Chapter 1: Historical Overview of Climate Change Science

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Executive Summary

The chapter focuses on the modern history of the scientific study of climate and climate change, and especially on quite recent developments. However, the subject has ancient roots. Understanding our planet has been a prime objective for theoretical and observational studies since the beginnings of modern science. The realization that Earth's climate might be sensitive to the atmospheric concentrations of gases that contribute to the greenhouse effect is several centuries old.

Nevertheless, our current scientific understanding of the climate system is very much a phenomenon of modern times. Recent decades have seen an explosive growth in climate research, with numbers of publications in scientific journals increasing exponentially with time. Furthermore, many indispensable tools of this research, including remote sensing and numerical modeling, were made possible only by revolutionary technological developments, including satellites and supercomputers.

By the 1950s, a few prescient scientists had realized that accumulation of carbon dioxide in the atmosphere from sources associated with human activities, notably the obtaining of energy from fossil fuels, might become a serious problem in the near future. They perceived that humanity was conducting a unique and inadvertent large-scale experiment on the atmosphere, the results of which might not be clear until substantial time had passed.

It was also in the 1950s that systematic and accurate measurements of atmospheric carbon dioxide concentration began. The earliest attempts to simulate the atmospheric general circulation numerically, which laid the foundations for today's comprehensive models of the climate system, also date from this period.

Observations of the climate system are the foundation of our science and receive heavy emphasis in this chapter. In recent decades, many efforts worldwide have led to substantial improvements in obtaining and analyzing historical climate observations. The amount of data has increased due to digitization of historical records, as well as to new measurements. Qualitative improvements are due to more accurate measurements and to progress in data processing. Over the last decade, global land-surface data sets have been able to increase the number of stations substantially. Several important instrumental time series are now significantly longer and are now better able to demonstrate whether climate trends reported earlier are continuing or not.

For more than four decades, satellite remote sensing has continued to revolutionize our ability to observe the climate system. For example, satellites, combined with extensive *in situ* measurements, observing clouds globally at a variety of wavelengths, provide a rich variety of information including cloud height, thickness, reflectivity, and information on the phase (liquid or solid) of the cloud water, among other variables. New satellite platforms and new instruments developed in recent years offer great promise for our future ability to monitor key aspects of the climate system.

Computer models constitute a second pillar sustaining our science. Whereas science historically has often progressed through the search for simple and general laws that could be derived from the complexity of the observable world, numerical models, by contrast, have used the fundamental laws of physics to reproduce much of the complexity displayed by nature. The remarkable success of climate simulation models, to an extent which was absolutely unexpected as recently as 50 years ago, has led to the development of the new discipline of numerical experimentation, through which scientists learn by intentionally modifying the simulated Earth in the computer, sometimes in ways that are fortunately impossible on the actual Earth.

The rapid development of more and more physically comprehensive and realistic models has provided increased confidence that the models can contribute significantly to our understanding of the climate system. Several of the topics treated in this chapter bear directly on the challenge of developing climate models with adequate veracity to address the questions that society has posed to the still young science of climate change. Increasing the trustworthiness and reliability of model predictions of future climate change is a goal underlying virtually all recent and ongoing climate change research.

Some of the research described in this chapter is extremely recent: the first attempts at including the ocean in comprehensive coupled numerical climate models were developed only over the last few decades. Until recently, most coupled atmosphere-ocean models required artificial adjustments to prevent a spurious drift of the numerical simulations away from a realistic climate state. Achieving the successful transition to fully coupled ocean-atmosphere models is among the most important accomplishments in climate modeling during the last 20 years. Nevertheless, this advance is only the initial phase of a wider and still ongoing evolution leading ultimately to the development of truly complete Earth system models, which will include the chemical and biogeochemical components of the climate system.

This account emphasizes that not all climate change research efforts have been met by clear success so far. The chapter points out areas where, despite great progress, we still lack an adequate physical understanding of key components of the climate system and their mutual interactions. These areas include aspects of the roles in climate change played by clouds, the cryosphere and the oceans.

The role of clouds in climate leads the list of gaps in our understanding. For at least several decades, it has been widely recognized in the research community that incomplete knowledge of clouds and cloud-radiation interactions and feedbacks accounts for much of the uncertainty in our ability to specify the sensitivity of climate to greenhouse gas changes and to predict the climate of future decades. Although much demonstrable progress has occurred, and in spite of a large and coordinated set of model and observational studies, the uncertainty range of future climate predictions associated with cloud feedbacks has not been reduced thus far.

The extreme complexity of the climate system, and the multiple interactions which maintain its mean behaviour as well as its fluctuations, impose definite limitations on our capacity to fully predict it. Theoretical approaches have complemented observational and numerical studies to allow a better determination of the nature and amplitude of the associated uncertainties and instabilities in climate change. We have come to better appreciate that climate change has inherently chaotic aspects and that the climate system is subject to abrupt changes, as paleoclimatic evidence reveals unambiguously.

Climate change science, like science in general, requires the collaborative work of many scientists for success and operates as a rigorous cooperative process for understanding the natural world. This work is facilitated by a substantial body of international programs, operated by international agencies. A specific example is the systematic intercomparison of model results. IPCC has played a prominent role in the collective assessment of this work.

The research described in this report is truly the achievement of the international community of scientists, past as well as present. The IPCC's First Assessment Report (FAR) appeared in 1990. It made a compelling qualitative case for anthropogenic interference with the climate system but lacked quantitative support. In the Second Assessment Report (SAR) in 1995 and 1996, the carbon budget for the 1980s was analyzed, and expanded analyses of the global budgets of trace gases and aerosols from both natural and anthropogenic sources were presented. The Third Assessment Report (TAR) in 2001 presented major advances in understandings of aerosols and ozone chemistry. This Fourth Assessment Report (AR4) builds on its predecessors, just as the science in recent years has built on the science that came before.

The modern history of the science of climate and climatic change is an example of how natural science typically evolves, displaying a simultaneous combination of dramatic advances in some areas with unsolved and seemingly intractable remaining issues in others.

1.1 Overview of the Chapter

The concept of this chapter is new. There is no counterpart in previous IPCC assessment reports for an introductory chapter providing historical context for the remainder of the report. Here, a restricted set of topics has been selected to illustrate key accomplishments and challenges in climate change science. The topics have been chosen for their relevance and importance to the IPCC mission and to the overall theme of human-induced climate change, and to illustrate the complex and uneven pace of scientific evolution. The time frame under consideration stops with the publication of the IPCC Third Assessment Report (TAR) in 2001.

In spite of their diversity, the topics treated in this chapter have common themes. They all share the underlying messages that climate change science is progressing and becoming more complex at an increasingly rapid rate, and that the new insights into our world that climate change science is providing matter profoundly to mankind, because they are relevant to where and how we live, work, and obtain our food.

1.2 The Nature of Earth Science

To understand the nature of Earth science, one must first understand the basic elements of how science in general progresses. Science may be stimulated by argument and debate, but it advances only through formulating hypotheses clearly and testing them objectively. This *testing is the key to science.* In fact, some philosophers of science insist that to be genuinely scientific, a statement must be susceptible to testing that could potentially show it to be false (Popper, 1934). Therefore, scientists are required to submit their research findings to the severe scrutiny of review by their peers and to disclose fully the methods and data which they use so that other scientists may attempt to replicate their results.

The insights and research results of individual scientists, even scientists of unquestioned genius, are confirmed or rejected by the combined efforts of many other scientists. It is not the opinion of the scientists that is important but rather the results of their testing. Indeed, the physicist Stephen Hawking, in *A Brief History of Time*, reminds us that publication of a book entitled *100 Authors Against Einstein* caused Einstein himself to remark, “If I were wrong, then one would have been enough!”

Thus *science is inherently self-correcting;* incorrect or incomplete scientific concepts ultimately do not survive repeated testing against observations of nature. Scientific theories are valuable only if they lead to predictions which can be evaluated by comparison with physical reality. Each successful prediction adds to the weight of evidence supporting the theory, and any unsuccessful prediction demonstrates that the theory is imperfect and requires improvement or abandonment.

Since new progress is inevitably based on the research and understanding that has gone before, *science is cumulative*, with useful features retained and non-useful features abandoned. Scientific insights, even unexpected insights, often emerge incrementally as a result of repeated attempts to test hypotheses as thoroughly as possible. Active research scientists, throughout their careers, typically spend large fractions of their working time studying in depth what other scientists have done. In practice, a superficial or amateurish acquaintance with the current state of a scientific research topic is an obstacle to progress. Indeed, a day in the library can save a year in the laboratory. Even Sir Isaac Newton (1675) famously wrote that if he had “seen further it is by standing on the shoulders of giants.” If this was true for the great Newton, it is even more true for scientists working today. Therefore, intellectual honesty and professional ethics require that a scientist acknowledge the work of predecessors and colleagues. Although, as in any field of human endeavour, some few scientists are unusually gifted and accomplished, the research described in this report is truly the collective achievement of the international community of scientists, past as well as present.

The attributes of science briefly described here can be used in assessing competing assertions about climate change. Can the statement under consideration, in principle, be proven false? Has it been rigorously tested? Did it appear in the peer-reviewed literature? Did it build on the existing research record or ignore the work of other scientists? If the answer to any of these questions is no, then less credence should be given to the assertion until it is tested and independently verified.

Earth sciences differ methodologically from the traditional laboratory sciences, of course, in that Earth scientists are unable to perform controlled experiments on the planet as a whole and then observe the results. This is an important consideration, because it is precisely the whole-Earth, system-scale experiments, incorporating the full complexity of interacting processes and feedbacks, that might ideally be required to verify or falsify climate change hypotheses fully (Schellnhuber et al., 2004). Nevertheless, *testing hypotheses empirically is still the key to Earth science*, although it is often done using available observations and numerical experiments that focus on specific parts of the Earth system. For example, to test hypotheses about the impact of local land use on surface temperature, data from surface observations can be stratified, based on whether they are from rural or urban sites. Models can sometimes partially circumvent the limits of observational data by intentionally modifying the simulated Earth in ways that are impossible on the actual Earth. Often, a combination of observations and models is used to make predictions and test hypotheses. For example, the global cooling and drying of the atmosphere that were observed after the eruption of Mount Pinatubo provided key tests of particular aspects of global models (e.g., Soden et al., 2002). In this particular example, the “results provided quantitative evidence of the reliability of water vapour feedback in current climate models."

Clearly, not all theories or early results are verified by later analysis. In the mid-1970s, several popular articles appeared about global cooling (e.g., Gwynne, 1975). Some of the speculation about cooling was based on Northern Hemisphere temperatures, which had shown a decrease for the preceding three decades. At the time, there were also some scientific hypotheses that projected human-induced cooling, but this research has subsequently been corrected or reinterpreted. For example, a model by Bryson and Dittberner (1976), developed to simulate global and hemispheric surface temperatures, indicated that a doubling of atmospheric concentrations of CO_2 would cause a 4.93°C decrease in global mean temperature. This result was quickly challenged by Woronko (1977). In their reply to the criticism, Bryson and Dittberner (1977) made it clear that indicating that increasing CO_2 would lead to a decrease in mean hemispheric surface temperature “would be directly counter to all known scientific evidence about the direct effect of CO_2 variation.” Instead, the decrease in temperature in the model is due to small particles (aerosols) in the model atmosphere, which are produced by the same processes (e.g., combustion of fossil fuels) that produce the CO_2. Bryson and Dittberner (1977) also acknowledged “that the residence time of tropospheric aerosols is short compared to that of CO_2” and that their results were “valid only within the range of values experienced” and therefore “would lead to absurd results for a doubling of CO_2” which “is far outside the range of data for which the linear approximation is assumed valid.”

This example of a prediction of "global cooling" is a classic illustration of the *self-correcting nature of Earth science* for many reasons. The scientists involved were reputable researchers. They followed the accepted paradigm of publishing in scientific journals, submitting their methods and results to the scrutiny of their peers, and responding to legitimate criticism. In this way, the evaluation of their research was shown to be largely a question of correctly explaining and interpreting the model results. This example also illustrates the danger of oversimplifying the conclusions of research. It would be possible to extract a quote from the paper of Bryson and Dittberner (1976) and report that scientists found “a slight net temperature *decrease* with an *increase* in CO_2,” but such a misleading statement would not do justice to either the complexities of the climate system or the nuanced conclusions of the scientists involved.

A recurring theme throughout this chapter is that climate science in recent decades has been characterized by the increasing rate of its progress and by the notable evolution of its methodology and tools, including the models and observations which support and enable the research. During the last four decades, the rate at which scientists have increased knowledge of atmospheric and oceanic processes has accelerated dramatically. Geerts (1999) has determined that the number of words and illustrations published in atmospheric science journals per year tripled between 1965 and 1995. Earth science generally has also grown during this period, as is clear from the annual page count in the prominent *Journal of Geophysical Research*. After correcting for occasional changes in the font and page sizes, Geerts (1999) estimates that this journal's page count has grown nearly exponentially in recent decades, with a doubling time of seven years. Figure 1.1 illustrates this expansion vividly. Part of the growth in page count is due to an increase in the number of articles, and part is due to an increase with time in the size of published papers, a phenomenon which has been noted for many journals. For example, papers in *Journal of the Atmospheric Sciences* doubled in average length between 1968 and 1987 (Johnson and Schubert, 1989).

