Chapter 1: Historical Overview of Climate Change Science

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Executive Summary

An awareness, and subsequently a partial understanding, of most of the interactive processes in the Earth system that govern climate and climate change predates the IPCC, often by many decades. A deeper understanding and quantification of these processes and their incorporation in climate models have progressed rapidly since the IPCC First Assessment Report in 1990.

As climate science and the Earth's climate have continued to evolve over recent decades, increasing evidence of anthropogenic influences on climate change has been found. Therefore, the IPCC has made increasingly more definitive statements about human impacts on climate.

Debate has stimulated a wide variety of climate change research. The results of this research have refined but not significantly redirected the scientific conclusions from the sequence of IPCC assessments.

1.1 Overview of the Chapter

The concept of this chapter is new. There is no counterpart in previous Intergovernmental Panel on Climate Change (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 significance to the IPCC task of assessing information relevant for understanding of the risk of human-induced climate change, and also to illustrate the complex and uneven pace of scientific progress. In this chapter, the time frame under consideration stops with the publication of the Third Assessment Report (TAR) (IPCC, 2001a). Developments subsequent to the TAR are described in the other chapters of this Fourth Assessment Report (AR4), and we refer to these chapters throughout.

In spite of their diversity, the topics treated in this chapter have an important common property. They all illustrate that climate change science is progressing and becoming more comprehensive at an increasingly rapid rate. The multidisciplinary science of climate change now provides insights into many urgent issues confronting humankind.

1.2 The Nature of Earth Science

Science may be stimulated by argument and debate, but it advances 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). In practice, contemporary scientists are required to submit their research findings to the careful scrutiny of their peers, which includes disclosing the methods and data which they use, so that their results can be checked through replication by other scientists. 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 belief or opinion of the scientists that is important, but rather the results of this testing. Indeed, when Albert Einstein was informed of the publication of a book entitled *100 Authors Against Einstein*, he is said to have remarked, “If I were wrong, then one would have been enough!” (Hawking, 1988). But that one opposing scientist would have needed proof in the form of testable results rather than opinion.

Thus science is inherently self-correcting*;* incorrect or incomplete scientific concepts ultimately do not survive repeated testing against observations of nature. Scientific theories are ways of explaining phenomena and providing insights that 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 underlying theory is imperfect and requires improvement or abandonment. Often, only certain kinds of questions tend to be asked about a problem, until contradictions build to a point where a sudden change of paradigm takes place (Kuhn, 1962). At that point, an entire field can be rapidly reconstructed under the new paradigm.

Despite occasional major paradigm shifts, the vast majority of scientific insights, even unexpected insights, emerge incrementally as a result of repeated attempts to test hypotheses as thoroughly as possible. Therefore, because almost every new advance is inevitably based on the research and understanding that has gone before, science is cumulative, with useful features retained and non-useful features abandoned. 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. Working scientists know that 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 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? 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. The IPCC assesses the scientific literature to create a report based on the best available science, as described in Section 1.6 of this chapter. It must be acknowledged, however, that the IPCC also contributes to science by stimulating and coordinating targeted research to answer important climate change questions.

A characteristic of Earth sciences is that Earth scientists are unable to perform controlled experiments on the planet as a whole and then observe the results. In this sense, Earth science is similar to the disciplines of astronomy and cosmology that cannot conduct experiments on galaxies or the cosmos. 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 fully verify or falsify climate change hypotheses (Schellnhuber et al., 2004). Nevertheless, countless empirical tests of numerous different hypotheses have built up a massive body of Earth science knowledge. This repeated testing has refined the understanding of numerous aspects of the climate system, from deep oceanic circulation to stratospheric chemistry. Sometimes a combination of observations and models can be used to test planetary-scale 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 climate models. Another example is provided by past IPCC projections of future climate change compared to current observations. Examination of Figure 1.1 reveals that the model projections of global average temperature from the First Assessment Report (FAR) (IPCC, 1990) were higher than those from the Second Assessment Report (SAR) (IPCC, 1996). Subsequent observations showed that the evolution of the actual climate system fell midway between the two modeled projections.

[INSERT FIGURE 1.1 HERE]

Clearly, not all theories or early results are verified by later analysis. In the mid-1970s, several articles about possible global cooling appeared in the popular press, primarily motivated by analyses indicating that Northern Hemisphere temperatures had decreased during the previous three decades (e.g., Gwynne, 1975). In the peer-reviewed literature, a paper by Bryson and Dittberner (1976) reported that increases in CO_2 should be associated with a decrease in global temperatures. When challenged by Woronko (1977), Bryson and Dittberner (1977) explained that the cooling resulting from their model was due to aerosols (small particles in the atmosphere) produced by the same combustion that caused the increase in CO_2. However, because the residence time of aerosols (a measure of how long they might be expected to remain in the atmosphere) is extremely short compared to the residence time of CO_2, the results were not applicable for long-term climate change projections. This example of a prediction of global cooling is a classic illustration of the self-correcting nature of Earth science. The scientists involved were reputable researchers who 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.

A recurring theme throughout this chapter is that climate science in recent decades has been characterized by the increasing rate of advancement of research in the field and by the notable evolution of scientific 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 added to the body of knowledge of atmospheric and oceanic processes has accelerated dramatically. An important example of climate science advancement is the increasing complexity of climate models. This is illustrated in Figure 1.2 which shows schematically the increasing complexity of the climate system as represented by climate models.

[INSERT FIGURE 1.2 HERE]

As scientists incrementally increase the totality of knowledge, they publish their results in peer-reviewed journals. Between 1965 and 1995 the number of articles published per year in atmospheric science journals tripled (Geerts, 1999). Focusing more narrowly, Stanhill (2001) found that the climate change science literature grew approximately exponentially with a doubling time of 11 years for the period 1951 to 1997. Furthermore, 95% of all the climate change science literature since 1834 was published after 1951. Because science is cumulative, this represents considerable growth in the 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.

