from the surface to deeper layers. Similarly, the regional distribution of upwelling, which brings carbon- and nutrient-rich water to surface layers, is poorly known and inconsistently simulated in models. The ventilation of the Southern Ocean provides an extreme, though not unique, example.

It has been pointed out by a number of modelling studies that if there were no marine biological system, then the pre-industrial atmospheric CO_2 concentration would have been 450 ppmv instead of 280 ppmv (Sarmiento and Toggweiler 1984; Maier-Raimer *et al*., 1996). Any complete model of the natural ocean carbon cycle should therefore include the biological system; however, most recent assessments of the oceanic uptake of anthropogenic CO_2 have assumed that the biological system would not be affected by climate change and have therefore only modelled the chemical solubility in addition to the physical circulation. This was based on the understanding that nitrate or other nutrients limit marine phytoplankton growth. There would therefore be no CO_2 fertilisation effect as has been suggested for terrestrial plants and that, unless there was a large change in the nutrient supply to the upper ocean because of a climate-induced shift in circulation, then no extra anthropogenic CO_2 could be sequestered to the deep ocean by the organic matter pump. More recently, a number of studies have suggested possible ways in which the organic matter pump might be affected by climate change over a 200-year time-scale (see Chapter 3, Sections 3.2.3.2 and 3.2.3.3). The main conclusion was that, because of the complexity of biological systems, it was not yet possible to say whether some of the likely feedbacks would be positive or negative. However, it is clear that our understanding of these issues needs to be improved.

Simulating the calcium carbonate system with a process-oriented model presents another level of complexity beyond simulating the organic matter formation-decomposition: the distribution of particular phytoplankton species (mainly coccolithophorids) must be simulated. The calcium carbonate pump, however, contributes relatively little to the vertical dissolved inorganic carbon (DIC) gradient compared to the organic matter and solubility pumps. The importance of this pump needs careful evaluation and its past (palaeo) role in the carbon cycle needs to be considered (see end of Chapter 3, Section 3.2.3.3).

In the ocean, models incorporating biology are relatively underdeveloped and incorporate empirical assumptions (such as fixed Redfield (nutrient) ratios) rather than explicitly modelling the underlying processes. As a result, present models may be unduly constrained in the range of responses they can show to changes in climate and ocean dynamics. A better understanding is required concerning the workings of nutrient constraints on productivity, the controls of nitrogen fixation, and the controls on the geographical distribution of biogeochemically important species and functional types in the ocean. To develop this understanding it will be necessary to combine remotely sensed information with a greatly expanded network of continuous biogeochemical monitoring sites, and to gather data on the space-time patterns of variability in species composition of marine ecosystems in relation to climate variability phenomena such as ENSO and NAO. (See Chapter 3, Sections 3.6.3 and 3.7).

14.2.4.2 The terrestrial system

The metabolic processes that are responsible for plant growth and maintenance and the microbial turnover, which is associated with dead organic matter decomposition, control the cycle of carbon, nutrients, and water through plants and soil on both rapid and intermediate time-scales. Moreover, these cycles affect the energy balance and provide key controls over biogenic trace gas production. Looking at the carbon fixation-organic material decomposition as a linked process, one sees that some of the carbon fixed by photosynthesis and incorporated into plant tissue is perhaps delayed from returning to the atmosphere until it is oxidised by decomposition or fire. This slower carbon loop through the terrestrial component of the carbon cycle affects the rate of growth of atmospheric CO_2 concentration and, in its shorter term expression, imposes a seasonal cycle on that trend (Chapter 3, Figure 3.2a). The structure of terrestrial ecosystems, which respond on even longer time-scales, is determined by the integrated response to changes in climate and to the intermediate time-scale carbon-nutrient machinery. The loop is closed back to the climate system, since it is the structure of ecosystems, including species composition, that largely sets the terrestrial boundary condition of the climate in terms of surface roughness, albedo, and latent heat exchange (see Chapter 3, Section 3.2.2).