[INSERT FIGURE 1.1 HERE]

Stanhill (2001) has carried out similar calculations for the specific field of climate change science, using as a primary source the publication *Meteorological and Geoastrophysical Abstracts*, which compiles abstracts from more than a thousand scientific publications worldwide. Stanhill finds that the climate change science literature in the period from 1951 to 1997 grew approximately exponentially with a doubling time of 11 years. Stanhill also notes that this period contains 95% of all the climate change science literature published between 1834 and 1997.

Because *science is cumulative*, every new research article incrementally increases the totality of knowledge. As the numbers of journal articles and pages published have grown, there has been a corresponding growth in our knowledge of climate processes and in the complexity of climate research, both observational and theory- or model-based. Climate science today is far more wide-ranging and physically comprehensive than was the case only a few decades ago. Indeed, our view of the climate system itself has undergone substantial change, and a quiet conceptual revolution has gradually taken place, through which modern scientists have come to realize that climate change depends on an array of intricately connected physical and biogeochemical processes. Figure 1.2 illustrates this point well by showing the evolution in the scope of relevant processes that are incorporated into comprehensive global climate models.

[INSERT FIGURE 1.2 HERE]

1.3 History of the IPCC Assessments of Climate Change

The World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988 with the assigned role of assessing the scientific, technical and socio-economic information relevant for understanding of the risk of human-induced climate change. The original 1988 mandate for the IPCC was extensive: “(a) Identification of uncertainties and gaps in our present knowledge with regard to climate changes and its potential impacts, and preparation of a plan of action over the short- term in filling these gaps; (b) Identification of information needed to evaluate policy implications of climate change and response strategies; (c) Review of current and planned national/international policies related to the greenhouse gas issue; (d) Scientific and environmental assessments of all aspects of the greenhouse gas issue and the transfer of these assessments and other relevant information to governments and intergovernmental organizations to be taken into account in their policies on social and economic development and environmental programs.” The IPCC is open to all members of UNEP and WMO and is not meant to carry out new research, nor to monitor climate-related data. However, the process of synthesis and assessment has often inspired new scientific research leading to new findings.

The IPCC has three Working Groups and a Task Force. Working Group I (WGI) assesses the scientific aspects of the climate system and climate change, while Working Groups II and III assess the vulnerability and adaptation of socio-economic and natural systems to climate change, and the mitigation options for limiting greenhouse gas emissions, respectively. The Task Force is responsible for the IPCC National Greenhouse Gas Inventories Programme. This brief history focuses on WGI.

A main activity of the IPCC is to provide an assessment of the state of knowledge on climate change on a regular basis, and this volume is the 4th such Assessment Report (AR4). The IPCC also prepares Special Reports and Technical Papers on topics on which independent scientific information and advice is deemed necessary, and it supports the UN Framework Convention on Climate Change (UNFCCC) through its work on methodologies for National Greenhouse Gas Inventories.

The First IPCC Assessment Report (FAR: “Climate Change, The IPCC Scientific Assessment”) was completed in 1990 (IPCC, 1990) under the leadership of Bert Bolin (IPCC Chair) and John Houghton (WGI Chair). The FAR, in a mere 365 pages with 8 color plates, made a compelling, but not quantitative, case for anthropogenic interference with the climate system. Most conclusions from the FAR remain valid today. For example, in terms of the greenhouse gases, "emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: CO_2, CH_4, CFCs, N_2O.” The FAR played an important role in the establishment, by the UN General Assembly, of the Intergovernmental Negotiating

Committee for a UN Framework Convention on Climate Change (UNFCCC). The UNFCCC was adopted in 1992 and entered into force in 1994. It provides the overall policy framework for addressing the climate change issue.

The WGI's contribution to the Second Assessment Report (SAR: "Climate Change 1995: The Science of Climate Change", 1996) expanded in pages by a factor of 2.5 *and* was immediately preceded by a large Special Report (IPCC, 1995) that contained scenarios and an intensive set of chapters on the carbon cycle, atmospheric chemistry, aerosols and radiative forcing. The SAR WGI culminated in the government plenary in Madrid (November 1995) at which the most debated finding on attribution of climate change continues to be reaffirmed by ongoing research: "The balance of evidence suggests a discernible human influence on global climate." The SAR provided key input to the negotiations that led to the adoption in 1997 of the Kyoto Protocol to the UNFCCC.

The IPCC Special Report on Aviation and the Global Atmosphere (IPCC, 1999) was a major interim assessment involving both WGI and WGIII and the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer. It assessed the impacts of civil aviation in terms of climate change and global air quality as well as looking at the effect of technology options for the future fleet. It was the first complete assessment of an industrial sub-sector. The summary related aviation's role relative to all human influence on the climate system: "The best estimate of the radiative forcing in 1992 by aircraft is 0.05 W m^{-2} or about 3.5% of the total radiative forcing by all anthropogenic activities. … Although improvements in aircraft and engine technology and in the efficiency of the air traffic system will bring environmental benefits, these will not fully offset the effects of the increased emissions resulting from the projected growth in aviation."

The WGI's contribution to the Third Assessment Report (TAR: "Climate Change 2001: The Scientific Basis", 2001a) was completed in 2000 and approved at the government plenary in Shanghai (January 2001). The predominant summary statements from the TAR WGI strengthened the SAR's attribution statement: "An increasing body of observations gives a collective picture of a warming world and other changes in the climate system," and, "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities." The TAR Synthesis Report (IPCC, 2001b) combined the assessment reports from the three Working Groups. By combining data on global (WGI) and regional (WGII) climate change, the Synthesis Report was able to strengthen the conclusion regarding human influence: "The Earth's climate system has demonstrably changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activities."

The WGI contribution to the Fourth Assessment Report (AR4) is contained in this volume.

1.4 Model Evolution and Model Hierarchies

Climate scenarios rely upon the use of numerical models. The continuous evolution of these models over recent decades has been driven by a considerable increase in computational capacity, from Megaflops in the 1970s to Teraflops now, which represents roughly a multiplication by one billion in three decades. This has induced a corresponding increase in complexity (by including more and more components and processes, as depicted in Figure 1.2), in the length of the simulations, and in spatial resolution. The models used to evaluate future climate changes have therefore evolved over time. Most of the pioneering work on CO_2-induced climate change was based on atmospheric general circulation models coupled to simple "slab" ocean models (i.e., models omitting ocean dynamics), from the early work of Manabe and Wetherald (1975), to the review of Schlesinger and Mitchell (1987). Similarly, most of the results presented in the FAR were from atmospheric models, rather than from models of the coupled climate system, and were used to analyze changes in the equilibrium climate resulting from a doubling of the CO_2. Current climate projections can investigate transient scenarios of climate evolution and make use of much more complex coupled ocean-atmosphere models, that may even include interactive chemical or biochemical components.

A parallel evolution toward increased complexity and resolution has occurred in the domain of numerical weather prediction (NWP), and has resulted in a large and verifiable improvement in operational weather forecast quality. There is, therefore, no doubt that present models are more realistic than those of a decade ago. There is also, however, a continuing awareness that models do not provide a perfect simulation of reality, because resolving all important spatial or time scales remains far beyond current capabilities, and because the behaviour of such a complex non-linear system is partly chaotic. Key processes that control climate sensitivity or abrupt climate changes (see sections below) cannot be represented in full detail in the context of global models, and our understanding of many such processes is still notably incomplete. As a consequence, the interpretation of complex models continues to rely on models that are either conceptually simpler, or limited to a number of processes, or to a specific region, therefore enabling a deeper understanding of the processes at work, or a more relevant comparison with observations. With the development of computer capacities, simpler models have not disappeared, and indeed a stronger emphasis has been given to the concept of a "hierarchy of models".

The list of these "simpler" models is very long. Simplicity may lie in the reduced number of equations (for example, a single equation for the global surface temperature); in the reduced dimensionality (D) of the problem (1D vertical, 1D latitudinal, 2D); or in the restriction to a few processes (for example, a mid-latitude quasi-geostrophic atmosphere with or without the inclusion of moist processes). The notion of model hierarchy is also linked to the idea of scale; global circulation models are complemented by regional models which exhibit a higher resolution over a given area, or process oriented models, such as cloud resolving models (CRMs), or large eddy simulations (LES). Earth Models of Intermediate Complexity (EMICs) are used to investigate long time scales, such as those corresponding to glacial to interglacial oscillations (Berger et al., 1998). This distinction between models according to scale is evolving quickly, driven by the increase in computer capacities. For example, global models explicitly resolving the dynamics of convective clouds may soon become feasible computationally.

Many important scientific debates in recent years have had their origin in the use of conceptually simple models. The study of idealized atmospheric representations of the tropical climate, for example has been renewed by the simple two-column approach proposed by Pierrehumbert (1995) in replacement of the earlier one-column models; this perspective has significantly modified our appreciation of the feedbacks which control climate. Simple linearized models have been used to investigate potential new feedback effects, such as the dynamical links between tropical and mid-latitude areas. Ocean box models have played an important role in the debates surrounding the possible decay of the Atlantic thermohaline circulation, as emphasized in the TAR. Simple models have also played a central role in the interpretation of IPCC scenarios: the investigation of climate scenarios presented in the SAR or the TAR has been extended to larger ensemble of cases through the use of idealized models.

We have known since the work of Lorenz (1963) that even simple models may display intricate behaviour because of their nonlinearities. The inherent nonlinear behaviour of the climate system appears in climate simulations at all time scales (Ghil, 1989). In fact, the study of non-linear dynamical systems has become important for a wide range of scientific disciplines, and the corresponding mathematical developments are essential to interdisciplinary studies. Simple models of ocean-atmosphere interactions, climate-biosphere interactions, or climate-economy interactions may exhibit a similar behaviour, characterized by partial unpredictability, bifurcations, and transition to chaos.

1.5 Examples of Research Progress in Historical Context

The greater part of this chapter is devoted to the explication of a number of specific examples illustrating the historical development of science in areas relevant to the climate change mission of IPCC.

1.5.1 Global Surface Temperature

Shortly after the invention of the thermometer in the early 1600s, efforts were underway to quantify and record the weather. The first meteorological network was formed in northern Italy in 1653 (Kingston, 1988). By the latter part of the 19th century, systematic observations of the weather were being made in almost all inhabited areas of the world. Formal international coordination of meteorological observations from ships commenced in 1853 (Quetelet, 1854).

Inspired by the paper *Suggestions on a Uniform System of Meteorological Observations* (Buijs-Ballot, 1872), the International Meteorological Organization (IMO) was formed in 1873. Succeeded by the World Meteorological Organization (WMO) in 1950, it still works to promote and exchange standardized meteorological observations. Yet even with uniform observations, there are still four major obstacles to turning instrumental observations into accurate global time series: (1) access to the data in usable form, (2) quality control to remove or edit erroneous data points, (3) homogeneity assessments and adjustments where necessary to ensure the fidelity of the data, and (4) area-averaging.

Köppen (1873) was the first scientist to overcome most of these obstacles. He created a near-global time series to study the effect of sunspot cycles. Later he identified increases in global temperature (Köppen, 1880, 1881). Much of his data came from Döve (1852), but wherever possible he used data directly from the original source, because Döve often lacked information about the observing methods. Köppen considered examination of the annual mean temperature to be an adequate technique for quality control of far distant stations. Using data from over 100 stations, he averaged annual observations from 1820 to 1871 into several major latitude belts which he then area-averaged into near-global time series.

The next global temperature time series was produced by Callendar (1938) expressly to investigate the influence of carbon dioxide on temperature. Callendar examined about 200 station records. Only a small portion of them were deemed defective, based on quality concerns determined by comparing differences with neighboring stations, or on homogeneity concerns based on station changes documented in the recorded metadata. After further removing two Arctic stations because he had “no compensating stations from the Antarctic region,” he created a global average using data from 147 stations.

Most of Callendar’s data came from World Weather Records (WWR; Clayton, 1927). Initiated by a resolution at the 1923 IMO Conference, WWR was a monumental international undertaking producing a 1,196-page volume of monthly temperature, precipitation and pressure data from hundreds of stations around the world, some with data starting in the early 1800s. In the early 1960s, J. Wolbach had these data digitized (National Climatic Data Center, 2002). The WWR project continues today under the auspices of the WMO with the digital publication of decadal updates to the climate records for thousands of stations world wide (National Climatic Data Center, 2005).

Willett (1950) also used WWR as the main source of data for 129 stations that he used to create a global temperature time series going back to 1845. While the resolution that initiated WWR called for the “publication of long and homogeneous records” (Clayton, 1927), Willett took this mandate one step further by carefully selecting a subset of “stations with as continuous and homogeneous a record as possible” from the most recent update of WWR, which included data through 1940. To avoid over-weighting certain areas such as Europe, only one record, the best available, was included from each 10° latitude and longitude square. Station monthly data were averaged into five-year periods and then converted to anomalies with respect to the five-year period 1935–1939. Each station’s anomaly was given equal weight to create the global time series.