1.3 Examples of Progress in Detecting and Attributing Recent Climate Change

1.3.1 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, 1961; 1998). These data have iconic status in climate change science as evidence of the effect of human activities on the chemical composition of the global atmosphere (see Chapter 7, Question 7.1). 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 for 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. In addition, the precision of the Keeling record clearly shows a long-term change in the seasonal exchange of CO_2 between the atmosphere, biosphere and ocean. Later observations of parallel trends in the atmospheric abundances of the $^{13}CO_2$ isotope (Francey and Farquhar, 1982) and molecular oxygen (O_2) (Keeling and Shertz, 1992; Bender et al., 1996) uniquely identify this rise in CO_2 with fossil fuel burning. (See Chapter 2, Section 2.3; Chapter 7, Sections 7.1, 7.3)

Although the increase in CO_2 abundance since the late 1950s may appear dramatic, a longer-term perspective of CO_2 (and other natural greenhouse gases) is needed to compare the magnitude of the anthropogenic increase with natural cycles in the past. The necessary data came from analysis of the composition of air enclosed in bubbles of Greenland and Antarctica ice cores. The initial measurements demonstrated that CO_2 abundances were significantly lower during the last ice age than over the last 10,000 years of the Holocene (Neftel et al., 1982). CO_2 concentration rose roughly exponentially from a pre-industrial (circa 1750) value of about 280 ppm to 367 ppm in 1999 (Neftel et al., 1985; Etheridge et al., 1996, TAR). Furthermore, variations in CO_2 during the last 10,000 years have not exceeded about 20 ppm (Indermuhle et al., 1999). (See Chapter 6, Sections 6.2, 6.3, 6.4)

Direct atmospheric measurements of two other major greenhouse gases, CH_4 (methane) and N_2O (nitrous oxide), first detected their increasing abundances. These measurements extend back only to the late 1970s (Steele et al., 1996) and do not have the historical perspective or continuity of the Keeling record. CH_4 abundances were initially increasing at a rate of about 1 %/yr (Graedel and McRae, 1980; Fraser et al., 1981; Blake et al., 1982) but then slowed to an average increase of 0.4 %/yr over the 1990s (Dlugokencky et al., 2003). The increase in N_2O abundance is smaller, about 0.25 %/yr; and more difficult to detect (Weiss, 1981; Khalil and Rasmussen, 1988). To go back in time, measurements were made from firn air trapped in snow pack dating back over 200 years, and these data show an accelerating rise in both CH_4 and N_2O into the 20th century (Machida et al., 1995; Battle et al., 1996). When ice-core measurements extended the CH_4 abundance back 1000 years, they showed a stable, relatively constant abundance of 700 ppb until the 19th century rise that led to an abundance of 1745 ppb in 1998 (at the time of the TAR). This peak abundance is much higher than the 300-to-700 ppb range seen over the last half-million years of glacial-interglacial cycles. 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 1998 abundance of 314 ppb is also well above the 180-to-260 ppb range of glacial-interglacial cycles (Flueckiger et al., 2002). (See Chapter 2, Sections 2.3; Chapter 6, Sections 6.2, 6.3, 6.4; Chapter 7, Sections 7.1, 7.4, 7.4)

Several synthetic halocarbons (CFCs, HCFCs, PFCs, halons, SF_6) are greenhouse gases with large Greenhouse Warming Potentials (GWPs). The chemical industry has been producing these gases and they have been leaking into 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 latitudinal distribution of anthropogenic emissions. Atmospheric abundances of all the synthetic halocarbons have been increasing until the 1990s, when some of the halocarbons being phased out under the Montreal Protocol began to fall (Montzka et al., 1999; Prinn et al., 2000). In the case of synthetic halocarbons, ice-core research has shown with one exception that these compounds did not exist in ancient air (Langenfelds et al., 1996) and thus confirms their human origins. (See Chapter 2, Sections 2.3; Chapter 7, Section 7.1]

At the time of the TAR one could say that the abundances of all the well-mixed greenhouse gases during the 1990s were greater than had ever occurred over the last half-million years (Petit et al, 1999). This record has since been extended (see Chapter 6, Section 6.3).

1.3.2 Global Surface Temperature

Shortly after the invention of the thermometer in the early 1600s, efforts got underway to quantify and record the weather. The first meteorological network was formed in northern Italy in 1653 (Kingston, 1988) and reports of temperature observations were published in the earliest scientific journals (e.g., Wallis and Beale, 1669). 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* (Buys-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 initially created a near-global time series to study the effect of sunspot cycles as it is the mean global surface temperature that can reveal responses to changes in large-scale climate forcings. Later he identified increases in global temperature (Köppen, 1880, 1881). Much of his data came from Dove (1852), but wherever possible he used data directly from the original source, because Dove 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 Köppen (1873) 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 neighbouring 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. Callendar (1961) evaluated 600 stations with about three-quarters of them passing his quality checks. Unbeknownst to Callendar, a former student of Willett, Mitchell (1963), in work first presented in 1961, had created his own updated global temperature time series using slightly fewer than 200 stations and averaging the data into latitude bands. Landsberg and Mitchell (1961) compared Callendar's results with Mitchell's and state 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), that 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 digitizing historical station data as well as addressing the continuing problem of acquiring up-to-date data as there can be a long lag between making an observation and the data getting into global datasets. During the 1970s and '80s, several teams produced global temperature time series. Advances 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. (1986a,b) 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 has been addressed in two ways. The first is by adjusting the temperature of urban stations to account for assessed urban heat island effects (e.g., Hansen et al., 2001, Karl et al., 1988) The second is by doing analyses that, like Callendar (1938), indicate that the urban heat island induced bias in the 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 surface 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 corrections adjusted the early bucket observations upwards by a few tenths of a degree C.

Most of the ship observations are taken in narrow shipping lanes, so the second advance 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 have subsequently increased to several hundred buoys transmitting data at any one time (McPhaden et al., 1998). Since 1982, satellite data, anchored to *in situin situ* observations, have contributed to near-global coverage (Reynolds and Smith, 1994). Also, several different approaches have been used to interpolate and combine land and ocean observations into global temperature time series with current analyses presented in Chapter 3. To place the current instrumental observations into a longer historical context requires the use of proxy data, which is discussed in Section 1.4.