Modelling interactions between terrestrial and atmospheric systems requires coupling successional models to biogeochemical models and physiological models that describe the exchange of water and energy between vegetation and the atmosphere at fine time-scales. At each step toward longer time-scales, the climate system integrates the more fine-scaled processes and applies feedbacks onto the terrestrial biome. At the finest time-scales, the influence of temperature, radiation, humidity and winds has a dramatic effect on the ability of plants to transpire. On longer time-scales, integrated weather patterns regulate biological processes such as the timing of leaf emergence or excision, uptake of nitrogen by autotrophs, and rates of organic soil decay and turnover of inorganic nitrogen. The effect of climate at the annual or interannual scale defines the net gain or loss of carbon by the biota, its water status for the subsequent growing season, and even its ability to survive.

As the temporal scale is extended, the development of dynamic vegetation models, which respond to climate and human land use as well as other changes, is a central issue. These models must not only treat successional dynamics, but also ecosystem redistribution. The recovery of natural vegetation in abandoned areas depends upon the intensity and length of the agricultural activity and the amount of soil organic matter on the site at the time of abandonment. To simulate the biogeochemistry of secondary vegetation, models must capture patterns of plant growth during secondary succession. These patterns depend substantially on the nutrient pools inherited from the previous stage. The changes in hydrology need also to be considered, since plants that experience water stress will alter the allocation of carbon to allocate more carbon to roots. Processes such as reproduction, establishment, and light competition have been added to such models, interactively with the carbon, nitrogen, and water cycles. Disturbance regimes such as fire are also incorporated into the models, and these disturbances are essential in order to treat successfully competitive dynamics and hence future patterns of ecosystem. It should be noted also that these forcing terms themselves might be altered by the changes that result from changes in the terrestrial system.

This coupling across time-scales represents a significant challenge. Immediate challenges that confront models of the terrestrial-atmosphere system include exchanges of carbon and water between the atmosphere and land, and the terrestrial sources and sinks of trace gases.

Prognostic models of terrestrial carbon cycle and terrestrial ecosystem processes are central for any consideration of the effects of environmental change and analysis of mitigation strategies; moreover, these demands will become even more significant as countries begin to adopt carbon emission targets. At present, several rather complex models are being developed to account for the ecophysiological and biophysical processes, which determine the spatial and temporal features of primary production and respiration (see Chapter 3, Sections 3.6.2 and 3.7.1). Despite recent progress in developing and evaluating terrestrial biosphere models, several crucial questions remain open. For example, current models are highly inconsistent in the way they treat the response of Net Primary Production (NPP) to climate variability and climate change – even though this response is fundamental to predictions of the total terrestrial carbon balance in a changing climate. Models also differ significantly in the degree of CO_2 fertilisation they allow, and the extent to which CO_2 responses are constrained by nutrient availability; the extent to which CO_2 concentrations affect the global distribution of C_3 and C_4 photosynthetic pathways; and the impacts of climate, CO_2 and land management on the tree-grass balance. These are all areas where modelling capability is limited by lack of knowledge, thus making it crucially important to expand observational and experimental research. Important areas are interannual variability in terrestrial fluxes and the interplay of warming, management, and CO_2 enrichment responses at the ecosystem scale. Moreover, these issues must be far better resolved if there is to be an adequate verification scheme to confirm national performance in meeting targets for CO_2 emissions. (See Chapter 3, Sections 3.6.2 and 3.7.1.)

Finally, while progress will be made on modelling terrestrial processes, more integrative studies are also needed wherein terrestrial systems are coupled with models of the physical atmosphere and eventually with the chemical atmosphere as well.

14.2.5 Precipitation, Soil Moisture, and River Flow: Elements of the Hydrological Cycle

Changes in precipitation could have significant impacts on society. Precipitation is an essential element in determining the availability of drinking water and the level of soil moisture. Improved treatment of precipitation (see Section Chapter 7, 7.2.3) is an essential step.