Callendar in turn created a new global temperature time series in 1961 and cited Willett (1950) as a guide for some of his improvements. This time Callendar (1961) evaluated 600 stations with about three-quarters of them passing his quality checks. Unbeknownst to Callendar, a former student of Willett’s, Mitchell (1963), in work first presented in 1961, had created his own updated global temperature time series using slightly fewer than 200 stations. Landsberg and Mitchell (1963) compared Callendar’s results with Mitchell’s and determined that there was generally good agreement except in the data-sparse regions of the Southern Hemisphere.

Meanwhile, research in Russia was proceeding on a very different approach to the problem. Under the leadership of Budyko (1969), this approach used smoothed, hand-drawn maps of monthly temperature anomalies as a starting point. While restricted to analysis of the Northern Hemisphere, this map-based approach not only allowed the inclusion of an increasing number of stations over time (e.g., 246 in 1881, 753 in 1913, 976 in 1940 and about 2000 in 1960) but also the utilization of data over the oceans as well (Robock, 1982).

Increasing the number of stations utilized has been a continuing theme over the last several decades with considerable effort being spent acquiring and digitizing station data. During the 1970s and ‘80s, several teams produced global temperature time series. Advancements especially worth noting during this period include the extended spatial interpolation and station averaging technique of Hansen and Lebedeff (1987) and the Jones et al. (1986) painstaking assessment of homogeneity and adjustment of the record of each of the thousands of stations in a global data set. Since then, global and national data sets have been rigorously adjusted for homogeneity using a variety of statistical and metadata-based approaches (Peterson et al., 1998).

One recurring homogeneity concern is potential urban heat island contamination in global temperature time series. This concern is currently being addressed in one global temperature time series by adjusting the long-term trend of urban stations so that they agree with the trend from nearby rural stations (Hansen et al., 2001) and in the other two time series by detailed analyses that, like that of Callendar (1938), indicate that the urban heat island bias in these global temperature time series is either minor or non-existent (Jones et al., 1990; Peterson et al., 1999).

As the importance of ocean data became increasingly recognized, a major effort got underway to seek out historical archives of ocean data, digitize and quality-control them. This work has since grown into the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; Worley et al., 2005). ICOADS has coordinated the acquisition, digitization, and synthesis of data ranging from transmissions by the Japanese merchant ships to South African whaling boats' logbooks. The amount of Sea Surface Temperature (SST) and related data acquired continues to grow.

As fundamental as the basic data work of ICOADS is, there were two other significant advancements in SST data. The first was adjusting the early observations to make them comparable to current observations. Prior to 1940, the majority of SST observations were made from ships by hauling a bucket on deck filled with sea water and placing a thermometer in it. This ancient method eventually gave way to thermometers placed in engine cooling water inlets, which are typically located several meters below the ocean surface. Folland and Parker (1995) developed an adjustment model that accounted for heat loss from the buckets and that varied with bucket size and type, exposure to solar radiation, ambient wind speed and ship speed. They verified their results using time series of night marine air temperature. Their adjustments warmed the early bucket observations by a few tenths of a degree C.

Most of the ship observations are taken in narrow shipping lanes, so the second advancement is increasing global coverage. This is done in several ways. Direct improvement of coverage has been achieved by the internationally coordinated placement of drifting and moored buoys. The buoys began to be numerous enough to make significant contributions to SST analyses in the mid-1980s and continue to the present with over 500 buoys transmitting data at any one time (Reynolds et al., 2002). Since 1982, satellite data, anchored to in situ observations, have contributed to near-global coverage (Reynolds and Smith, 1994). Also, the different patterns of SST determined during the satellite era have been used as guides to filling in the fields during the pre-satellite era (Smith and Reynolds, 2004).

In recent years, several different approaches have been used to combine land and ocean observations into global temperature time series. Currently there are three major groups producing global surface temperature time series using homogeneity-adjusted data from both land and ocean. The three groups are NOAA (Smith et al., 2005), NASA (Hansen et al., 2001), and a UK Met Office – University of East Anglia collaboration (Jones and Moberg, 2003). Their results agree very well despite using very different homogeneity assessments and spatial averaging techniques. All three of these global temperature time series incorporate many millions of monthly land-based meteorological station temperature values and gridded monthly SST observations which are derived from over 400 million individual readings of thermometers at land stations and over 140 million individual in situ SST observations. To place the current time series based on instrumental observations into a longer historical context requires the use of proxy data, discussed in the next section.

While many of the recent observations are automatic, the vast majority of *in situ* observations have depended on the dedication of tens of thousands of individuals over more than a century of human history. Mankind owes a great debt to the largely selfless work of these individual weather observers as well as to international organizations such as the IMO, WMO and Global Climate Observing System (GCOS), which encourage the taking and sharing of high-quality meteorological observations. While modern researchers put a great deal of time and effort into adjusting the data to account for all known problems and biases, century-scale global temperature time series would not have been possible without the conscientious work of individuals and organizations worldwide quantifying and documenting their local environment.

1.5.2 Past Climate Observations, Astronomical Theory and Abrupt Climate Changes

Since the work of Louis Agassiz (1837), who developed the hypothesis that Europe had experienced past glacial ages, there has been a growing awareness that long-term climate observations can advance our understanding of the physical processes affecting climate change. The scientific study of one such mechanism, involving modifications in the geographical and temporal patterns of solar energy reaching the Earth's surface, due to changes in the Earth's orbital parameters, has a long history. The pioneering contributions of Milankovitch (1941) to the astronomical theory of climate change are widely known. However, Milankovitch had predecessors, and the historical review of Imbrie and Imbrie (1979) has helped call attention to much earlier contributions, such as those of James Croll, originating in 1864.

Throughout the 19th and 20th centuries, a wide range of studies, including geomorphology or the evidence of past vegetal or animal life, has provided new insight into the Earth’s past climates, covering periods of hundreds of million years. At much smaller time scales, techniques such as the study of tree rings have provided a very valuable climatic record over the last centuries. These studies have revealed that the primary era (which started about 600 million years ago) displayed evidence of both warmer and colder climatic conditions than presently, that the tertiary era (from 65 million years ago to the quaternary) was generally warmer, whereas the quaternary era (the last 2 million years) displayed continuous oscillatory changes between glacial and interglacial conditions.

The history of paleoclimatic research, however, has strongly accelerated during the last several decades, during which quantitative and dated records of climate fluctuations over the last hundred thousand years have brought a more comprehensive view of how climate changes may occur, as well as the means to test elements of the astronomical theory. By the 1950s, studies of deep sea cores suggested that the deep ocean temperatures may have been different during glacial times (Emiliani, 1955), and Ewing and Donn (1956) proposed that changes in ocean circulation actually could initiate an ice age. The work of Emiliani in the 1960s has shown the potential of isotopic measurements in deep-sea sediments to help explain quaternary changes (e.g., Emiliani, 1969). In the 1970s it became possible to analyze a deep-sea core time series of more than 700,000 years, thereby using the last reversal of the Earth's magnetic field to establish a dated chronology. This deep-sea observational record clearly showed the same periodicities found in the astronomical forcing, immediately providing strong support to Milankovitch's ideas (Hays et al., 1976).

Simultaneously, ice cores have provided other key information about past climates; in particular, the bubbles sealed in the ice are the only available samples of past atmospheres, and they provide a continuous history of their chemical composition. The first deep ice cores from Vostok in Antarctica (Jouzel et al., 1987; Barnola et al., 1987) provided additional evidence of the role of astronomical forcing. They also revealed a highly correlated evolution of temperature changes and atmospheric composition, which was subsequently confirmed over longer time scales of more than 400 000 years (Jouzel et al., 1993). This discovery had a strong impact on the perception of the linkage between greenhouse gases and climate, in spite of the fact that it did not unambiguously demonstrate the possible feedback of atmospheric chemical composition on climate changes.

The same data which confirmed the astronomical theory also revealed its limits. The realization that a linear response of the climate system to astronomical forcing could not explain entirely the observed quaternary fluctuations stemmed from unexplained peculiarities of the climate record: very rapid ice age terminations and the dominance of the longer time scales in the spectral record.

The importance of unforced variability was reinforced by the discovery of past “abrupt” climate changes. Abrupt, in this context, designates events of “large” (typically a few degrees) amplitude, occurring at time scales significantly shorter than the thousand years which characterize astronomically driven changes. Abrupt temperature changes were first revealed by the analysis of deep ice cores from Greenland (Dansgaard et al., 1984). Oeschger et al. (1984) recognized that the rapid changes during the termination of the last ice age correlated with coolings in Gerzensee (Switzerland) and suggested that regime shifts of the Atlantic ocean circulation were causing these wide-spread changes. The synthesis of paleoclimatic observations by Broecker and Denton (1989) triggered a rapid progress during the next decade. By the end of the 1990s it became clear that “abrupt” climate changes, as expressed in the Greenland ice cores during the last ice age, were numerous (Dansgaard et al., 1993), very rapid (Alley et al., 1993), and of large amplitude (Severinghaus and Brook, 1999). They are now referred to as Dansgaard-Oeschger events. The importance of internal climate variability and processes was reinforced in the early 1990s by the analysis of new Northern-Hemisphere ice core records, from the GRIP (Johnsen et al., 1992) and GISP2 (Grootes et al., 1993) drillings, which produced additional evidence for unforced climate changes, and revealed a large number of "abrupt" changes throughout the last glacial cycle. At about the same time, long deep-ocean sediment cores were used to reconstruct the ocean hydrology dominated by the thermohaline circulation of deep and surface water (Bond et al., 1992; Broecker, 1997) and demonstrated the role of the ocean in these abrupt climate changes.

By the end of the 1990s, the available range of paleoclimate proxies for modern observables had expanded greatly. The analysis of deep corals provided indicators for nutrient content and surface-to-deep water mass exchange (Adkins et al., 1998) and showed abrupt variations characterized by synchronous changes of surface and deep water mass properties (Shackleton et al., 2000). Precise measurements of the methane abundances (a global quantity) in polar ice cores showed that they changed in concert with the Dansgaard-Oeschger events and thus allowed for synchronization across ice cores (Blunier et al., 1998). The characteristics of the Antarctic temperature variations and their relation to the Dansgaard-Oeschger events in Greenland were consistent with the simple concept of a bipolar seesaw caused by changes in the thermohaline circulation of the Atlantic Ocean (Stocker, 1998). This underlined the important role of the ocean in transmitting the signals of abrupt climate change.

While these well-documented abrupt changes are global in extent, there are many examples of abrupt changes on regional scales. For example, severe droughts, which last for many years and exert strong pressure on societies, have occurred not only during the ice ages (as in the Dansgaard-Oeschger events) but also during the last 10,000-year period warm period (Holocene) (deMenocal, 2001). This result alters the notion of relative climate stability during warm epochs, as previously suggested by the polar ice cores. In summary, the global extent and the coherent picture of a rather unstable ocean-atmosphere system has opened the debate of whether man's interference through continued emission of greenhouse gases and aerosols could trigger such events, both regional and global, in the future (Broecker, 1997).

These findings have strongly influenced the modern perception of the climate system as subject to possible instabilities, which have occurred in the past and might occur again in the future, albeit in a somewhat different context, as the result of human activities. As a consequence, the scientific attitude toward past climate observations has changed drastically. The idea that past climates could provide analogues for future climate was mentioned in the IPCC's First Assessment Report (IPCC, 1990) but largely dismissed. The realization that climate history is the result of a unique combination of many different processes, and that it is very unlikely that the climate system will faithfully repeat in the future exactly what it did in the past, is now widely accepted. However, past climates have revealed a wide range of unexpected processes, which constitute as many challenges which climate models need to meet through process-oriented model-data comparisons.

Dating, and in particular relative dating between the records of different climatic parameters, constitutes a key issue for further progress in the process-oriented study of past climates. For example, the recent use of ice core temperature proxies based on isotopes of atmospheric constituents such as nitrogen, oxygen, or argon now permit dated comparison with greenhouse gas records for ice cores from both hemispheres. Together with the study of ocean records, these methods are now approaching the point where it will become possible to appreciate the role of greenhouse gases as a link between the climate changes of the two hemispheres. Proxy data from various sources (multi-proxy data) are combined using statistical and dynamical methods to obtain a comprehensive picture of the climate of the past.

The combination of instrumental and proxy data began in the 1960s with the investigation of the influence of climate on the proxy data, which continues until today. This includes the analysis of climatic signals in tree rings (Fritts, 1962), corals (Weber and Woodhead ,1972; Dodge and Vaisnys, 1975; Dunbar and Wellington, 1981), and ice cores (Dansgaard et al., 1984; Jouzel et al., 1983; 1987). In dendroclimatology these studies soon progressed to cross-validated calibration of tree ring data against instrumental meteorological data. The resulting transfer functions could be used to reconstruct the climate from chronologies at individual sites (e.g., Hughes et al., 1978; Lara and Villalba, 1993; Michaelsen et al., 1987; Briffa et al., 1990), or from entire networks (Fritts et al., 1971; Schweingruber et al., 1991; Briffa et al., 1992). Historical data were also soon calibrated against instrumental data and used to extend long instrumental series (Lamb, 1969; van den Dool, 1978), and to produce reconstructions (e.g., Pfister, 1992; Pfister et al., 1998), although often without independent validation (one exception is Brazdil, 1992).