[INSERT FIGURE 1.3 HERE]

Figure 1.3 depicts several historical global temperature time series, together with the current global temperature time series used in Figure 3.2.6. While the data and the analyses techniques have changed over time, all the time series show a high degree of consistency since 1900. The differences caused by using alternate data sources and interpolation techniques increase when the data are sparser. This phenomenon is illustrated by Willet (1950), whose early time series is notably different from the rest. Willett notes that his data coverage remained fairly constant after 1885 but drops off dramatically before that time to only 11 stations before 1850. The high degree of agreement between the time series resulting from these many different analyses increases the confidence that the change they are indicating is real.

Despite the fact that many recent observations are automatic, the vast majority of data that go into global surface temperature calculations - over 400 million individual readings of thermometers at land stations and over 140 million individual *in situ* SST observations - have depended on the dedication of tens of thousands of individuals for well over a century. Climate science owes a great debt to the 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 and their institutions put a great deal of time and effort into acquiring the data and 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, dedicated to quantifying and documenting their local environment. (See Chapter 3)

1.3.3 Detection and Attribution

While often linked together, detection and attribution are distinct and separate processes. Detection of climate change is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. Attribution of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence. 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 is calculated to 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 simulations with no changes in external forcing (e.g., no increases in atmospheric CO_2-concentration) provide valuable information on the natural internal variability of the climate system on time scales of years to centuries. Estimates of century-scale natural climate fluctuations are difficult to obtain directly from observations due to the relatively short length of most observational records and a lack of understanding of the full range and effects of the various and ongoing external influences. 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 simulations 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. While it was not possible to detect anthropogenic warming in 1980, Madden and Ramanathan (1980) predicted it would be evident “at least within the next decade.” A decade later Wigley and Raper (1990b) 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. Climate-change patterns or “fingerprints” were 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, season, and history over the 20th century).

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 (Santer et al., 1995, 1996a,b,c; Tett et al., 1999; Hegerl et al., 1996, 1997, 2000; Hasselmann, 1997; Stott et al., 2000; Barnett et al., 1999). 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.

1.4 Examples of Progress in Understanding Climate Processes

1.4.1 The Earth's Greenhouse Effect

The realization that Earth's climate might be sensitive to the atmospheric concentrations of gases that create a greenhouse effect is more than a century 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” (panes of glass covering a thermometer in a darkened box) to provide an early analogy to the greenhouse effect. It was a conceptual leap to recognize that the air itself could also trap thermal radiation. In 1824, Joseph Fourier, citing Saussure, argued “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 “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 (as opposed to the major, bimolecular atmospheric constituents O_2 and N_2) 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.” In 1895 Svante Arrhenius followed with a climate prediction based on greenhouse gases, suggesting that a 40% increase or decrease in the atmospheric abundance of the trace gas CO_2 might trigger the glacial advances and retreats. A hundred years later it would be found that CO_2 did indeed vary by this amount between glacial and interglacial periods. However, it now appears that initial climatic change precedes the change in CO_2 but is enhanced by the feedback of the CO_2 greenhouse effect. (See Chapter 6, Section 6.3)

G. S. Callendar (1938) solved a set of equations linking greenhouse gases and climate change. He found a doubling of CO_2 resulted in an increase in the mean global temperature of 2°C, with considerably more warming at the poles, and linked increasing fossil fuel combustion with a rise in CO_2 and its greenhouse effects: “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 1.3°C warming of the Arctic since the 19th century and wrongly believed this climatic fluctuation could possibly be explained in terms of greenhouse warming. Similar model predictions 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.” (See Chapter 9)

In trying to understand the carbon cycle, and specifically how fossil-fuel emissions would change atmospheric CO_2, the new, interdisciplinary field of carbon-cycle science began. One of the first problems to address was the atmosphere-ocean exchange of CO_2. Revelle and Suess (1957) explained why emitted CO_2 is observed to accumulate in the atmosphere rather than being absorbed by the oceans: while mixing of CO_2 can occur rapidly into the upper, well-mixed layer of the ocean, the mixing time with the deep ocean is many centuries, and for that reason, the atmospheric concentration will build up substantially, but decay only slowly. By the time of the TAR, the interaction of climate change with the circulation and biogeochemistry of the oceans is projected to alter this fraction of anthropogenic CO_2 emissions taken up by the oceans. (See Chapter 7, Sections 7.1, 7.3; Chapter 10, Section 10.4]

In the 1950s, Charles David Keeling began systematic measurements of atmospheric CO_2. The greenhouse gases of concern remained CO_2 and H_2O, the same two identified by Tyndall a century earlier. It was not until the 1970s that other greenhouse gases – methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) -- were widely recognized as important anthropogenic greenhouse gases over (Ramanathan, 1975; Wang et al., 1976). (See Chapter 2, Section 2.3)

By the 1970s, the importance of aerosol-cloud effects in reflecting sunlight was known (Twomey, 1977), and atmospheric aerosols (suspended small particles) were being proposed as climate-forcing constituents. Charlson and others (e.g., Charlson et al., 1990) led a long campaign to build a consensus that sulfate aerosols were, by themselves, cooling the Earth's surface by directly reflecting sunlight. Moreover, the increases in sulfate aerosols were anthropogenic and linked with the main source of CO_2, burning of fossil fuels. The current picture of the atmospheric constituents driving climate change contains a much more diverse mix of greenhouse agents than was known to earlier scientists. (See Chapter 2, Section 2.4)

1.4.2 Past Climate Observations, Astronomical Theory and Abrupt Climate Changes

Throughout the 19th and 20th centuries, a wide range of studies, including geomorphology or the evidence of past plant 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 several centuries. These studies have revealed that the Palaeozoic Era, beginning 600 million years before present (BP), displayed evidence of both warmer and colder climatic conditions than the present, that the Tertiary Period (65 million to 2 million years BP) was generally warmer, whereas the Quaternary Period (2 million years BP to present, the ice ages) displayed continuous oscillatory changes between glacial and interglacial conditions.

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 the 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.