Soil moisture is a key component in the land surface schemes in climate models, since it is closely related to evapotranspiration and thus to the apportioning of sensible and latent heat fluxes. It is primary in the formation of runoff and hence river-flow. Further, soil moisture is an important determinant of ecosystem structure and therein a primary means by which climate regulates (and is partially regulated by) ecosystem distribution. Soil moisture is an important regulator of plant productivity and sustainability of natural ecosystems. In turn terrestrial ecosystems recycle water vapour at the land-surface/atmosphere boundary, exchange numerous important trace gases with the atmosphere, and transfer water and biogeochemical compounds to river systems (see also the discussion in Chapter 7, Section 7.4.3 and Chapter 8, Section 8.5.4). New efforts are needed in the development of models, which successfully represent the space-time dynamics interaction between soil, climate and vegetation. If water is a central controlling aspect, then the interaction necessarily passes all the way through the space-time dynamics of soil moisture. Finally, adequate soil moisture is an essential resource for human activity. Consequently, accurate prediction of soil moisture is crucial for simulation of the hydrological cycle, of soil and vegetation biochemistry, including the cycling of carbon and nutrients, and of ecosystem structure and distribution as well as climate.

River systems are linked to regional and continental-scale hydrology through interactions among precipitation, evapotranspiration, soil water, and runoff in terrestrial ecosystems. River systems, and more generally the entire global water cycle, control the movement of constituents over vast distances, from the continental land-masses to the world’s oceans and to the atmosphere. Rivers are also central features of human settlement and development.

It appears, however, that a significant level of variance exists among land models, associated with unresolved differences among parametrization details (particularly difficulties in the modelling of soil hydrology) and parameter sets. In fact, many of the changes in land-surface models since the SAR fall within this range of model diversity. It is not known to what extent these differences in land-surface response translate into differences in global climate sensitivity (see Chapter 8, Section 8.5.4.3) although the uncertainty associated with the land-surface response must be smaller than the uncertainty associated with clouds (Lofgren, 1995). There is model-based evidence indicating that these differences in the land-surface response may be significant for the simulation of the local land-surface climate and regional atmospheric climate changes (see Chapter 7, Section 7.4).

Much attention in the land-surface modelling community has been directed toward the diversity of parametrizations of water and energy fluxes (see Chapter 7, Sections 7.4, 7.5, and Chapter 8, Section 8.5). Intercomparison experiments (see Chapter 8, Section 8.5.4) have quantified the inter-model differences in response to prescribed atmospheric forcing, and have demonstrated that the most significant outliers can be understood in terms of unrealistic physical approximations in their formulation, particularly the neglect of stomatal resistance. Some coupled models now employ some form of stomatal resistance to evaporation.

Climate-induced changes in vegetation have potentially large climatic implications, but are still generally neglected in the coupled-model experiments used to estimate future changes in climate (see Chapter 8).

There is, obviously, a direct coupling between predicted soil moisture and predicted river flows and the availability of water for human use. Complex patterns of locally generated runoff are transformed into horizontal transport as rivers through the drainage basin. Moreover, any global perspective on surface hydrology must explicitly recognise the impact of human intervention in the water cycle, not only through climate and land-use change, but also through the operation of impoundments, inter-basin transfers, and consumptive use.

Recognition of the importance of land hydrology for the salinity distribution of the oceans is one reason for seeking improvements in models for routing runoff to the oceans (see more precise cites here and in Chapter 7). Most coupled models now return land runoff to the ocean as fresh water (see Chapter 8). Runoff is collected over geographically realistic river basins and mixed into the ocean at the appropriate river mouths. Although this routing is performed instantaneously in some models, the trend is toward model representation of the significant time-lag (order of a month) in runoff production to river-ocean discharge. What is needed for a variety of reasons, however, is for river flow itself to be treated in models of the climate system. (See Chapter 7, Section 7.4.3.)

On land, surface processes have until very recently been treated summarily in Atmospheric General Circulation Models (AGCMs). The focus of evaluating AGCMs has been on large-scale dynamics and certain meteorological variables; far less so on the partitioning of sensible and latent heat flux, or the moisture content of the planetary boundary layer. When the goals of climate modelling are expanded to include terrestrial biosphere function, such aspects become of central importance as regulators of the interaction between the carbon and water cycles. Terrestrial flux and boundary-layer measurements represent a new, expanding and potentially hugely important resource for improving our understanding of these processes and their representation in models of the climate system. (See Chapter 7, Section 7.4.1.)