For proxy data from ice cores, lake sediments and corals, fitting transfer functions was more difficult and progress was slower. Climatic influences on ice cores were investigated through comparison or correlation studies (Barlow et al., 1993; Appenzeller et al., 1998; White et al., 1997). The first cross-validated transfer functions for coral data have been presented by Crowley et al. (1999). Most of the previous coral studies did not undertake independent validation for correlations or transfer functions (for a review see Dunbar and Cole (1999)).

With the development of multiproxy reconstructions, instrumental data have not only been used as predictands, but long instrumental series have also been included as predictors in reconstructions, e.g., for circulation indices (Luterbacher et al., 1999) and climate fields (Wanner et al., 1995; Luterbacher et al., 2000; Mann et al., 1998, 1999).

Paleoclimate reconstructions cited in the first assessment report (IPCC, 1990) are mainly based on pollen records, insect and animal remains, oxygen isotopes and other geological data from lake varves, ocean sediments, and ice cores, as well as on glacier termini. Reconstructions included the Pliocene climate optimum, the Eemian interglacial, the Mid-Holcene optimum, but also shorter periods such as the Younger Dryas, the Medieval warm period and the Little Ice Age, and thus provided estimates of climate variability on time scales from millions of years to several decades. The primary reconstructions were for specific regions for which a particular proxy record was considered to be representative. By mapping them together, an approximate description of continental- to hemispheric-scale mean climate could be obtained for certain time slices, though this was done in a somewhat subjective way, and merging the records is complicated by dating uncertainties.

An extended multi-proxy network was used by Mann et al. (1995) to estimate global temperatures for the past five centuries, while a similar network was used by Mann et al. (1998) to estimate spatial patterns of temperature anomalies over the past six centuries by regression models for the leading principal components of the temperature field. Jones et al. (1998) used averaged normalized paleoclimatic series from various proxies to estimate hemispheric temperatures over the last millennium. The approach of Mann et al. (1998) was extended back to 1000 AD by Mann et al. (1999). This study, which merged instrumental data from 1902 to 1999 with multi-proxy paleoclimate reconstructions from 1000 to 1980, was presented in the TAR (IPCC, 2001a).

1.5.3 Cryospheric Topics

The cryosphere, which includes the ice sheets of Greenland and Antarctica, continental (including tropical) glaciers and snow fields, sea ice and permafrost, is an important climate indicator. It might seem logical to expect that the cryosphere overall would shrink in a warming climate; however, increased precipitation due to a strengthened hydrological cycle may counter this effect.

In situ monitoring of some cryospheric elements has a long tradition. Data of thaw and freeze dates for lake and river ice start in 1444 with Lake Suwa in Japan. Records of glacial length go back to the mid-1500s. Internationally coordinated long-term glacier observations, however, started in 1894 with the establishment of the International Glacier Commission in Zurich, Switzerland. The longest time series of a glacial *mass* balance was started in 1948, with the *Storglaciären* in northern Sweden followed by *Storbreen* in Norway (begun in 1949). Today a global network of mass balance monitoring for some 60 glaciers is coordinated through the World Glacier Monitoring Service. On the other hand, systematic measurements of permafrost (thermal state and active layer) began in earnest only in recent decades (coordinated under the Global Terrestrial Network for Permafrost).

The main climate variables of the cryosphere (extent, albedo, topography and mass) should in principle be observable from space, given proper calibration and validation through in situ observing efforts. Indeed, satellite data would be required in order to have full global coverage. The polar-orbiting NIMBUS-5, launched in 1972, yielded the earliest all-weather, all-season imagery of global sea ice, using microwave instruments (Parkinson et al., 1987), enabling a major advance in our understanding of the dynamics of the cryosphere. Launched in 1978, TIROS-N yielded the first monitoring from space of snow on land surfaces (Dozier et al., 1981). These are but a few examples of cryospheric elements now routinely monitored from space. A significant piece still missing in cryospheric monitoring is the variability of ice volume. Two satellite missions dedicated to filling this gap are scheduled to take place during this decade: NASA's IceSat and ESA's Cryosat.

The cryosphere derives its importance for the climate system from a variety of effects, including its high reflectivity (albedo) for solar radiation, its low thermal conductivity, its large thermal inertia, its potential for affecting ocean circulation (through exchange of freshwater and changes in air-sea heat exchange), and its large potential for affecting sea level (through growth and melt of land ice). Finally, greenhouse gases can be released from the ocean as the sea ice retreats and from frozen ground as it thaws.

The importance of the latter effect came to be realized widely only in the 1990s, starting with the works of Kvenvolden (1988, 1993), MacDonald (1990) and Harriss et al. (1993). Carbon dioxide (CO_2) and methane (CH_4) trapped in permafrost are released into the atmosphere as the permafrost thaws due to a warmer climate. Since CO_2 and CH_4 are greenhouse gases, atmospheric temperature will in turn increase, resulting in a feedback loop and more permafrost thawing. The permafrost and seasonally-thawed soil layers at high latitudes contain a significant amount (about one quarter) of the global total amount of soil carbon. Because global warming signals are amplified in high-latitude regions, the potential for permafrost thawing, and greenhouse gas releases, is thus large.

The albedo feedback mechanism has a much longer history. The albedo is the fraction of solar energy reflected back to space, which over the cryosphere is large (about 0.8) compared to the Earth’s average planetary albedo (about 0.3). In a warming climate, it is anticipated that the cryosphere would shrink, the Earth's overall albedo would decrease, and more solar energy would be absorbed to warm the earth still further. This powerful feedback loop – the albedo feedback - was recognized in the 19th century by Croll (1890) and was first introduced in climate models by Budyko (1969) and Sellers (1969).

Although the principle of the albedo feedback is simple, a quantitative understanding of the effect is still far from complete. Is it, for instance, the main reason to expect amplified warming signals at high latitudes? The snow and ice program of the SHEBA (“Surface Heat Budget of the Arctic Ocean”) ice camp experiment in 1997–1998 was designed to develop a quantitative understanding of the processes that collectively make up the ice albedo feedback (see e.g., Curry et al., 1995; Curry et al., 2001).

Recent climate modelling results have pointed to high-latitude regions as areas of particular importance and vulnerability to global climate change. Despite the climatic significance of these typically cryospheric regions, many physical processes (of which only a few are discussed above) are still not well understood, quantified, or represented in the climate models. By the time of the TAR, several climate models incorporated physically based treatments of ice dynamics, although the land ice processes were only rudimentary. Improving the representation in climate models of the cryosphere, together with its many interactions with other elements of the climate system, is still an area of intense research and continuing progress.

1.5.4 Ocean and Atmosphere Dynamics

The atmosphere and surface ocean circulations were observed and analyzed globally as early as in the sixteenth and seventeenth centuries, in close association with the development of worldwide trade based on sailing. This effort led to important conceptual and theoretical works (Lorenz, 1967). A description of the tropical atmospheric cells, for example, was first published by Edmund Halley in 1686, whereas in 1735 George Hadley proposed a theory linking the existence of the trade winds with those cells. These early studies helped to forge concepts which are still useful in analyzing and understanding model simulations. The exploration of the deeper ocean and of higher levels in the atmosphere, however, has taken more time. The balloon record of Gay-Lussac, who reached an altitude of 7016 m in 1804, remained unbroken for more than 50 years. The stratosphere was discovered by Teisserenc de Bort and Richard Assmann as recently as the early 20th century. For more than two centuries, it has been recognized that the oceans’ cold subsurface waters must originate at high latitudes. However, it was not appreciated until the latter half of the 20th century that the deep ocean circulation may be variable on anything less than geological time scales, and that the ocean's "Meridional Overturning Circulation" (the MOC, also often referred to as the "thermohaline circulation" or THC) may actually be crucially important for climate.

By the 1950s studies of deep sea cores suggested that the deep ocean temperatures had varied in the distant past. Technology also evolved to enable measurements that could confirm that the deep ocean is not only not static, but in fact is highly variable. One key technological accomplishment was Swallow and Stommel's 1960 Aries experiment (Crease, 1962). By the late 1970s, current meters could monitor deep currents for substantial amounts of time, and the first ocean observing satellite (SeaSat) revealed that significant information about ocean variability is imprinted on the sea surface. At the same time, Oort and Vonder Haar (1976) estimated that the oceans may be responsible for as much as half of the poleward heat transport, and state estimation was used to quantify the MOC based on models and data (Wunsch, 1978).

In parallel with these developments yielding new insights through observations, theoretical and numerical explorations of multiple (stable or unstable) equilibria began. Stommel (1961) proposed a mechanism, based on the opposing effects that temperature and salinity have on density, by which ocean circulation could fluctuate between states. Numerical climate models incorporating models of the ocean circulation were also developed during this period, including the pioneering work of Kirk Bryan and Syukuro Manabe (Bryan, 1969; Manabe and Bryan, 1969). In fact, the approximately equal division of atmosphere-ocean heat transport was anticipated by these models. The idea that the ocean circulation could change radically, and might perhaps even possess several distinct states, gained support through the simulations of coupled climate models (Bryan and Spelman, 1985; Bryan, 1986; Manabe and Stouffer, 1988). Model simulations using a hierarchy of models showed that the ocean circulation system was particularly vulnerable to changes in the freshwater balance, either by direct addition of freshwater or by changes in the hydrological cycle. A strong case emerged for the hypothesis that rapid changes in the Atlantic thermohaline circulation were responsible for the Dansgaard-Oeschger events.

Although scientists now better appreciate the strength and variability of the global-scale MOC, its roles in climate are still hotly debated. Is it a passive recipient of atmospheric forcing and so merely a diagnostic consequence of climate change, or is it an active contributor? Observational evidence for the latter proposition was presented by Sutton and Allen (1997), who saw sea surface temperature anomalies propagating along the Gulf Stream/North Atlantic Current system for years, implicating internal oceanic timescales. Is a radical change in the MOC likely in the near future? The modern observational record indicates that the water masses of the North Atlantic are becoming fresher over time (e.g., Lazier, 1995), thus raising the possibility that this ocean might be approaching Stommel's other stable regime. Monitoring the MOC directly, however, remains a substantial challenge; the TAR recommended that appropriate observations for comparisons with climate models were needed, and that "the realism of the representation of oceanic mechanisms involved in the THC [(the MOC)] changes needs to be carefully evaluated in the models".

Developments in the understanding of the interactions between atmosphere and oceans constitute a striking example of the continuous interplay between theory, observations, and, more recently, model simulations. This interplay is dramatically illustrated by the rapid advances in understanding the El Niño-Southern Oscillation (ENSO) phenomenon, which originates in the Pacific but affects climate globally. Sir Gilbert Walker (1928) discovered an atmospheric pressure seesaw pattern between the Indian Ocean and the eastern Pacific which he dubbed the "Southern Oscillation." He related it to occurrences of drought and heavy rains in India, Australia, Indonesia and Africa. He also proposed that there must be a certain level of predictive skill in that system. El Niño is the name given to the rather unusual oceanic conditions – warm waters spoiling the otherwise productive fishing grounds occurring in the eastern tropical Pacific off the coast of Peru every few years. The International Geophysical Year of 1957–1958 coincided with a large El Niño, allowing a remarkable set of observations of the phenomenon.

A decade later a mechanism was presented that connected Walker's observations to El Niño (Bjerknes, 1969). This mechanism involves the interaction, through the SST field, between the east-west atmospheric circulation of which Walker's Southern Oscillation was an indicator (Bjerknes appropriately referred to this as the "Walker circulation") and variability in the pool of equatorial warm water of the Pacific Ocean.

Observations made in the 1970s (e.g., Wyrtki, 1975) showed that prior to ENSO warm phases, the sea level in the western Pacific rises significantly, and by the mid-1980s, after an unusually disruptive El Niño struck in 1982–1983, an observing system (the Tropical Ocean-Global Atmosphere (TOGA) array; see McPhaden et al., 1998) was in place to monitor ENSO. The resulting data confirmed the idea that the phenomenon was inherently one involving coupled atmosphere-ocean interactions and yielded much-needed detailed observational insights. By 1986, the first ENSO forecasts were made (see Barnett et al, 1988).

The mechanisms and predictive skill of ENSO are still under discussion. In particular, it is not clear how ENSO changes with, and perhaps interacts with, a changing climate. The TAR states “..increasing evidence suggests the ENSO plays a fundamental role in global climate and its interannual variability, and increased credibility in both regional and global climate projections will be gained once realistic ENSOs and their changes are simulated."

Just as the phenomenon of El Niño has been familiar to the people of tropical South America for centuries, a seesaw pattern of climate variability in the North Atlantic has similarly been known by the people of Northern Europe since the days of the Viking explorers. The Danish missionary Hans Egede made the following well-known diary entry in the mid-18th century: “In Greenland, all winters are severe, yet they are not alike. The Danes have noticed that when the winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely” (van Loon and Rogers, 1978).

Walker, in his studies in the Indian Ocean, actually studied *global* maps of sea level pressure correlations, and recognized not only the Southern Oscillation, but also a Northern Oscillation, which he subsequently divided into a North Pacific and a North Atlantic Oscillation, (Walker, 1924). However, it was Exner (1913, 1924) who made the first correlation maps showing the spatial structure in the Northern Hemisphere, where the North Atlantic Oscillation (NAO) pattern stands out clearly.