The pace of paleoclimatic research has accelerated over the last decades. Quantitative and well dated records of climate fluctuations over the last hundred thousand years have brought a more comprehensive view of how climate changes occur, as well as the means to test elements of the astronomical theory. By the 1950s, studies of deep-sea cores suggested that the 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. In the 1960s the works of Emiliani (1969) and of Shackleton (1967) showed the potential of isotopic measurements in deep-sea sediments to help explain quaternary changes. 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, 1993; 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 400,000 years (Petit et al., 1999). This discovery drove research to understand the causal links between greenhouse gases and climate change. The same data that confirmed the astronomical theory also revealed its limits: a linear response of the climate system to astronomical forcing could not explain entirely the observed quaternary fluctuations ranging from fast ice age terminations to longer cycles of glaciations.

The importance of astronomically unforced variability was reinforced by the discovery of abrupt climate changes. Abrupt, in this context, designates events of large amplitude regionally, typically a few °C, that occur on time scales significantly shorter than the thousand years which characterize changes in astronomical forcing. 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 abrupt 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) invigorated the community over the next decade. By the end of the 1990s it became clear that the abrupt climate changes, as found in the Greenland ice cores during the last ice age, were numerous (Dansgaard et al., 1993), indeed abrupt (Alley et al., 1993), and of large amplitude (Severinghaus and Brook, 1999). They are now referred to as Dansgaard-Oeschger events. A similar variability is seen in the North Atlantic Ocean, with north-south oscillations of the polar front (Bond et al., 1992) and associated changes in ocean temperature and salinity (Cortijo et al., 1999).

The importance of internal climate variability and processes was reinforced in the early 1990s with analysis of records with high temporal resolution: the new Greenland Ice Core Project (GRIP; Johnsen et al., 1992) and Greenland Ice Sheet Project 2 (GISP2; Grootes et al., 1993) ice cores, ocean cores with high sedimentation rates, lacustrine sediments, and also cave stalagmites. All this new data produced additional evidence for unforced climate changes, and revealed a large number of “abrupt” changes throughout the last glacial cycle. Long deep-ocean sediment cores were used to reconstruct the thermohaline circulation of deep and surface water (Bond et al., 1992; Broecker, 1997) and show the participation of the ocean in these abrupt climate changes.

By the end of the 1990s, the available range of paleoclimate proxies for climate variables that are now observed directly 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 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 work underlined the role of the ocean in transmitting the signals of abrupt climate change.

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

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; Dunbar and Wellington, 1981), and ice cores (Dansgaard et al., 1984; Jouzel et al., 1987, 1993). In dendroclimatology these studies soon progressed to cross-validated calibration of tree ring data against instrumental meteorological data. The resulting transfer functions can 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). Human proxy data (e.g., blossoming dates, harvest dates, grain prices, ships' logs, newspapers and weather diaries) has also proven a valuable source of climatic reconstruction for the period before instrumental records became available. In some countries such as Iceland, China and Ireland, ancient manuscripts can provide fragmentary insights into past conditions. Such documentary data were also calibrated against instrumental data and used to extend long instrumental series (Lamb, 1969; van den Dool et al., 1978), and to produce reconstructions (e.g., Pfister, 1992), although often without independent validation (one exception is Brazdil, 1992).

Paleoclimate reconstructions cited in the FAR are based on pollen records, insect and animal remains, oxygen isotopes and other geological data from lake varves, loess, ocean sediments, ice cores, and glacier termini. They provided estimates of climate variability on time scales from millions of years to several decades. A climate proxy is a local record of a physical quantity (e.g., thickness of tree rings) that is interpreted as a climate variable (e.g., temperature or rainfall) using a transfer function that is based on physical principles and recently observed correlations between the two records. 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; Dunbar and Wellington, 1981), and ice cores (Dansgaard et al., 1984; Jouzel et al., 1987). Historical documentary data (e.g., blossoming dates, harvest dates, grain prices, ships' logs, newspapers, weather diaries, ancient manuscripts) are also a valuable source of climatic reconstruction for the period before instrumental records became available. Such documentary data also need calibration against instrumental data to extend and reconstruct the instrumental record (Lamb, 1969; van den Dool, 1978; Pfister, 1992; Brazdil, 1992). With the development of multi-proxy reconstructions, the climate data has been extended not only from local to global, but also from instrumental data to patterns of climate variability (Wanner et al., 1995; Mann et al., 1998; Luterbacher et al., 1999). A great advance in the use of proxy data was made by Mann et al. (1998). Prior to that time most reconstructions were at single sites and only loose efforts had been made to combine records. For the first time, great care was taken with annually resolved time series to make sure that dating lined up and thus the true spatial patterns of temperature variability and change could be derived, and true northern hemispheric values were obtained.

The IPCC WGI First Assessment Report (IPCC, 1990) briefly noted that past climates could provide analogues. Fifteen years of research have identified a range of variations and instabilities in the climate system that have occurred both during the last two million years of glacial-interglacial cycles and in the super-warm period of 50 million years ago. It is very unlikely that these past climates will repeat in the immediate future, yet they do reveal a wide range of climate processes that need to be understood in terms of 21st century climate change. (See Chapter 6)

1.4.3 Solar Variability and the Total Solar Irradiance

As early as 1910, Abbot believed that he had detected a downward trend in Total Solar Irradiance (TSI) that coincided with a general cooling of climate. The solar cycle variation in irradiance corresponds to an 11-year cycle in radiative forcing of about 0.23 W m^{-2}. There is increasingly reliable evidence of its influence on atmospheric temperatures and circulations, particularly in the higher atmosphere (Labitzke and van Loon, 1997; Reid, 1991, van Loon and Labitzke, 2000; Balachandran and Rind, 1995; Brasseur, 1993; Haigh, 1996). 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 in solar radiation could cause surface temperature changes on the order of a few tenths of a degree centigrade.

The solar radiation can be derived from the sunspot number. 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 (1801) 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. Heinrich Schwabe (1844) 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 for atmospheric effects 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}. 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. The TSI being highest when sunspots are at their maximum is the opposite of Langley’s (1876) hypothesis.

These 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 datasets indicate quasi-periodic changes in solar radiation of 0.24–0.30% on the centennial time scale.