The spatial resolution of current global climate models, roughly 200 km, is too coarse to simulate the impact of global change on most individual river basins. To verify the transport models will require budgets of water and other biogeochemical constituents for large basins of the world. This requires ground-based meteorology in tandem with remotely sensed data for a series of variables, including information on precipitation, soils, land cover, surface radiation, status of the vegetative canopy, topography, floodplain extent, and inundation. Model results can be constrained by using a database of observed discharge and constituent fluxes at key locations within the drainage basins analysed. Climate time-series and monthly discharge data for the past several decades at selected locations provide the opportunity for important tests of models, including appraisal of the impact of episodic events, such as El Niño, on surface water balance and river discharge. It will be necessary to inventory, document, and make available such data sets to identify gaps in our knowledge, and where it is necessary to collect additional data. Even in the best-represented regions of the globe coherent time-series are available for only the last 30 years or less. This lack of data constrains our ability to construct and test riverine flux models. Standardised protocols, in terms of sampling frequency, spatial distribution of sampling networks, and chemical analyses are needed to ensure the production of comparable data sets in disparate parts of the globe. Upgrades of the basic monitoring system for discharge and riverborne constituents at the large scale are therefore required.

In sum, hydrological processes and energy exchange, especially those involving clouds, surface exchanges, and interactions of these with radiation are crucial for further progress in modelling the atmosphere. Feedbacks with land require careful attention to the treatments of evapotranspiration, soil moisture storage, and runoff. All of these occur on spatial scales which are fine compared with the model meshes, so the question of scaling must be addressed. These improvements must be paralleled by the acquisition of global data sets for validation of these treatments. Validation of models against global and regional requirements for conservation of energy is especially important in this regard. As noted in Chapter 8 (Section 8.5.4.3), "Uncertainty in land surface processes, coupled with uncertainty in parameter data combines, at this time, to limit the confidence we have in the simulated regional impacts of increasing CO_2."

14.2.6 Trace Gases, Aerosols, and the Climate System

The goal is a completely interactive simulation of the dynamical, radiative, and chemical processes in the atmosphere-ocean-land system with a central theme of characterising adequately the radiative forcing in the past, in the present, and into the future (See Chapter 6, Sections 6.1 and 6.2; see also Chapter 9, Section 9.1). Such a model will be essential in future studies of the broad question on the role of the oceans, terrestrial ecosystems, and human activities in the regulation of atmospheric concentrations of CO_2 and other radiatively active atmospheric constituents. It will be required for understanding tropospheric trace constituents such as nitrogen oxides, ozone, and sulphate aerosols. Nitrogen oxides are believed to control the production and destruction of tropospheric ozone, which controls the chemical reactivity of the lower atmosphere and is itself a significant greenhouse gas. Tropospheric sulphate aerosols, carbonaceous aerosols from both natural and anthropogenic processes, dust, and sea salt, on the other hand, are believed to affect the Earth's radiation budget significantly, by scattering solar radiation and through their effects on clouds. Systematic observations of different terrestrial ecosystems and surface marine systems under variable meteorological conditions are needed along with the development of ecosystem and surface models that will provide parametrizations of these exchanges.

Models that incorporate atmospheric chemical processes provide the basis for much of our current understanding in such critical problem areas as acid rain, photochemical smog production in the troposphere, and depletion of the ozone layer in the stratosphere. These formidable problems require models that include chemical, dynamical, and radiative processes, which through their mutual interactions determine the circulation, thermal structure, and distribution of constituents in the atmosphere. That is, the problems require a coupling of the physics and chemistry of the atmosphere. Furthermore, the models must be applicable on a variety of spatial (regional-to-global) and temporal (days-to-decades) scales (see Chapter 6). A particularly important and challenging issue is the need to reduce the uncertainty on the size and spatial pattern of the indirect aerosol effects (see Chapter 6, Section 6.8).