The NAO significantly affects weather and climate, ecosystems, and human activities of the North Atlantic sector. But what is the underlying mechanism? The recognition that the NAO is associated with variability and latitudinal shifts in the westerly flow of the jet stream originates with the works of Willett, Namias, Lorenz, Rossby and others in the 1930s, 1940s and 1950s (Stephenson et al., 2003). Because atmospheric planetary waves are hemispheric in nature, changes in one region will often be connected with changes in other regions, a phenomenon dubbed “teleconnection” (Wallace and Gutzler, 1981). The NAO is now seen as primarily a stochastic process internal to the atmosphere (as evidenced by numerous atmosphere-only model simulations). However, it is the low-frequency variability of the phenomenon that fuels continued investigations among climate scientists. For instance the long time scales, and hence the long "memory," of the ocean may allow for some persistence, and thereby some predictive skill, in the NAO.

Bjerknes (1964) recognized the connection between the NAO index (which he referred to as the “zonal index”) and sea surface conditions. He speculated that ocean heat advection could play a role on longer time scales. The circulation of the Atlantic Ocean is radically different from that of the Indian and Pacific Oceans, in that the MOC is strongest in the Atlantic with warm water flowing northwards, even south of the equator, and cold water returning at depth. It is therefore not surprising that the oceanic contributions to the NAO and to the Southern Oscillation are different. By modifying the sea surface temperatures, variations in the MOC are thought to trigger changes in the NAO.

1.5.5 Greenhouse Gases, Aerosols, and Radiative Forcing

The modern scientific conception of the complex and interconnected climatic roles of greenhouse gases and aerosols has undergone rapid evolution over the last two decades. This time period coincides approximately with that of the existence of the IPCC itself, which began in 1988. Thus, it is instructive to view the evolution of this topic as it has been treated in the successive IPCC reports.

The IPCC's First Assessment Report or FAR (IPCC, 1990) was visionary in its recognition of the many important links in the Earth system that form the relationship between a changing climate and atmospheric composition, chemistry, the carbon cycle, and natural ecosystems. The science of the time, as summarized in the FAR, could make a clear case for anthropogenic interference with the climate system. In terms of greenhouse agents, the main conclusions from the FAR Policymakers Summary are still valid today: (1)

"emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: CO_2, CH_4, CFCs, N_2O"; (2) "some gases are potentially more effective (at greenhouse warming)"; (3) feedbacks between the carbon cycle, ecosystems, and atmospheric greenhouse gases in a warmer world will impact CO_2 abundances; and (4) global warming potentials (GWPs) of the greenhouse gases provide a metric for comparing different emissions. The climatic importance of tropospheric ozone, sulfate aerosols, and atmospheric chemical feedbacks were proposed by some scientists at the time and noted in the assessment. For example, early global chemical modeling results argued that global tropospheric ozone (O_3), a greenhouse gas, was controlled by the highly reactive gases: odd-nitrogen (NOx), carbon monoxide (CO), and non-methane hydrocarbons (NMHC) or equivalently, volatile organic compounds (VOC). In terms of sulfate aerosols, both the direct radiative effects and the indirect effects on clouds were acknowledged, but the importance of carbonaceous aerosols from fossil fuel and biomass combustion was not recognized at the time.

The concept of radiative forcing (RF) was established at the time (and summarized in FAR Chapter 2). RF agents included direct greenhouse gases, solar radiation, aerosols, and the Earth's albedo. What was new and only briefly mentioned was that "many gases produce indirect effect on the global radiative forcing." The innovative global modeling work of Derwent (1990) showed that emissions of the reactive but non-greenhouse gases - NOx, CO, and NMHC - altered atmospheric chemistry on a scale to change the abundance of other greenhouse gases. Indirect GWPs for NOx, CO, and VOC were proposed. The knowledge of chemical feedbacks was limited to short-lived increases in tropospheric ozone. By 1990, it was clear that tropospheric ozone had increased over the 20th century and stratospheric ozone had decreased since 1980, but these radiative forcings were not evaluated. Neither was the effect of anthropogenic sulfate aerosols, except to note in the FAR that "it is conceivable that this radiative forcing has been of a comparable magnitude, but of opposite sign, to the greenhouse forcing earlier in the century." Reflecting in general the community's concerns about this relatively new measure of climate forcing, RF bar charts appear only in the underlying FAR chapters, but not in the FAR Summary. Only the long-lived greenhouse gases are shown, although sulfate aerosols' direct effect in the future is noted with a question mark (depending on future emissions).

Although there were clear cases for more complex chemical and aerosol effects, the scientific community was unable at the time to reach general agreement on the existence, scale, and magnitude of these indirect effects. Nevertheless, these early discoveries drove the research agendas in the early 1990s. The widespread development of global chemistry-transport models (CTMs) had just begun with international workshops (Pyle et al., 1996; Jacob et al., 1997; Rasch, 2000). In 1992, the indirect chemical effects of CO, NOx, and VOC were reaffirmed (IPCC, 1992), and the feedback of methane on its own lifetime first noted, but the indirect RF values from the FAR were backed away from in this IPCC report and denoted in a table with a '+', '0' or '-'. Aerosol-climate interactions still focused on sulfates, and the assessment of their direct RF cooling of the northern hemisphere was now somewhat quantitative as compared to the FAR. Stratospheric ozone depletion is noted as being a significant and negative RF, but not quantified. Ecosystems research at this time was identifying the responses to climate change and CO_2 increases as well as altering the CH_4 and N_2O fluxes from natural systems; however, in terms of a community assessment it was only qualitative (i.e., a '+', '0' or '-' in the 1992 assessment).

By 1995, when work was in progress on the IPCC Second Assessment Report or SAR (IPCC, 1996) and its special report on radiative forcing (IPCC, 1995), significant breakthroughs had occurred. The special report presented an intensive set of chapters on the carbon cycle, atmospheric chemistry, aerosols and radiative forcing. The carbon budget for the 1980s was analyzed not only from bottom-up emissions estimates, but also from a top-down approach using the observed evolution of carbon isotopes and O_2/N_2 ratios. Similarly, expanded analyses of the global budgets of trace gases and aerosols from both natural and anthropogenic sources showed the rapid expansion of biogeochemical research. The first RF bar chart appears, comparing all the major components of RF change from pre-industrial to present. In terms of atmospheric chemistry, the first open-invitation modeling study for IPCC recruited 21 atmospheric chemistry models to participate in a controlled study of photochemistry and chemical feedbacks. These studies (Olson et al., 1997) demonstrated a robust consensus in some indirect effects (i.e., the CH_4 feedback on its lifetime became an IPCC summary recommendation), but too great uncertainties in others (i.e., the prediction of tropospheric O_3 changes). The abstract theory of chemical feedbacks in the CH_4-CO-OH system (Prather, 1994) combined with these model studies firmly established that the atmospheric residence time (and hence climate impact) of anthropogenic

CH_4 emissions was about 50% greater than expected. There was still no consensus on quantifying the past or future changes in tropospheric OH (the sink for CH_4) or O_3.

In the early 1990s, research on aerosols as greenhouse agents expanded. The range of climate-relevant aerosols based on new research was extended for the first time beyond sulfates to include nitrates, organics, soot, mineral dust, and sea salt. Quantitative estimates of aerosol indirect effects on clouds were sufficiently well established to be included in assessments, and carbonaceous aerosols from biomass burning were recognized as being comparable in importance to sulfate (Penner et al., 1992). Uncertainty ranges are given in the special report (IPCC, 1995) for sulfate RF (–0.25 to –0.9 W/m^2) and biomass burning aerosols (–0.05 to –0.6). The aerosol indirect RF is estimated to be about equal to the direct RF, but with larger uncertainty. Mt. Pinatubo volcano's injection of stratospheric aerosols is noted as the first modern test of a known climate forcing, and indeed one climate model accurately predicted the temperature response (Hansen et al., 1992). In the one-year interval between the special report and the SAR, our understanding of aerosols grew. The direct anthropogenic aerosol forcing (from sulfate, fossil fuel soot, and biomass burning aerosols) was reduced to -0.5 W/m^2. The RF bar chart is now broken into aerosol components (sulfate, fossil-fuel soot, and biomass burning aerosols) with a separate range for indirect effects.

During the 1990s there were concerted research programs in the U.S. and EU to evaluate the global environmental impacts of aircraft, both the current civil aviation and a proposed supersonic fleet. Various national assessments, which culminated in the IPCC special report on Aviation and the Global Atmosphere (IPCC, 1999), integrated the climate and global air quality assessment of the impacts of the aviation sub-sector. An open invitation for atmospheric model participation resulted in community participation and a consensus on many of the environmental impacts of aviation (e.g., the increase in tropospheric O_3 and decrease in CH4 due to NOx emissions were quantified). Direct aerosol effects of sulfate and soot were likewise quantified along with immediate linear contrails, but the cirrus clouds that are sometimes generated downwind of contrails were not. Thus quantitative assessment of the RF from indirect effects such as the NOx photochemical impact on tropospheric O_3 and CH_4 were included, but aerosol-cirrus effects were not. The scientific community has difficulty agreeing on and assigning uncertainties in most such assessments, but this IPCC assessment defined 2/3 likelihood probability ranges for most impacts based on mixed objective/subjective criteria. These probability ranges were propagated through to a total RF, even though the basic latitudinal dissimilarity of the different RF was noted (i.e., contrails and O_3 change are predominantly in northern mid-latitudes whereas CO_2 and CH_4 changes are global). That assessment affirmed that RF was a first-order measure of the global mean surface temperature response, although it would be inadequate for regional climate change. The RF bar chart for aviation included the best estimate for the individual components plus their 2/3-likelihood uncertainty ranges.

By the end of the 1990s, research on atmospheric composition and climate forcing had made many important advances. The IPCC Third Assessment Report or TAR (IPCC 2001a) was able to provide a more quantitative evaluation in some areas, but took a sobering step backwards in others. For example, a large, open-invitation modeling workshop was held for both aerosols (11 global models) and tropospheric O_3-OH chemistry (14 global models). This workshop brought together as collaborating authors most of the international scientific community involved in developing and testing global models for atmospheric composition. In terms of atmospheric chemistry, a strong consensus was reached for the first time that we could predict the changes in tropospheric O_3 in response to scenarios for CH_4 and the indirect greenhouse gases (CO, NOx, VOC). Further, combining these models with observational analysis, an estimate of the change in tropospheric O_3 since the pre-industrial era – with uncertainties – was reported. Similar advances were made from the aerosol workshop on evaluating the impact of different aerosol types. The consistent propagation of uncertainties could not be agreed upon and was not carried forward. There were many different representations of uncertainty (e.g., a range in models vs. an expert judgment) in the TAR, and the consensus RF bar chart did not generate a total RF or uncertainties for use in the subsequent IPCC Synthesis Report (IPCC, 2001b).

1.5.6 Solar Variability and the Total Solar Irradiance

Naked-eye observations of sunspots date back to ancient times, but it was only after the invention of the telescope in 1607 that it became possible to monitor routinely the number, size and position of these “stains” on the surface of the Sun. Throughout the 17th and 18th centuries, numerous observers noted the variable concentrations and ephemeral nature of sunspots, but very few sightings were reported between 1672 and 1699 (for an overview see Hoyt et al., 1994). This period of low solar activity, now known as the Maunder Minimum, was one of several which occurred during the climate period now commonly referred to as the Little Ice Age (Eddy, 1976). There is no exact agreement as to which dates mark the beginning and end of the Little Ice Age, but from about 1350 to about 1850 is one reasonable estimate.

During the latter part of the 18th century Wilhelm Herschel noted the presence not only of sunspots but of bright patches, now referred to as faculae, and of granulations on the solar surface. He believed that when these indicators of activity were more numerous, solar emissions of light and heat were greater and could affect the weather on Earth. He tested this theory by comparing sunspot numbers with wheat prices in London (Herschel, 1801). In 1844 Heinrich Schwabe published his discovery of a “10-year cycle” in sunspot numbers. Samuel Langley (1876) compared the brightness of sunspots with the surrounding photosphere. He concluded that they would block the emission of radiation and estimated that at solar maximum the sun would be about 0.1% less bright than at the minimum of the cycle, and that the Earth would be 0.1–0.3°C cooler.

Measurement of the absolute value of total solar irradiance (TSI) is difficult from the Earth’s surface because of the need to correct for the influence of the atmosphere. Langley (1884) attempted to minimise the atmospheric effects by taking measurements from high on Mt. Whitney in California, and to estimate the correction by taking measurements at several times of day, i.e. with the solar radiation having passed through different atmospheric path-lengths. Langley's value of TSI of 2903 W m^{-2} is considerably larger than current estimates, of about 1365 W m^{-2}, and mathematical errors in data analysis may have contributed to this overestimate. Between 1902 and 1957 thousands of measurements of TSI were made from mountain sites by Charles Abbot and a number of other scientists around the globe. Values ranged from 1322 to 1465 W m^{-2}. Foukal et al. (1977) deduced from Abbot’s daily observations that higher values of TSI were associated with more solar faculae.