The TAR states that the changes in solar irradiance are not the major cause of the temperature changes in the twentieth century unless those changes can induce unknown large feedbacks in the climate system. The effects of solar flares on the atmosphere (e.g., on cloud nucleation), or the shift towards UV with activity and the interaction of the increased UV at times of high solar activity with the ozone in the stratosphere, which via an altered vertical stabiltiy changes the tropospheric circulation, are still unknown. More research to investigate the effects of solar behaviour on climate is needed before the magnitude of solar effects on climate can be stated with certainty.

1.4.4 Biogeochemistry and Radiative Forcing

The modern scientific understanding of the complex and interconnected roles of greenhouse gases and aerosols in climate change has undergone rapid evolution over the last two decades. While the concepts were recognized and outlined in the 1970s, the publication of generally accepted quantitative results coincides with, and was driven in part by, the IPCC, 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 FAR codified the key physical and biogeochemical processes in the Earth system that relate a changing climate to atmospheric composition, chemistry, the carbon cycle, and natural ecosystems. The science of the time, as summarized in the FAR, made a clear case for anthropogenic interference with the climate system. In terms of greenhouse agents, the main conclusions from the WGI 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) provide a metric for comparing the climatic impact of different greenhouse gases, one that integrates both the radiative influence and the biogeochemical cycles. The climatic importance of tropospheric ozone, sulfate aerosols, and atmospheric chemical feedbacks were proposed by 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 emissions of the highly reactive gases: odd-nitrogen (NOx), carbon monoxide (CO), and non-methane hydrocarbons (NMHC, also known as 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. (See Chapters 2, 7, 10)

The concept of radiative forcing (RF), the radiative imbalance (W m^{-2}) at the top of the atmosphere caused by the addition of a greenhouse gas (or other change), was established at the time and summarized in WGI FAR Chapter 2. RF agents included the direct greenhouse gases, solar radiation, aerosols, and the Earth's surface 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 and thus changed the abundance of other greenhouse gases. Indirect Global Warming Potentials (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 (i.e., dependent on future emissions). (See Chapters 2, 7)

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 the Supplementary Report (IPCC, 1992) to the FAR, the indirect chemical effects of CO, NOx, and VOC were reaffirmed, and the feedback of CH_4 on tropospheric OH was noted, but the indirect RF values from the FAR were retracted 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. (See Chapters 2, 7)

By 1995, when work was in progress on SAR and its precursor 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 including carbon isotopes. A first carbon-cycle assessment was done through an international model and analysis workshop examining terrestrial and oceanic uptake to better quantify the relationship between CO_2 emissions and the resulting increase in atmospheric abundance. 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. Anthropogenic soot aerosol, with a positive RF, was not in the 1995 pre-assessment but was added to the SAR. 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 such as the CH_4 impact on atmospheric chemistry, but great uncertainty in others such as the prediction of tropospheric O_3 changes. The model studies plus the theory of chemical feedbacks in the CH_4-CO-OH system (Prather, 1994) firmly established that the atmospheric residence time (and hence climate impact and GWP) of CH_4 emissions was about 50% greater than expected. There was still no consensus on quantifying the past or future changes in tropospheric O_3 or OH (the primary sink for CH_4). (See Chapters 2, 7, 10)

In the early 1990s, research on aerosols as climate-forcing 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). 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 radiative 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, the scientific 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. (See Chapters 2, 7; Chapter 8, Section 8.2; Chapter 9, Section 9.2)

Throughout the 1990s there were concerted research programs in the U. S. A. and E. U. to evaluate the global environmental impacts of aviation. Several national assessments culminated in the IPCC *Special Report on Aviation and the Global Atmosphere* (IPCC, 1999), which assessed the impacts on climate and global air quality. 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 CH_4 due to NOx emissions were quantified). The direct RF of sulfate and of soot aerosols was likewise quantified along with that of contrails, but the impact on cirrus clouds that are sometimes generated downwind of contrails was not. The assessment re-affirmed that RF was a first-order metric for the global mean surface temperature response, but noted that it was inadequate for regional climate change, especially in view of the largely regional forcing from aerosols and tropospheric O_3. (See Chapter 2, Section 2.6; Chapter 10, Section 10.2)

By the end of the 1990s, research on atmospheric composition and climate forcing had made many important advances. The TAR was able to provide a more quantitative evaluation in some areas. 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 science could predict the changes in tropospheric O_3 in response to scenarios for CH_4 and the indirect greenhouse gases (CO, NOx, VOC) and that a quantitative GWP for CO could be given. 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. 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). (See Chapters 2, 7; Chapter 9, Section 9.2)

1.4.5 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 component of the climate system. It might seem logical to expect that the cryosphere overall would shrink in a warming climate or expand in a cooling climate. However, potential changes in precipitation, for instance due to an altered hydrological cycle, may counter this effect both regionally and globally.

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 heat) and atmospheric circulation (through topographic changes), its large potential for affecting sea level (through growth and melt of land ice), and its potential for affecting the greenhouse gas balance (through for instance changes in the permafrost). Some of these effects are discussed below. Chapter 4 of this report is dedicated to the cryosphere, and assesses the most recent developments.

The importance of the permafrost effect on climate 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 is likely to increase in turn, 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 consequent greenhouse gas releases, is thus large.

Studies of the albedo feedback mechanism have a much longer history. The albedo is the fraction of solar energy reflected back to space, which over the cryosphere is large (about 0.7 to 0.9) 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). But 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 latest results are discussed in subsequent chapters of this report.

The potential cryospheric impact on ocean circulation and sea level are of particular importance because it may lead to "large-scale discontinuities" (TAR) through both the shutdown of the large-scale meridional circulation of the world oceans (see the next section), and the disintegration of large continental ice sheets. Mercer (1968, 1978) proposed that atmospheric warming could cause the ice shelves of western Antarctica to disintegrate, and that as a consequence the entire West Antarctic Ice Sheet would lose its land connection and come afloat. The West Antarctic Ice Sheet contains roughly 10% of the Antarctic ice volume and might cause a sea level rise of about 5 meters if released. Recent developments on the understanding of the stability of the West Antarctic Ice Sheet are assessed in Chapters 4 and 6.