Most of the effort in three-dimensional atmospheric chemistry models over the last decade has been in the use of transport models in the analysis of certain chemically active species, e.g., long-lived gases such as nitrous oxide (N_2O) or the chlorofluorocarbons (CFCs). In part, the purpose of these studies was not to improve our understanding of the chemistry of the atmosphere, but rather to improve the transport formulation associated with general circulation models and, in association with this improvement, to understand sources and sinks of CO_2. The additional burden imposed by incorporating detailed chemistry into a comprehensive general circulation model has made long-term simulations and transient experiments with existing computing resources challenging. Current three-dimensional atmospheric chemistry models which focus on the stratosphere seek a compromise solution by employing coarse resolution (both vertical and horizontal dimensions); incorporating constituents by families (similar to the practice used in most two-dimensional models); omitting or simplifying parametrizations for tropospheric physical processes; or conducting "off line" transport simulations in which previously calculated wind and temperature fields are used as known input to continuity equations including chemical source/sink terms. This last approach renders the problem tractable and has produced much progress towards understanding the transport of chemically reacting species in the atmosphere. The corresponding disadvantage is the lack of the interactive feedback between the evolving species distributions and the atmospheric circulation. Better descriptions of the complex relationship between hydrogen, nitrogen, and oxygen species as well as hydrocarbons and other organic species are needed in order to establish simplified chemical schemes that will be implemented in chemical/transport models. In parallel, better descriptions of how advection, turbulence, and convection affect the chemical composition of the atmosphere are needed. (See Chapter 4, Section 4.5.2.)

We also need improved understanding of the processes involving clouds, surface exchanges, and their interactions with radiation. The coupling of aerosols with both the energy and water cycles as well as with the chemistry components of the system is of increasing importance. Determining feedbacks between the land surface and other elements of the climate system will require careful attention to the treatments of evapotranspiration, soil moisture storage and runoff. All of these occur on spatial scales that are small compared with the model meshes, so the question of scaling must be addressed. These improvements must be paralleled by the acquisition of global data sets for validation of these treatments. Validation of models against global and regional requirements for conservation of energy is especially important in this regard. (See Chapter 4, Section 4.5.1.)

The problems associated with how to treat clouds within the climate system are linked to problems associated with aerosols. Current model treatments of climate forcing from aerosols predict effects that are not easily consistent with the past climate record. A major challenge is to develop and validate the treatments of the microphysics of clouds and their interactions with aerosols on the scale of a general circulation model grid. A second major challenge is to develop an understanding of the carbon components of the aerosol system. Meeting this challenge requires that we develop data for a mechanistic understanding of carbonaceous aerosol effects on clouds as well as developing an understanding of the magnitude of the anthropogenic and natural components of the carbonaceous aerosol system. (See Chapter 6, Sections 6.7 and 6.8; see also Chapter 4, Section 4.5.1.2.)

As attention is turned toward the troposphere, the experimental strategy simply cannot adopt the stratospheric simplifications. The uneven distribution of emission sources at the surface of the Earth and the role of meteorological processes at various scales must be addressed directly. Fine-scaled, three-dimensional models of chemically active trace gases in the troposphere are needed to resolve transport processes at the highest possible resolution. These models should be designed to simulate the chemistry and transport of atmospheric tracers on global and regional scales, with accurate parametrizations of sub-scale processes that affect the chemical composition of the troposphere. It is therefore necessary to pursue an ambitious long-term programme to develop comprehensive models of the troposphere system, including chemical, dynamical, radiative, and eventually biological components. (See Chapter 4, Sections 4.4 to 4.6.)

The short-lived radiatively important species pose an observational challenge. The fact that they are short-lived implies that observations of the concentrations are needed over wide spatial regions and over long periods of time. This is particularly important for aerosols. The current uncertainties are non-trivial (see again Chapter 6, Figure 6.7) and need to be reduced.