In 1978 the Nimbus-7 satellite was launched with a cavity radiometer and provided evidence of variations in TSI (Hickey et al., 1980). Additional observations were made from the Solar Maximum Mission, launched in 1980, with an active cavity radiometer (Willson et al., 1980). Both of these missions showed that the passage of sunspots and faculae across the Sun’s disk influenced TSI. At the maximum of the 11-year solar activity cycle, the TSI is larger by about 0.1% than at the minimum.

Abbot (1910) believed that he had detected a downward trend in TSI that was coincident with a general cooling of climate, but it is more likely that the cooling was due to several major volcanic eruptions which, through enhancing the stratospheric sulfate layer, also acted to reduce the solar irradiance reaching the ground. The solar cycle variation in irradiance corresponds to an 11-year cycle in radiative forcing of about 0.23 Wm^{-2}. There is increasingly reliable evidence of its influence on atmospheric temperatures and circulations, particularly in the higher atmosphere (Labitzke and van Loon, 1997; van Loon and Labitzke, 2000; Balachandran and Rind, 1995; Brasseur, 1993; Haigh, 1996). Satellite data have been used in combination with the historically recorded sun spot number to estimate the solar radiation over the last 1000 years (Eddy, 1976; Lean, 1997; Lean et al., 1995; Hoyt and Schatten, 1993, 1997). These data indicate changes in solar radiation of 0.24 – 0.30% on the centennial time scale. Calculations with energy balance models (Wigley and Raper, 1990a; Reid, 1991; Crowley and Kim, 1996; Bertrand et al., 1999) and 3-dimensional models (Wetherald and Manabe, 1975; Cubasch et al., 1997; Cubasch and Voss, 2000; Lean and Rind, 1998; Tett et al., 1999) suggest that such relatively small changes could cause surface temperature changes on the order of several tenths of a degree centigrade, but such changes are still less than what was observed over the twentieth century.

1.5.7 Model Ensembles and Model Intercomparisons

The first U.S. National Academy of Sciences report on global warming (Charney et al., 1979), on the basis of two models, spoke of a factor of three uncertainty in the prediction of equilibrium global mean surface temperature increase due to doubled atmospheric carbon dioxide, from 1.5°C to 4.5°C. This range remained part of conventional wisdom at least as recently as the IPCC Third Assessment Report or TAR (IPCC, 2001a).

The existence of a range in model results is not a surprise, because it is well known that climate predictions, like weather forecasts, are intrinsically uncertain. This uncertainty is due to a variety of factors. In his seminal paper on deterministic chaos, Lorenz (1963) showed how relatively small differences in the initial conditions of a simple nonlinear system can, in finite time, lead to qualitatively very different solutions of the systems. Because the underlying thermo-hydrodynamic governing equations of climate are fundamentally nonlinear, uncertainties in the initial conditions thus make perfect deterministic forecasts impossible for valid theoretical reasons. In addition, the accuracy of climate model simulation is influenced by uncertainties in our ability, first to determine realistically, and then to solve computationally, the full set of physical equations that govern climate. The models are not completely comprehensive, because they do not explicitly represent small scales, such as those which generate most cloud systems, and because they do not yet include the totality of the subsystems and processes which affect climate (see Figure 1.2). Those different sources of errors tend to interact and reinforce each other; errors in the physical parameterizations of unresolved small-scale processes, such as those involving atmospheric and oceanic turbulence, or microphysical and radiative interactions in clouds, can propagate upscale and influence weather and climate phenomena whose characteristic size is much larger than the truncation scale of the discretized model equations.

To assess and disentangle those effects, the scientific community has organized successive systematic comparisons of the different existing models, and has favored an increase in the number and the range of the simulations being carried out. The first published comparison of model simulations in response to increasing carbon dioxide content, by Schlesinger and Mitchell (1987), was based on single realizations of three models and revealed the important role of convective parameterizations. Subsequently, Cess et al. (1989) compared results of documented differences in simulated cloud behaviour among a number of models, together with their consequent disagreement in predicting climate response to carbon dioxide.

As it was difficult to pinpoint the differences in the models’ reaction to differences in their initial conditions, their boundary conditions, their parameterizations or their numerical schemes, several model intercomparison projects (MIPs) were set up in the 1990s, to propose controlled conditions for model evaluation. Notable among these were AMIP, which studied atmospheric GCMs, and CMIP, which studied coupled ocean-atmosphere GCMs. It proved important in MIPs to standardize the model forcing parameters and the model output so that file formats, variable names, units, etc., are easily recognized by data users. The fact that the model results were stored separately and independently of the modeling centres, and that the analysis of the model output was performed mainly by research groups independent of the modelers, has added confidence in the results. Summary diagnostic products such as the Taylor (2000) diagram were developed for MIPs.

AMIP opened a new era for climate modelling, setting standards of quality control, providing organizational continuity, and ensuring that results are reproducible. Results from AMIP have provided a number of insights into climate model behaviour (Gates et al., 1999) and quantified improved agreement between simulated and observed atmospheric properties as new versions of models are developed. These results suggest that the most problematic remaining areas of coupled GCM simulations involve cloud-radiation processes, the cryosphere, the deep-ocean and ocean-atmosphere interactions.

Comparing different models is not enough; using multiple simulations from a single model (the so called Monte Carlo, or ensemble, approach) has proved a necessary and complementary approach to assess the stochastic nature of the climate system (e.g., Palmer, 2000). The first Monte Carlo climate change simulations with global GCMs used a set of different initial and boundary conditions (Cubasch et al., 1994; Barnett, 1995). Computational constraints limited them to a relatively small number of samples (fewer than ten).

Clearly, intercomparison of existing models and ensemble model studies are still undergoing rapid development. It is worth emphasizing that the progress in modeling and in making model comparisons has been extraordinarily rapid during the last decade. At the time AMIP was designed, running a 10-year simulation forced by seasonally varying SST conditions was already an impressive achievement; some modeling groups were still relying on experiments with the boundary conditions and solar radiation input fixed in a “perpetual” January or July. Coupled ocean-atmosphere models were still experimental, and many climate change simulations were investigating the effects of doubling carbon dioxide using atmospheric models coupled to a simple "slab" ocean model with no explicit ocean dynamics. Running ensembles was essentially impossible until recent advances in computer power occurred.

These systematic comprehensive climate model studies are exceptionally demanding on computer resources. Their progress has marked the evolution from the FAR to the TAR, and is likely to continue in the years to come.

1.5.8 Model Clouds and Climate Sensitivity

The modeling of cloud processes and feedbacks provides a striking example of the unequal pace of scientific progress in our discipline.

On the one hand, cloud representation may arguably constitute the area in which atmospheric models have improved most continuously. In the early 1980s, most models were still using prescribed clouds and prescribed cloud properties to compute the transport of atmospheric radiation. Succeeding generations of models have used relative humidity or other simple predictors to diagnose cloudiness, thus providing a foundation of increased realism for the models, but at the same time possibly causing inconsistencies in the representation of the multiple roles of clouds as bodies interacting with radiation, or generating precipitation, or influencing small-scale convective or turbulent circulations. The present generation of models generally incorporates a comprehensive representation of clouds based on consistent physical principles. Comparisons of models to observational data clearly show that, on the average, the representation of clouds in climate models is much more realistic now than only a few years ago.

In spite of this undeniable progress, however, clouds still constitute the main source of uncertainties affecting the amplitude of climate projection. This apparent contradiction may be explained by calculations using idealized models of radiative equilibrium. Such calculations suggest that changes in global cloud amount by only one or two percent, if they occurred as part of climate change, might either double or halve the climate model sensitivity to changes in atmospheric carbon dioxide. Clouds, which cover about 60% of the Earth's surface, are responsible for about two-thirds of the planetary albedo. At present, the albedo is about 30%. An albedo change of only 1% would cause a change in the blackbody radiative equilibrium temperature of about 1°C. This is about the same black-body temperature response as would occur in response to adding 4 Watts per square meter to the earth's surface radiation budget, which is approximately the direct radiative forcing due to doubling the atmospheric carbon dioxide concentration. Clouds also contribute importantly to the planetary greenhouse effect.

Thus, even on the simplest theoretical grounds, it is clear that the sensitivity of the Earth's climate to changing atmospheric greenhouse gas concentrations may depend strongly on cloud feedbacks. But changes in cloud cover constitute only one of the many parameters that affect cloud radiative interaction. In addition, cloud optical thickness, cloud height and cloud microphysical properties can also be modified by atmospheric temperature changes and add to the complexity of feedbacks, as evidenced through satellite observations analyzed by Tselioudis and Rossow (1994).

The extraordinary sensitivity of climate models to cloud feedbacks was first revealed by extensive model intercomparisons (Cess et al., 1989), showing a factor of three in the range of the model sensitivity results. It was emphasized further through a now-classic set of GCM experiments, carried out by Senior and Mitchell (1993). They produced global average surface temperature changes (due to doubled carbon dioxide) ranging from 1.9 to 5.4°C, simply by altering the way in which cloud optical properties were treated in the model. It is somewhat unsettling that the results of a complex climate model can be so drastically altered by substituting one reasonable cloud parameterization for another, thereby approximately replicating the overall inter-model range of sensitivities. Consistently, other GCM groups have also obtained widely varying results by trying other techniques of incorporating cloud microphysical processes and their radiative interactions (e.g., Le Treut and Li, 1991; Roeckner et al., 1987), in contrast to the approach which Senior and Mitchell (1993) followed. The model intercomparisons presented in the TAR showed no clear resolution of this unsatisfactory situation.

In the opinion of many experts, additional observational research is key to the development of improved model treatments of clouds. The importance of reliable observations has been the motivation for pioneering efforts such as the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1991). This international collaborative effort, which is still continuing, has developed a consistent analysis of cloud cover and cloud properties using operational meteorological satellites for more than two decades. The ISCCP data have greatly aided the development of cloud representations in climate models since the mid-1980s (Le Treut and Li, 1988; Del Genio et al., 1996). These data have been complemented by other data sets, such as those associated with high-resolution spectrometers (HIRS), or microwave absorption (SSMI).

However, these data alone cannot provide a comprehensive three-dimensional description of clouds and their relevant properties. The large range in simulated cloud feedbacks in models, together with the limitations of existing measurements and the growing realization of the complexity of cloud-radiation interactions, have all provided strong incentives to obtain additional satellite observations. As a result, satellite remote sensing instrumentation has rapidly evolved in several directions, including higher resolution (e.g., AIRS and IASI), radars (e.g., CLOUDSAT), lidars (e.g., CALIPSO), and polarization (e.g., PARASOL). Many members of this new generation of instruments will be ready for launch in the current time frame, after more than a decade of dedicated development efforts. Their benefits are therefore expected to be realized in the near future.

Simultaneously, the research community has come to the realization that a parallel effort must be carried out for ground-based measurements, not only to provide an adequate reference for satellite observations, but also to make possible a detailed and empirically-based analysis of the entire range of space and time scales involved in cloud processes. The earliest and most comprehensive such effort has been the Atmospheric Radiation Measurement (ARM) Program in the U. S., which has established multi-instrumental observational sites to monitor the full complexity of cloud systems on a long-term basis (Ackerman and Stokes, 2003). Shorter field campaigns dedicated to the observation of specific phenomena have also been established, such as for convective systems (TOGA-COARE; Webster and Lukas, 1992), or stratocumulus (ASTEX).

The use of these novel data has often required that new theoretical tools be developed to aid in validating parameterizations in a mode that emphasizes the role of cloud processes participating in climatic feedbacks. One such approach has been to focus on comprehensively observed episodes of cloudiness for which the large-scale forcing is known, using single-column models (Randall et al., 1996; Somerville, 2000), to evaluate GCM parameterizations with both observations and higher-resolution cloud-resolving models. Another approach is to make use of the more global and continuous satellite data, on a statistical basis, through an investigation of the correlation between climate forcing and cloud parameters (Bony et al., 1997), in such a way as to provide a test of feedbacks between different climate variables.

Cloud feedbacks have long been regarded as the largest single source of uncertainty in predicting climate change due to increasing concentrations of greenhouse gases. If this uncertainty has not yet been reduced, nevertheless it is certainly true that recent years have witnessed a considerable development of the scientific tools necessary to tackle the problem.

1.5.9 Coupled Ocean-Atmosphere Models

Most of the climate projections presented in the FAR (IPCC, 1990) were the results of atmospheric models coupled with simple “slab” ocean models, i.e., models omitting all ocean dynamics. Replacing those models by fully coupled ocean-atmosphere models may arguably have constituted the most significant leap forward in climate modelling during the last 20 years. Although it is fair to recognize that this advance has not produced any profound modification in the major patterns of the mean simulated climate change, it has opened up the possibility of exploring transient climate scenarios, and it constitutes a first step toward the development of comprehensive “Earth-system models” that include explicit representations of chemical and biogeochemical cycles.

The first attempts at coupling atmospheric and oceanic models were carried out during the late 1960s and early 1970s (Manabe and Bryan, 1969; Manabe et al., 1975; Bryan et al., 1975). Since these early developments, coupled models have faced difficulties which have considerably delayed their development, including: (i) the initial state of the ocean is not precisely known; (ii) a surface flux imbalance (in either energy or fresh water) much smaller than the observational accuracy is enough to cause a drifting of coupled

GCM simulations into unrealistic states; and (iii) there is no stabilizing feedback that can compensate for any errors in the simulated salinity.