In situIn situ monitoring of some cryospheric elements has a long tradition. Due to its importance for fisheries and agriculture, significant documentary evidence exists. For instance, sea-ice extent has been documented by seagoing communities for centuries. Records of thaw and freeze dates for lake and river ice start with Lake Suwa in Japan in 1444, and extensive records of snowfall in China were made during the Qing Dynasty. Records of glacial length go back to the mid-1500s. However, internationally coordinated long-term glacier observations 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 1946, 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. Equally recent are the systematic measurements of permafrost (thermal state and active layer), beginning in earnest around 1950 and coordinated under the Global Terrestrial Network for Permafrost.

The main climate variables of the cryosphere (extent, albedo, topography and mass) are in principle observable from space, given proper calibration and validation through *in situin situ* observing efforts. Indeed, satellite data are 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 the scientific 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 is remote sensing of the variability of ice volume.

Recent climate modelling results have pointed to high-latitude regions as areas of particular importance and ecological vulnerability to global climate change. 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. The modelling aspects are further discussed in Chapter 8.

1.4.6 Ocean and Coupled Ocean-Atmosphere Dynamics

Developments in the understanding of the oceanic and atmospheric circulations, as well as their interactions, constitute a striking example of the continuous interplay among theory, observations, and, more recently, model simulations. The atmosphere and ocean surface circulations were observed and analyzed globally as early as the sixteenth and seventeenth centuries, in close association with the development of worldwide trade based on sailing. These efforts led to a number of important conceptual and theoretical works. 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 both the atmospheric general circulation itself and model simulations (Lorenz, 1967).

A comprehensive description of these circulations has however been delayed by the lack of necessary observations in the higher atmosphere or deeper ocean. 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 independently discovered near the turn of the 20th century by Aßmann (1902) and Teisserenc de Bort (1902), and the first manned balloon flight into the stratosphere was made in 1901 (Berson and Süring, 1901). Similarly for the deep oceans: Even though it was recognized over two hundred years ago (Rumford, 1800, see also Warren, 1981) that the oceans' cold subsurface waters must originate at high latitudes, it was not appreciated until the middle of the 20th century that the strength of the deep circulation might be varying over time, or that the ocean's Meridional Overturning Circulation (MOC; often referred to as the "thermohaline circulation", see the Glossary for more information) may be very important for Earth's 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 quite dynamic (Swallow and Stommel's 1960 subsurface float experiment Aries, referred to by 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, the first estimates of the strength of the meridional transport of heat and mass were made (Oort and Vonder Haar, 1976; Wunsch, 1978), using a combination of models and data. Since then the technological developments have accelerated, but nevertheless, monitoring the MOC directly still remains a substantial challenge (see Chapter 5).

In parallel with the technological 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 Bryan (1969) and Manabe and Bryan (1969). 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 appeared to be 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 meridional circulation were responsible for the abrupt Dansgaard-Oeschger climate change events.

Although scientists now better appreciate the strength and variability of the global-scale ocean circulation 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, and therefore implicated internal oceanic timescales. Is a radical change in the MOC likely in the near future? Brewer et al. (1983) and Lazier (1995) showed that the water masses of the North Atlantic were indeed changing (some becoming significantly fresher) in the modern observational record, a phenomenon that at least raises the possibility that ocean conditions may be approaching the point where the circulation might shift into Stommel's other stable regime. Recent developments on the ocean's various roles in climate can be found in Chapters 5, 6, 9 and 10.

Studying the interactions between atmosphere and ocean circulations was also facilitated through continuous interactions between observations, theories and simulations, as is dramatically illustrated by the century-long history of the advances in understanding the El Niño-Southern Oscillation (ENSO) phenomenon. This coupled air-sea phenomenon originates in the Pacific but affects climate globally, and has raised concern since at least the 19th century. Sir Gilbert Walker (1928) describes how H. H. Hildebrandsson in 1897 noted large-scale relationships between interannual trends in pressure data from a world-wide network of 68 weather stations, and how Norman and Lockyer in 1902 confirmed Hildebrandsson's discovery of an apparent "seesaw" in pressure between South America and the Indonesian region. Walker named this seesaw pattern the "Southern Oscillation" and 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 involving anomalously warm waters (that spoil 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 often 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) had been put 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 experimental ENSO forecasts were made (Cane et al., 1986, Zebiak and Cane, 1987).

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 spatial pattern affecting climate variability in the North Atlantic, and described as a seesaw pattern, 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).

Teisserenc de Bort, Hann, Exner, Defant and Walker all contributed to the discovery of the underlying dynamic structure. Walker, in his studies in the Indian Ocean, actually studied *global* maps of sea level pressure correlations, and named 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 (reviewed by 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 may be partly described as a high-frequency stochastic process internal to the atmosphere. This understanding is evidenced by numerous atmosphere-only model simulations. It is also considered an expression of one of Earth's "annular modes." (See Chapter 3) It is, however, the low-frequency variability of this phenomenon that fuels continued investigations among climate scientists. The long time scales are the indication of potential predictive skill in the NAO. The mechanisms responsible for the correspondingly long "memory" are still debated, although they are likely to have a local or remote oceanic origin. 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 would therefore not be surprising if the oceanic contributions to the NAO and to the Southern Oscillation were different.

Earth's climate is characterized by many modes of variability, involving both the atmosphere and ocean, and also the cryosphere and biosphere. One central question for climate scientists, addressed in particular in Chapter 9, is to determine in which ways human activities influence the dynamic nature of Earth's climate, and to identify what would have happened without any human influence at all.

1.5 Examples of Progress in Modeling the Climate

1.5.1 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, with supercomputer speeds increasing by roughly a factor of a million in the three decades from the 1970s to the present day. This computational progress has permitted a corresponding increase in model 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, as shown in Figure 1.4. 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 time-dependent scenarios of climate evolution and can make use of much more complex coupled ocean-atmosphere models, sometimes even including interactive chemical or biochemical components.

[INSERT FIGURE 1.4 HERE]

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 also because the behaviour of such a complex non-linear system may in general be chaotic.

It has been known since the work of Lorenz (1963) that even simple models may display intricate behaviour because of their non-linearities. The inherent non-linear 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.

In addition, key processes that control climate sensitivity or abrupt climate changes cannot be represented in full detail in the context of global models, and the scientific understanding of many such processes is still notably incomplete. As a consequence, there is a continuing need to assist in the use and interpretation of complex models through 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 improved the understanding 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 improving the understanding of 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.