In sum, there needs to be an expanded attack on the key contributors to uncertainty about the behaviour of the climate system today and in the future. As stated in Chapter 13, Section 13.1.2, "Scenarios should also provide adequate quantitative measures of uncertainty. The sources of uncertainty are many, including the trajectory of greenhouse gas emissions in the future, their conversion into atmospheric concentrations, the range of responses of various climate models to a given radiative forcing and the method of constructing high resolution information from global climate model outputs (see Chapter 13, Figure 13.2). For many purposes, simply defining a single climate future is insufficient and unsatisfactory. Multiple climate scenarios that address at least one, or preferably several, sources of uncertainty allow these uncertainties to be quantified and explicitly accounted for in impact assessments."

In addition to this needed expansion in the attack on uncertainties in the climate system, there is an important new challenge that should now be addressed more aggressively. It is time to link more formally physical climate-biogeochemical models with models of the human system. At present, human influences generally are treated only through emission scenarios that provide external forcings to the climate system. In future comprehensive models, human activities will interact with the dynamics of physical, chemical, and biological sub-systems through a diverse set of contributing activities, feedbacks, and responses. This does not mean that it is necessary or even logical to attempt to develop prognostic models of human actions since much will remain inherently unpredictable; however, the scenarios analysis could and should be more fully coupled to the coupled physical climate-biogeochemical system.

As part of the foundation-building to meet this challenge, we turn attention now to the human system.

14.3 The Human System

14.3.1 Overview

Human processes are critically linked to the climate system as contributing causes of global change, as determinants of impacts, and through responses. Representing these linkages poses perhaps the greatest challenge to modelling the total Earth system. But understanding them is essential to understanding the behaviour of the whole system and to providing useful advice to inform policy and response. Significant progress has been made, but formidable challenges remain.

Human activities have altered the Earth system, and many such influences are accelerating with population growth and technological development. The use of fossil fuels and chemical fertilisers are major influences, as is the human transformation of much of the Earth's surface in the past 300 years.

Land-use change illustrates the potential complexity of linkages between human activity and major non-human components of the Earth system. The terrestrial biosphere is fundamentally modified by land clearing for agriculture, industrialisation, urbanisation, and by forest and rangeland management practices. These changes affect the atmosphere through an altered energy balance over the more intensively managed parts of the land surface, as well as through changed fluxes of water vapour, CO_2, CH_4 and other trace gases between soils, vegetation, and the atmosphere. Changed land use also greatly alters the fluxes of carbon, nutrients, and inorganic sediments into river systems, and consequently into oceanic coastal zones.

The response of the total Earth system to these changes in anthropogenic forcing is currently not known. Sensitivity studies with altered land cover distributions in general circulation models have shown that drastic changes, such as total deforestation of all tropical or boreal forests, may lead to feedbacks in atmospheric circulation and a changed climate that would not support the original vegetation (e.g., Claussen, 1996). Regional climate simulations, on the other hand, have shown that at the continental scale, important teleconnections may exist through which more modest tropical forest clearing may cause a change in climate in undisturbed areas. Coupling the global to the local is a key challenge; regional studies may prove to be uniquely valuable.

Human land-use change will continue and probably accelerate due to increasing demands for food and fibre, changes in forest and water management practices, and possibly large-scale projects to sequester carbon in forests or to produce biomass fuels. In addition, anthropogenic changes in material and energy fluxes, resulting from such activities as fossil fuel combustion and chemical fertiliser use, are expected to increase in the coming decades. Predictions of changes in the carbon and nitrogen cycles are sensitive to estimates of human activity and predictions of the impacts of these global changes must take into account human vulnerability, adaptation, and response. Predicting the future response of the Earth system to changes in climate and in parallel to changes in land use and land cover will require projections of trends in the human contributions to these global changes; this sort of modelling presents difficult challenges because of the multiple factors operating at local, regional, continental, and global levels to influence local land-use decisions.

In sum, the human element probably represents the most important aspect both of the causes and effects of climate change and environmental impacts. Any policy intervention will have human activities as its immediate target.

14.3.2 Humans: Drivers of Global Change: Recipients of Global Change

The provision of useful guidance to inform policy requires observation and description of human contributions to global change, as well as theoretical studies of the underlying social processes that shape them. We also need to understand how global change affects human welfare. This requires not merely studies of direct exposure but also of the capacity to respond.