The fundamental nature of these difficulties became more apparent when it was shown that the simulated climate sensitivity could depend strongly on the details of cloud feedbacks, and therefore on the mean simulated climate (Cess et al., 1989). This dependence on the base state obviously includes many other simulated climate features (e.g., latitudinal temperature gradients), and extends to the model transient behaviour. Similar problems also explain why, although thermodynamic (Semtner, 1976) or dynamic thermodynamic (Hibler, 1977) representations of sea ice have been available for many years, their introduction into climate models remains a source of difficulties.

The strong emphasis placed on the realism of the simulated base state has provided a rationale for introducing flux corrections (Sausen et al., 1988). These were essentially empirical corrections that could not be justified on physical principles, and consisted of arbitrary additions of surface fluxes of heat and salinity. Flux corrections were developed for the sole reason of counteracting the model tendencies to drift with time away from a realistic climate state. The First and Second Assessment Reports of IPCC Working Group 1 pointed out the apparent need for flux adjustments as a problematic feature of climate modelling (Cubasch et al., 1990; Gates et al., 1996).

In the Third Assessment Report, the situation had evolved, and about half the coupled GCMs assessed did not employ flux adjustments. That report noted that “some non-flux adjusted models are now able to maintain stable climatologies of comparable quality to flux adjusted models” (McAvaney et al., 2001). Since that time, evolution away from flux correction (or flux adjustment) has continued at some modeling centres, although many state-of-the-art models continue to use it.

The design of the coupled model simulations is also strongly linked with the methods chosen for model initialization. In “flux-adjusted models” the initial ocean state is necessarily the result of preliminary and typically thousand-year-long simulations, to bring the ocean model into equilibrium. “Non-flux-adjusted” models often make the choice of using a simpler procedure based on observations such as those compiled by Levitus et al. (1994), although some spin-up phase is also very often necessary.

One may argue that the best “flux-adjusted” models suffered less climate drift than the best “non-flux-adjusted” models. “Non-adjusted” models are also possible because they make use of ad-hoc tuning of radiative parameters. However, the newest generation of non-adjusted models offers a consistent framework in which to introduce more interactive processes such as the representation of the ocean-atmosphere carbon exchange, and the associated ocean biochemistry, and these developments clearly have enabled further modelling progress. Two coupled carbon-cycle/climate experiments (Cox et al., 2000; Friedlingstein et al., 2001) were already presented in the TAR.

1.5.10 Detection and Attribution

While often linked together, detection and attribution are distinct and separate processes. Detection refers to the process of demonstrating that an observed change in climate is significantly different (in a statistical sense) from natural (internal) climate variability. Attribution is the process of attributing the detected climate change to a specific cause or causes. Unequivocal attribution would require controlled experimentation with our climate system, which is obviously not possible. In practical terms, attribution of anthropogenic climate change is understood to mean: (a) detection as defined above; (b) demonstration that the detected observed change is consistent with computer model predictions of the climate-change “signal” that should occur in response to anthropogenic forcing; and (c) demonstration that the detected change is not consistent with alternative, physically-plausible explanations of recent climate change that exclude important anthropogenic forcings.

Both detection and attribution rely on observational data as well as model output. Model runs with no changes in external forcing (e.g., no increases in atmospheric CO_2) provide valuable information on the natural internal variability of the climate system on time scales of years to centuries. Estimates of century-time scale natural climate fluctuations are difficult to obtain directly from observations due to the relatively short length of most observational records. Attribution, on the other hand, requires output from model runs that incorporate historical estimates of changes in key anthropogenic and natural forcings, such as well-mixed greenhouse gases, volcanic aerosols, and solar irradiance. These runs can be performed with changes in a single forcing only (which helps to isolate the climate effect of that forcing), or with simultaneous changes in a whole suite of forcings.

In the early years of detection and attribution research, the focus was on a single time series – the estimated global-mean changes in the Earth’s surface temperature. Some of the earliest work in this area was by Wigley and Raper (1990b), who used a simple energy-balance climate model to show that the observed change in global-mean surface temperature over 1867 to 1982 could not be explained by natural internal variability. This finding was later confirmed using variability estimates from more complex coupled ocean-atmosphere general circulation models (e.g., Stouffer et al., 1994).

As the science of climate change progressed, detection and attribution research ventured into more sophisticated statistical analyses that examined complex patterns of climate change. Today, climate-change patterns or “fingerprints” are no longer limited to a single variable (temperature) or to the Earth’s surface. More recent detection and attribution work has made use of precipitation and global pressure patterns, and analyzes vertical profiles of temperature change in the ocean and atmosphere. This makes it easier to address attribution issues. While two different climate forcings may yield similar changes in global-mean temperature, it is highly unlikely that they produce exactly the same four-dimensional “fingerprint” (i.e., the climate changes that are identical as a function of latitude, longitude, height, and time). .

Such model-predicted fingerprints of anthropogenic climate change are clearly statistically identifiable in observed data. The common conclusion of a wide range of fingerprint studies conducted over the past decade is that observed climate changes cannot be explained by natural factors alone (see, e.g., Santer et al., 1995, 1996a,bc; Tett et al., 1999; Hegerl et al., 1996, 1997, 2000; Hasselmann, 1997; Stott et al., 2000; Barnett et al., 1999, 2001; Mitchell et al., 2001; Gillett et al., 2003). A substantial anthropogenic influence is required in order to best explain the observed changes. The evidence from this body of work strengthens the scientific case for a discernible human influence on global climate.

1.5.11 The Greenhouse Effect

The realization that Earth's climate might be sensitive to the atmospheric concentrations of gases that create a greenhouse effect is several centuries old. Fleming (1998) provides many details and references. In terms of the energy balance of the climate system, Edme Mariotte noted in 1681 that although the Sun's light and heat easily passes through glass and other transparent materials, heat from other sources (“chaleur de feu”) does not. The ability to generate an artificial warming of the Earth’s surface was demonstrated in simple greenhouse experiments such as Horace Benedict de Saussure's 1760s experiments using a “heliothermometer” (planes of glass covering a thermometer in a darkened box) to provide an early analogy to the greenhouse effect. A glass greenhouse may heat not only by trapping terrestrial infrared radiation but also by suppressing convection, and thus it was a conceptual leap to recognize that the air itself could also trap thermal radiation. In 1824, Joseph Fourier, citing Saussure, argued that “the temperature [of the Earth] can be augmented by the interposition of the atmosphere, because heat in the state of light finds less resistance in penetrating the air, than in repassing into the air when converted into non-luminous heat.” In 1836, Poulliet followed up on Fourier’s ideas and argued that “the atmospheric stratum… exercises a greater absorption upon the terrestrial than on the solar rays.” There was still no understanding of exactly what substance in the atmosphere was responsible for this absorption.

In 1859, John Tyndall identified the absorption of thermal radiation with complex molecules through laboratory experiments and noted that changes in the amount of any of the radiatively active constituents of the atmosphere such as water vapour or carbon dioxide could have produced “all the mutations of climate which the researches of geologists reveal.” Svante Arrhenius followed up with a climate prediction in 1895 based on greenhouse gases, suggesting that a reduction or augmentation of about forty percent in the abundance of atmospheric carbon dioxide, admittedly a minor constituent, might trigger feedback phenomena that could account for the glacial advances and retreats. This prediction was remarkable in that a hundred years later it would be found that CO_2 did indeed vary by this amount between glacial and interglacial periods, although additional forcing is needed to explain the climate changes.

Theoretical modeling of climate change in response to greenhouse gases continued in 1938 with G.S. Callendar’s model, in which a doubling of CO_2 resulted in an increase in the mean global temperature of 2ºC, with considerably more warming at the poles. Callendar (1938) linked increasing fuel combustion with increasing carbon dioxide concentrations, enhanced atmospheric back radiation, and rising temperatures: “As man is now changing the composition of the atmosphere at a rate which must be very exceptional on the geological time scale, it is natural to seek for the probable effects of such a change. From the best laboratory observations it appears that the principal result of increasing atmospheric carbon dioxide… would be a gradual increase in the mean temperature of the colder regions of the earth.” In 1947, Ahlmann reported a 1.3ºC warming of the Arctic since the 19th century and believed this climatic fluctuation could possibly be explained in terms of greenhouse warming. Similar predictions based on numerical climate models were echoed by Plass in 1956: “If at the end of this century, measurements show that the carbon dioxide content of the atmosphere has risen appreciably and at the same time the temperature has continued to rise throughout the world, it will be firmly established that carbon dioxide is an important factor in causing climatic change.”

At about the same time, another puzzle was solved. The oceans contain almost all the heat and CO_2 in the climate system. That being so, why do we observe carbon dioxide increasing in the atmosphere rather than being absorbed in the sea? Revelle and Suess (1957) provided the answer: in circumstances of increasing greenhouse gases, the oceans can absorb only a small fraction of what they can absorb in a steady state.

In the 1950s, systematic and accurate measurements of atmospheric CO_2 were begun by Charles David Keeling. At this time the greenhouse gases of concern remained carbon dioxide and water vapour, the same two identified by Tyndall a century earlier. It was not until the 1970s that other greenhouse gases (including methane, nitrous oxide and the chlorofluorocarbons) were recognized as important anthropogenic agents in climate forcing for the 20th century (Ramanathan, 1975; Wang et al., 1976). Although the importance of aerosol-cloud effects in reflecting sunlight were noted at this time (Twomey, 1977), it was much later that the mix of climate change agents was extended from gases alone to include small particles (aerosols) with the growing consensus that sulfate aerosols tend to cool the Earth's surface by directly reflecting sunlight (Charlson et al., 1990). Moreover, the increases in sulfate aerosols were anthropogenic and linked with the main sources of CO_2, burning of fossil fuels. Our current picture of the atmospheric constituents that can drive climate change contains a much more diverse mix of greenhouse agents than was known to earlier scientists.

1.5.12 The Human Fingerprint on Greenhouse Gases

The high-accuracy measurements of atmospheric CO_2 concentration, initiated by Charles David Keeling in 1958, constitute the master time series of change in atmospheric composition driven by human activity (Keeling, 1998). These data (Figure 1.3) have iconic status in climate change science as evidence of the effect of human activities on the chemical composition of the global atmosphere. Keeling’s measurements on Mauna Loa in Hawaii are unique not only for their persistence in establishing an effectively continuous record of the burning of fossil fuel, but also establishing for the first time an accuracy and precision that allowed the rate of fossil fuel burning to be separated from the natural breathing of the biosphere. The precision of the Keeling record is sufficient to detect a long-term change in the seasonal cycle of the biosphere.

[INSERT FIGURE 1.3 HERE]

Although the increase in CO_2 abundance since the late 1950s is dramatically clear, a longer-term perspective of the atmospheric abundances of CO_2 and other natural greenhouse gases is also needed, in order to investigate the possibility that the observed rise in the late 20th century might be part of a natural cycle. The necessary data came from analysis of the composition of air enclosed in bubbles of Greenland and Antarctica ice cores. First measurements demonstrated that CO_2 abundances were significantly lower during the last ice age (Neftel et al., 1982), and that they have steadily risen from a pre-industrial value of 280 ppm to about 370 ppm during the last 200 years (Neftel et al., 1985; Etheridge et al., 1996). Furthermore, natural variations of CO_2 during the last 10,000-year warm phase do not exceed 20 ppm (Indermühle et al., 1999). This result shows that the increase over the last half of the 20th century was not part of a natural cycle. The early 21st-century CO_2 abundance is unprecedented in modern times, in both magnitude and rate of increase, and can only be explained by emissions from of fossil fuel consumption.

Direct atmospheric measurements of two other major greenhouse gases, CH_4 (methane) and N_2O (nitrous oxide), detected their increasing abundances. These measurements, extending back only to the late 1970s (Steele et al., 1996), do not have the long historical perspective of the Keeling carbon dioxide record. These observations showed CH_4 abundances initially increasing about 1 %/yr (Graedel and McRae, 1980; Fraser et al., 1981; Blake et al., 1982) and then slowing to an average increase of 0.4 %/yr over the 1990s (Dlugokencky et al., 2003). The rate in increase in N_2O abundance is smaller, about 0.25 %/yr; and was difficult to detect (Weiss, 1981; Khalil and Rasmussen, 1988). Once again, the question of whether these increases are primarily part of a natural cycle or are driven anthropogenically is not easily answered without looking further back in time. Measurements from firn air (air held in older well-bonded snow) give a record of the last two centuries and show an accelerating rise during the 20th century (Machida et al., 1995; Battle et al., 1996). When ice core measurements first extended the CH_4 abundance back 1000 years, they showed a stable, relatively constant abundance until the 19th century rise that connects smoothly with the recent atmospheric measurements. Subsequent measurements from other ice cores have confirmed these results, and it is now certain that CH_4 abundances today (1750 ppb) are much higher than the range over the last half-million years of glacial-interglacial cycles (300 to 700 ppb). Moreover, this increase can be readily explained by anthropogenic emissions. For N_2O the results are similar: the relative increase over the industrial era is smaller (14%), yet the current abundance (314 ppb) is also well above the glacial-interglacial cycle (180 to 270 ppb) (Flueckiger et al., 2002; Sowers et al.. 2003).