1.5.2 Model Clouds and Climate Sensitivity

The modeling of cloud processes and feedbacks provides a striking example of the unequal pace of progress in climate science.

On the one hand, cloud representation may constitute the area in which atmospheric models have improved most continuously. In the early 1980s, most models were still using prescribed cloud amounts, as functions of location and altitude, and prescribed cloud radiative properties, to compute the transport of atmospheric radiation. The cloud amounts were very often derived from the zonally-averaged climatology of London (1957). Succeeding generations of models have used relative humidity or other simple predictors to diagnose cloudiness (Slingo, 1987), 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, and generating precipitation, as well as influencing small-scale convective or turbulent circulations. Following the pioneering studies of Sundquist (1978), an explicit representation of clouds was progressively introduced into climate models, beginning in the late 1980s. Models first used simplified representations of cloud microphysics, following, for example, Kessler (1969), but more recent generations of models generally incorporate a much more comprehensive and detailed representation of clouds, based on consistent physical principles. Comparisons of model results with observational data presented in the TAR have shown that, on the basis of zonal averages, the representation of clouds in most climate models was also more realistic in 2000 than had been the case only a few years before.

In spite of this undeniable progress, however, the amplitude and even the sign of cloud feedbacks was noted in the TAR as highly uncertain, and this uncertainty was cited as one of the key factors explaining the spread in model simulations of future climate, for a given emissions scenario.

Simple calculations using idealized models of radiative equilibrium 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. Satellite measurement have provided reliable estimates of the Earth radiation budget since the early seventies (Vonder Haar and Suomi, 1971). Clouds, which cover about 60% of the Earth's surface, are responsible for about two-thirds of the planetary albedo, which is about 30%. An albedo change of only 1% would cause a change in the black-body radiative equilibrium temperature of about 1°C. 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, which adds to the complexity of feedbacks, as evidenced, for example, through satellite observations analyzed by Tselioudis and Rossow (1994).

The importance of cloud feedbacks was revealed by the dedicated analysis of model results (Hansen et al, 1984) and the first extensive model intercomparisons (Cess et al., 1989) also showed a very large model dependency. The strong effect of cloud processes on climate model sensitivities to greenhouse gases 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.

The possibility of constraining the amplitude of cloud feedbacks through the simulation of past climate changes is at best very limited (Ramstein et al, 1998). Therefore, an emphasis on observational research of how clouds behave on smaller interannual or seasonal time scales remains as a necessary path to constrain model development, and indeed a long history of cloud observations now runs parallel to that of model development. Operational ground-based measurements carried out for the purpose of weather prediction constitute a valuable source of information which has been gathered by Warren et al (1986, 1988). The International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1991) has developed an analysis of cloud cover and cloud properties using the measurements of operational meteorological satellites over a period of more than two decades. These data have been complemented by other satellite remote sensing data sets, such as those associated with the Nimbus-7 THIR instrument (Stowe et al., 1988), with high-resolution spectrometers such as HIRS (Susskind et al., 1987), and with microwave absorption (SSMI).

Simultaneously, the cloud research community has come to realize that a parallel effort needs to be carried out for a wider range of 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 longest-lasting and most comprehensive such effort has been the Atmospheric Radiation Measurement (ARM) Program in the U.S.A., which has established elaborately instrumented 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 TOGA-COARE for convective systems (Webster and Lukas, 1992), or ASTEX for stratocumulus (Albrecht et al., 1995).

Observational data have clearly helped the development of models. The ISCCP data have greatly aided the development of cloud representations in climate models since the mid-1980s (e.g., Le Treut and Li, 1988;

Del Genio et al., 1996). However, existing data have not yet brought about any reduction in the existing range of simulated cloud feedbacks. More recently, new theoretical tools have been 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 observationally known, using single-column models (Randall et al., 1996; Somerville, 2000) and higher-resolution cloud-resolving models to evaluate GCM parameterizations. 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. Whether these data and methodologies will result in significant progress in the effort to reduce current uncertainties is still an open question.

1.5.3 Coupled Models: Evolution, Use, Assessment

The first National Academy of Sciences of the U. S. A. report on global warming (Charney et al., 1979), on the basis of two equilibrium simulations with two different models, spoke of a range of global mean surface temperature increase due to doubled atmospheric carbon dioxide, from 1.5°C to 4.5°C, a range which has remained part of conventional wisdom at least as recently as the TAR. These climate projections, as well as those treated later in the intercomparison of three models by Schlesinger and Mitchell (1987) and most of those presented in the FAR, were the results of atmospheric models coupled with simple “slab” ocean models, i.e., models omitting all ocean dynamics.

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). Replacing “slab” ocean models by fully coupled ocean-atmosphere models may arguably have constituted one of the most significant leap forward in climate modelling during the last 20 years (Trenberth, 1993), although both the atmospheric and oceanic components have undergone highly significant changes, as emphasized, for example, in Section 1.5 for cloud representation. This advance has led to significant modification in the patterns of simulated climate change, particularly in oceanic regions. It also has opened up the possibility of exploring transient climate scenarios, and it constitutes a step toward the development of comprehensive “Earth-system models” that include explicit representations of chemical and biogeochemical cycles.

Throughout their short history, coupled models have faced difficulties which have considerably impeded 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 direct stabilizing feedback that can compensate for any errors in the simulated salinity. The strong emphasis placed on the realism of the simulated base state provided a rationale for introducing flux adjustments or flux corrections (Sausen et al., 1988) in early simulations. These were essentially empirical corrections that could not be justified on physical principles, and that consisted of arbitrary additions of surface fluxes of heat and salinity in order to prevent the drift of the simulated climate away from a realistic state. The National Center for Atmospheric Research (NCAR) model may have been the first to realize non-flux-corrected coupled simulations systematically, and it was able to achieve simulations of climate change into the 21st century, in spite of a persistent drift that affected many of its early simulations. Both the FAR and the SAR pointed out the apparent need for flux adjustments as a problematic feature of climate modelling (Cubasch et al., 1990; Gates et al., 1996).