Causal models of social processes have large uncertainties, and pose problems that are of a qualitatively different character than those encountered in modelling non-human components of the Earth system. This is due, first and foremost, to the inherent reflexivity of human behaviour; i.e., the fact that human beings have intellectual capabilities and emotional endowments enabling them to invent new solutions and transcend established “laws” in ways that no other species can do. As a consequence, predictive models may well alter the behaviour that they seek to predict and explain – indeed, such models are sometimes deliberately used exactly for that purpose. Moreover, the diversity of societies, cultures, and political and economic systems often frustrates attempts to generalise findings and propositions from one setting to another. Representation of human behaviour at the micro (individual) and macro (collective) scale may require fundamentally different approaches (see Gibson *et al*., 1998).

These kinds of difficulties intrinsically limit the predictive power that can be ascribed to models of social processes. As a consequence, research on human drivers and responses to climate change cannot be expected to produce conventional predictions beyond a very short time horizon. This does not imply, however, that research on human behaviour and social processes cannot provide knowledge and insight that can inform policy deliberations. A considerable amount of basic knowledge and insight exist, and this knowledge can be used, *inter alia*, for constructing scenarios showing plausible trajectories and identifying the critical factors that will have to be targeted in order to switch from one trajectory to another. From the perspective of policy-makers, this can indeed be an important contribution.

To make the most of this potential, further progress is required along two main frontiers. One challenge is to develop a more integrated understanding of social systems and human behaviour. With some exceptions, the first generation of models in this area represented “the human system” by a few key variables. For example, resource use was often conceived of as a function of population size and income level. The performance of such simplistic models was by-and-large poor. It is abundantly clear that the impact of human activities as drivers of climate change depends upon a complex set of interrelated factors, including also technologies in use, social institutions, and individual beliefs, attitudes, and values. At present, it seems fair to say that we have a reasonably good theoretical grasp of important types of institutions, such as markets and hierarchies, in ideal-type form. What we need to understand better is how their impure real-world counterparts work, and to improve our understanding of the intricate interplay of institutional complexes, i.e., how markets, governments and other social institutions interact to shape human behaviour. Research in political economy clearly indicates that phenomena such as economic growth are to a significant extent affected by the functioning of interlocking networks of institutional arrangements.

Similarly, we have a fairly good grasp on particular kinds of intellectual processes – in particular, the logic of rational choice – but we are doing less well when it comes to understanding how beliefs, attitudes and values change and how change in these factors in turn affects manifest human behaviour, such as consumption patterns. To address these challenges we need more interdisciplinary research designed to integrate knowledge from different fields and sub-fields into a more holistic understanding of “the human system”. The intellectual and organisational problems involved should not be underestimated, but we are confident that the prospects for making progress along this frontier are better now than ever before.

The other main challenge is to find better ways of integrating models of the biogeophysical Earth system with models of social systems and human behaviour. Some encouraging progress has been made at this interface, particularly over the last decade. For example, there has been a rapid increase in attempts to integrate representations of human activities in models with explicit formal linkages to other components of the Earth system. Such integrated assessment models have offered preliminary characterisations of human-climate linkages, particularly through models of multiple linked human and climate stresses on land cover. Moreover, they have provided preliminary characterisation of broad classes of policy responses, and have been employed to characterise and prioritise policy-relevant uncertainties.

Yet, effective integration is frustrated by at least two main obstacles. One is incongruity of temporal and spatial scales. Social science research cannot match the long time horizons of much natural science research. On the other hand, in studying consequences for human welfare and responses to these consequences, social scientists need estimates of biophysical impacts of climate change differentiated by political units or even smaller social systems. Aggregate global-scale estimates are of limited use in this context; human sensitivity to climate change varies significantly across regions and social groups, and so does response capacity. We can expect to see some progress in alleviating the spatial resolution problem, as regional-scale models of climate change are further developed, but we have to recognise that the scale problems are fundamental and that no quick fixes are in sight. The other problem pertains to the interface between different methodological approaches. In particular, concerted efforts are required to develop better tools for coupling approaches relying on numerical modelling with "softer" approaches using interpretative frameworks and qualitative methods. Some of these differences are too profound to be eliminated, but that does not imply that bridges cannot be built. Learning how to work more effectively across these methodological divides is essential to the further development of integrated global change research. Again, some encouraging progress is being made.