The synthetic halocarbons (CFCs, HCFCs, PFCs, halons, SF_6) are potent greenhouse gases that the chemical industry has been producing and emitting to the atmosphere since about 1930. Lovelock (1971) first measured CFC-11 ($CFCl_3$) in the atmosphere, noting that it could serve as an artificial tracer, with its north-south gradient reflecting the anthropogenic emissions. Concentrations of all of the synthetic halocarbons increased in the atmosphere until the late 1990s, when the impact of the CFC phaseout under the Montreal Protocol began to be felt (Montzka et al., 1999; Prinn et al., 2000). In this case too, the research on ice cores has shown that these compounds did not exist in ancient air (Langenfelds et al., 1996) and thus confirms their human origins. Overall, we have a nearly continuous record of the atmospheric abundances of all the well-mixed greenhouse gases and now know that today's abundances are greater than ever occurred over the last half-million years (Petit et al, 1999).

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Question 1.1: What Factors Determine Earth's Climate?

The climate of our planet is primarily a result of factors that are often taken for granted because they either do not change or change only very slowly, such as the orbit of the Earth or the shape and arrangements of the continents and oceans. Interestingly, the Earth's climate also depends critically on the most ephemeral of weather features: clouds. Everyone has noticed that on a sunny day a passing cloud cools the Earth's surface by providing shade. This cooling is accomplished by reflecting sunlight back out to space. While individual clouds may be short lived, for the planet as a whole they are a major climate factor, both cooling by reflecting sunlight and warming by increasing the greenhouse effect. On a globally averaged basis, the incoming and outgoing energy shown in the Figure control the climate. But at any one location, the climate is also greatly impacted by atmospheric and oceanic circulation; circulation that is driven by incoming and outgoing energy.

[INSERT QUESTION 1.1, FIGURE 1 HERE]

About thirty percent of the sunlight that reaches our planet is reflected. As the figure shows, while the surface – not only snow and ice but land, vegetation and water – reflects a significant portion of sunlight, most of the reflectivity comes from clouds and small particles in the atmosphere called aerosols which are released by human activities and by natural sources. The most dramatic change in aerosol-produced reflectivity comes when a major volcanic eruption ejects material very high into the atmosphere. Rain typically can clear aerosols out of the atmosphere in a week or two, but when a violent eruption sends small particles far above the highest cloud, aerosols may influence climate for about a year or two. Major volcanic eruptions can cause a measurable drop in mean global surface temperature that can last for months or years.

The Earth gains energy by absorbing solar energy and loses energy through outgoing longwave radiation. Everything on Earth emits longwave radiation continuously, 24 hours a day. That is the heat energy one feels radiating out from a fire. The warmer an object, the more heat energy it will radiate. This is true for the earth. As the Figure shows, the entire Earth emits longwave (or infrared) radiant energy, including the Earth's surface, the atmosphere, and clouds. Clouds therefore radiate energy out to space and back to the surface. Clouds radiating longwave energy back to the surface form one reason why cloudy nights tend not to cool as much as clear nights. Should changes in the amount of absorbed solar radiation or changes in greenhouse gases occur (the radiative effect of recent greenhouse gas changes is about one half of one percent of the total outgoing longwave radiation), the Earth-atmosphere-ocean system will warm up or cool down until an equilibrium is reached in which outgoing longwave radiant energy balances incoming absorbed solar energy.

Because the Earth is a sphere, more solar energy arrives for a given surface area in the tropics than in higher latitudes, where the sun is at a lower angle. Much of this energy is transported from the equatorial areas to higher latitudes via atmospheric and ocean circulation, including storm systems. The release of latent heat, which occurs when the energy that was used to evaporate water is released as the water vapour condenses in clouds (see Figure), drives much of the atmospheric circulation. Atmospheric circulation in turn drives much of the ocean circulation through the action of winds on the surface waters of the ocean, and through changes in the temperature and salinity of the sea.

The general circulation pattern of the atmosphere and ocean is the dominant factor causing some parts of the Earth to be deserts and allowing other areas to be lushly vegetated. Within the large-scale circulation patterns are complex climate phenomena such as monsoons and El Niño. These phenomena can dramatically affect the weather experienced in various locations. They also affect how energy is transported around the globe and where the energy is released, thereby temporarily altering the global mean temperature on scales of months to decades.

Question 1.2: What is the Relationship Between Climate Change and Weather?

Climate in a narrow sense is usually defined as the 'average weather', or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities of weather over a period of time ranging from months to thousands or millions of years. Since climate is made up of weather, the relationship between climate change and weather is a close one. Climate change causes changes in weather, and it is the statistical descriptions of changes in the weather that are identified as climate change. To understand this relationship more deeply, it can be useful to examine how scientists address weather and climate differently. Climate is commonly used to describe the background conditions of the atmosphere, hydrosphere, cryosphere and even biosphere, as shown in the Figure, that determine what weather may occur. For example, a weather forecast may call for rain tomorrow afternoon while a climate forecast may indicate that conditions are such that the next three months are likely to be rainier than normal.

[INSERT QUESTION 1.2, FIGURE 1 HERE]

Meteorologists put a great deal of effort into observing, understanding and predicting the day-to-day evolution of weather systems. Using information based on the physics that governs how the atmosphere moves, warms, cools, rains, snows and evaporates water, meteorologists are typically able to predict the weather successfully several days into the future. A major limiting factor to the predictability of weather is the observations used to start the analysis. In the 1960's, meteorologist Edward Lorenz discovered that very slight differences in initial conditions can produce very different forecast results. This is the so-called "butterfly effect": a butterfly flapping its wings in China can (in principle) change the weather pattern over North America weeks later. At the core of the butterfly effect is chaos theory, which deals with how small changes in certain variables can cause apparent randomness in complex systems. However, the butterfly analogy is, of course, an exaggeration. A more realistic example might be how tiny differences in the swing of a golf club can cause large differences in where the ball goes.

However, chaos theory does not imply a total lack of order. For example, slightly different conditions early in its history might alter the day a storm system would arrive or the exact path it would take, but the average temperature or precipitation (or *climate*) would still be about the same for that region and that period. Because a primary problem facing weather forecasting is understanding all the conditions at the start of the forecast period, it can be useful to think of climate as background conditions. More precisely, climate can be viewed as the status of the earth-atmosphere-hydrosphere-cryosphere-biosphere (see Figure) that serves as the global background conditions that determine the concurrent array of weather patterns. An example of this would be an El Niño climate event impacting the weather experienced in coastal Peru. The El Niño helps put different bounds on the probable evolution of weather patterns that the butterfly and other random effects can produce.

Another example is found in the familiar contrast between summer versus winter. Projecting that summer will be warmer than winter (outside the tropics) is obviously easy, yet doing it on the basis of physical laws is the essence of what climate models do, albeit in a complex and subtle way. The march of the seasons is due to changes in the geographical patterns of energy absorbed and radiated away by the earth-atmosphere-ocean system. Likewise, projections of future climate are shaped by fundamental changes in radiation, most famously the downward longwave radiation caused by greenhouse gases. Projecting average changes in climate due to changes in greenhouse gases 50 years from now is a very different and more tractable problem than forecasting weather patterns 50 days from now. To put it another way, averages can be more predictable than individual events. As an example, the date of the death of a specific person is not predictable, but the statistics of life expectancy for large populations are reliable.

In recent years, scientists have realized that human activities can be agents of climatic change. Human-caused, or anthropogenic, climate change can be due to factors such as changes in the atmospheric concentrations of gases that contribute to the greenhouse effect, or to changes in small particles (aerosols) in the atmosphere, or to changes in land use, for example. As climate changes, whether because of natural or anthropogenic factors, the weather is affected, often in a probabilistic sense. If the average temperature several decades from now has increased relative to its present value, then some weather phenomena in specific regions may become more or less frequent than at present. Understanding not only the changes in mean weather conditions but also the changes in extreme weather events has recently become a major focus of climate change research.

Question 1.3: What is the Natural Greenhouse Effect?

The Earth has a natural greenhouse effect due to clouds and to gases present in the atmosphere in very small amounts, notably water vapour, carbon dioxide, ozone, methane and nitrous oxide. These so-called greenhouse gases are relatively transparent to incoming solar radiation but fairly opaque to the outgoing radiant energy that the Earth emits. Thus, the Earth's atmosphere allows a large amount of sunlight to pass through it and to be absorbed at the surface of the Earth, thereby warming our planet. Then, as the warmed surface sends out infrared or heat radiation, the greenhouse gases and clouds in the atmosphere absorb some of this energy and re-emit a portion of it back to the surface, where it is absorbed, as shown in the Figure. This process makes the Earth's surface warmer than it would be without this natural greenhouse effect. In fact, the present rich variety of life on Earth owes its very existence to the natural greenhouse effect. Today, the average surface temperature for the world is a comfortable 14°C. Without the natural greenhouse effect, the average temperature would be –19°C, well below the freezing point of water.

[INSERT QUESTION 1.3, FIGURE 1 HERE]

Because the sun is much hotter than the Earth, it emits radiant energy in much shorter wavelengths than does the Earth. Solar radiation is most intense in the visible portion of the spectrum, while the Earth's radiation is maximal in the infrared portion. This fundamental fact of basic physics has profound consequences for the climate. The Earth's atmosphere is fairly transparent to sunlight, but it contains several gases in relatively small amounts which render the atmosphere partially opaque to the infrared radiant energy emitted by the Earth. The atmosphere also contains clouds composed mainly of solid and liquid water. The natural greenhouse effect refers to a set of physical processes by which these "greenhouse gases" and clouds increase the average temperature of the surface of our planet to a value substantially higher than would be the case if there were no atmosphere. The name "greenhouse effect" comes from the analogy with a greenhouse made of glass which allows sunlight to enter but restricts infrared energy from leaving, thus warming the interior.

Interestingly, the atmospheric greenhouse effect is not due to the most common gases in the atmosphere. The two most abundant gases in the atmosphere, nitrogen (N_2 comprising 78% of the dry atmosphere) and oxygen (O_2 comprising 21%) have only two atoms per molecule. Simple molecules of only one or two atoms are incapable of either absorbing or re-emitting significant amounts of infrared radiation. Therefore, it is only the less plentiful but more complex molecules made up of three or more atoms that can contribute to the greenhouse effect. Detailed calculations have been carried out to assess the relative importance of the main greenhouse gases, and a typical recent result is that their contributions to the clear-sky greenhouse effect are water vapour (H_2O) 60%, carbon dioxide (CO_2) 26%, ozone (O_3) 8%, and methane (CH_4) and nitrous oxide (N_2O) 6%.

The natural greenhouse effect is neither harmful nor mysterious. Its basic principles are well-understood and are firmly based on fundamental physics. Only by emitting as much energy to space as it absorbs from the sun can the Earth reach an equilibrium. Because of the natural greenhouse effect, the Earth emits energy to space not only from its surface, as would be the case with no greenhouse effect, but also from all levels throughout the atmosphere. However, atmospheric temperatures generally decrease with altitude above the Earth's surface, and colder bodies radiate less energy than warmer ones. Thus, to arrive at an equilibrium by emitting to space an amount equal to its absorbed solar energy, the Earth-atmosphere system must attain a higher temperature in the presence of a greenhouse effect than would be the case in the absence of a greenhouse effect.

We know that the qualitative effect of adding more of a greenhouse gas such as carbon dioxide to the atmosphere will be to strengthen the natural greenhouse effect and thus to warm the climate system, but the quantitative effect is still subject to some uncertainty. One important set of questions concerns how water vapour amounts might be expected to change as the climate warms due to a human-caused increase in carbon dioxide. The water vapour holding capacity of the atmosphere is known to increase with temperature by about 7% per Celsius degree. Human activities also alter water vapour directly through irrigation, aircraft emissions, and so on, but these prove to be minor compared with the natural cycle of water through the climate system. Hence it is the change in the atmosphere's water holding capacity that matters most. Models generally suggest that a warmer atmosphere will contain more water vapour. Measuring water vapour amounts accurately is itself a difficult technical task, but recent observational evidence implies that an overall increase in atmospheric water vapour of about 5% has actually occurred over the 20th century. Of this highly significant increase, some 2% appears to have occurred since 1988.

Furthermore, this moistening trend appears to have occurred not only near the surface, but also in the upper troposphere, a region of the atmosphere several kilometers above the surface where the water vapour contribution to the greenhouse effect is especially important. These observations strengthen confidence in the prevailing hypothesis that the water vapour feedback is positive, i.e., that a warming atmosphere will lead to additional atmospheric water vapour and thus a stronger greenhouse effect, thereby reinforcing the warming. Quantitatively, this positive water vapour feedback may be strong enough to approximately double the change in the greenhouse effect due to the added carbon dioxide alone.

The story does not end here, however, because science still has much to learn about feedbacks involved in the natural greenhouse effect, including the complex role of clouds. In brief, the basic nature of the natural greenhouse effect is clear, but some of the important processes involved are not yet fully understood in detail.