14.4 Outlook

There is a growing recognition in the scientific community and more broadly that:

- The Earth functions as a system, with properties and behaviour that are characteristic of the system as a whole. These include critical thresholds, "switch" or "control" points, strong non-linearities, teleconnections, chaotic elements, and unresolvable uncertainties. Understanding the components of the Earth system is critically important, but is insufficient on its own to understand the functioning of the Earth system as a whole.

- Humans are now a significant force in the Earth system, altering key process rates and absorbing the impacts of global environmental changes. The environmental significance of human activities is now so profound that the current geological era can be called the "Anthropocene" (Crutzen and Stoermer, 2000).

A scientific understanding of the Earth system is required to help human societies develop in ways that sustain the global life support system. The clear challenge of understanding climate variability and change and the associated consequences and feedbacks is a specific and important example of the need for a scientific understanding of the Earth as a system. It is also clear that the scientific study of the whole Earth system, taking account of its full functional and geographical complexity over time, requires an unprecedented effort of international collaboration. It is well beyond the scope of individual countries and regions.

The world's scientific community, working in part through the three global environmental change programmes (the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), and the World Climate Research Programme (WCRP)), has built a solid base for understanding the Earth system. The IGBP, IHDP and WCRP have also developed effective and efficient strategies for implementing global environmental change research at the international level. The challenge to IGBP, IHDP and WCRP is to build an international programme of Earth system science, driven by a common mission and common questions, employing visionary and creative scientific approaches, and based on an ever closer collaboration across disciplines, research themes, programmes, nations and regions.

We need to build on our existing understanding of the Earth system and its interactive human and non-human processes through time in order to:

- improve evaluation and understanding of current and future global change; and

- place on an increasingly firm scientific basis the challenge of sustaining the global environment for future human societies.

The climate system is particularly challenging since it is known that components in the system are inherently chaotic, and there are central components which affect the system in a non-linear manner and potentially could switch the sign of critical feedbacks. The non-linear processes include the basic dynamical response of the climate system and the interactions between the different components. These complex, non-linear dynamics are an inherent aspect of the climate system. Amongst the important non-linear processes are the role of clouds, the thermohaline circulation, and sea ice. There are other broad non-linear components, the biogeochemical system and, in particular, the carbon system, the hydrological cycle, and the chemistry of the atmosphere.

Given the complexity of the climate system and the inherent multi-decadal time-scale, there is a central and unavoidable need for long-term consistent data to support climate and environmental change investigations. Data from the present and recent past, credible global climate-relevant data for the last few centuries, along with lower frequency data for the last several millennia, are all needed. Research observational data sets that span significant temporal and spatial scales are needed so that models can be refined, validated, or perhaps, most importantly, rejected. The elimination of models because they are in conflict with climate-relevant data is particularly important. Running unrealistic models will consume scarce computing resources, and the results may add unrealistic information to the needed distribution functions. Such data must be adequate in temporal and spatial coverage, in parameters measured, and in precision, to permit meaningful validation. We are still unfortunately short of data for the quantitative assessment of extremes on the global scale in the observed climate.

In sum, there is a need for:

- more comprehensive data, contemporary, historical, and palaeological, relevant to the climate system;

- expanded process studies that more clearly elucidate the structure of fundamental components of the Earth system and the potential for changes in these central components;

- greater effort in testing and developing increasingly comprehensive and sophisticated Earth system models;

- increased emphasis upon producing ensemble calculations of Earth system models that yield descriptions of the likelihood of a broad range of different possibilities, and finally;

- new efforts in understanding the fundamental behaviour of large-scale non-linear systems.

These are significant challenges, but they are not insurmountable. The challenges to understanding the Earth system including the human component are daunting, and the pressing needs are significant. However, the opportunity for progress exists, and, in fact, this opportunity simply must be realised. The issues are too important, and they will not vanish. The challenges simply must be met.

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