By the time of the TAR, however, the situation had evolved, and about half the coupled GCMs assessed in the TAR 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 a number of state-of-the-art models continue to rely on 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, so as to bring the ocean model into equilibrium. “Non-flux-adjusted” models often employ a simpler procedure based on ocean observations, such as those compiled by Levitus et al. (1994), although some spin-up phase is also often necessary. One may argue that the best “flux-adjusted” models suffered less climate drift than the best "non-flux-adjusted" models and that "non-adjusted" models were possible only because they made use of ad-hoc tuning of radiative parameters.

This considerable advance in model design has not diminished the existence of a range of model results. This is not a surprise, however, because it is known that climate predictions are intrinsically affected by uncertainty (Lorenz, 1963). Two distinct kinds of prediction problems have been defined by Lorenz (1975). The first kind is defined as the prediction of the statistical properties of the climate system in response to a given initial state. Predictions of the first kind are initial-value problems and, because of the non-linearity and instability of the governing equations, such systems are not predictable indefinitely into the future. Predictions of the second kind deal with the determination of the response of the climate system to changes in the external forcings. These predictions are not concerned directly with the chronological evolution of the climate state, but rather with the long-term average of the statistical properties of climate. Predictions of the second kind do not depend on initial conditions. Instead, they are intended to determine how the statistical properties of the climate system (e.g., the annual average global mean temperature, or the expected number of winter storms, or hurricanes, or the average monsoon rainfall) change as some external forcing parameter, CO_2 content for example, is altered. Estimates of future climate scenarios as a function of the concentration of atmospheric greenhouse gases are typical examples of predictions of the second kind.

Uncertainties in climate predictions (of the second kind) arise mainly from model uncertainties and errors. To assess and disentangle these effects, the scientific community has organized a series of systematic comparisons of the different existing models, and it has worked to achieve an increase in the number and range of simulations being carried out in order to more fully explore the factors affecting the accuracy of the simulations.

An early example of systematic intercomparison of models is provided by Cess et al. (1989) who compared results of documented differences among model simulations in their representation of cloud feedback, and showed how the consequent effects on atmospheric radiation resulted in different model response to doubling of the CO_2 concentration. A number of ambitious and comprehensive "model intercomparison projects" (MIPs) were set up in the 1990s, to undertake controlled conditions for model evaluation. First among these was AMIP (where "A" denotes atmospheric), which studied atmospheric GCMs. The development of coupled models has induced the development of CMIP (where "C" denotes coupled), which studied coupled ocean-atmosphere global-circulation models (GCMs), and their response to idealized forcings, such as 1% yearly increase in the atmospheric CO_2 concentration. It proved important in carrying out the various 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 and CMIP opened a new era for climate modelling, setting standards of quality control, providing organizational continuity, and ensuring that results are generally 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. In general, results of the MIPs suggest that the most problematic remaining areas of coupled model simulations involve cloud-radiation processes, the cryosphere, the deep ocean, and ocean-atmosphere interactions.

Comparing different models is not sufficient, however. 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. The first ensemble climate change simulations with global GCMs used a set of different initial and boundary conditions (Cubasch et al., 1994; Barnett, 1995). Computational constraints limited early ensembles to a relatively small number of samples (fewer than ten). These ensemble simulations clearly indicated that even with a single model a large spread in the climate projections can be obtained.

Intercomparison of existing models and ensemble model studies, i.e., those involving many integrations of the same model, are still undergoing rapid development. Running ensembles was essentially impossible until recent advances in computer power occurred, as 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.

1.6 The IPCC Assessments of Climate Change and Uncertainties

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. It does not directly support new research, nor monitor climate-related data. However, the IPCC process of synthesis and assessment has often inspired 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 and how it has described uncertainty in the quantities presented.

A main activity of the IPCC is to provide on a regular basis an assessment of the state of knowledge on climate change, and this current 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 FAR played an important role in the discussions 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 and legal basis for addressing the climate change issue.

The FAR was completed under the leadership of Bert Bolin (IPCC Chair) and John Houghton (WGI Chair). The WGI FAR, in a mere 365 pages with 8 color plates, made a persuasive, but not quantitative, case for anthropogenic interference with the climate system. Most conclusions from the FAR were non-quantitative and remain valid today (see also Section 1.4.4 above). 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.” (see Chapters 2, 3; Chapter 7, Section 7.1). On the other hand, the FAR did not foresee the phase-out of CFCs, missed the importance of biomass-burning aerosols and dust to climate, and stated that unequivocal detection of the enhanced greenhouse effect was more than a decade away. The latter two areas highlight the advance of climate science, and in particular the merging of models and observations in the new field of detection and attribution (see Chapter 9, Section 9.1).

The Policymakers Summary of the WGI FAR gave a broad overview of climate change science and its Executive Summary separated key findings into areas of varying levels of confidence ranging from “certainty” to providing an expert “judgment”. Much of the summary is not quantitative (e.g., the radiative forcing bar charts do not appear in the summary). Similarly, scientific uncertainty is hardly mentioned; when ranges are given, as in the projected temperature increases of 0.2 to 0.5°C/decade, no probability or likelihood is assigned to explain the range. (see Chapter 10). In discussion of the climate sensitivity to doubled CO_2, the combined subjective and objective criteria are explained: the range of model results was 1.9 to 5.2°C; most were close to 4.0°C; but the newer model results were lower; and hence the best estimate was 2.5°C with a range of 1.5 to 4.5°C. The likelihood of the value being within this range was not defined.

The importance of identifying those areas where climate scientists had high confidence was, however, recognized in the Policymakers Summary.

The Supplementary Report (IPCC, 1992) re-evaluated the radiative forcing (RF) values of the FAR and included the new IS92a-f scenarios for future emissions. It also included updated chapters on climate observations and modeling. (See Chapters 3, 4, 5, 6, 8) The treatment of scientific uncertainty remained as in the FAR. For example, the calculated increase in global mean surface temperature since the 19th century was given as 0.45 ± 0.15°C, with no quantitative likelihood for this range. (See Chapter 3, Section 3.2)

The SAR was planned with and coupled to a preliminary Special Report (IPCC, 1995) that contained intensive chapters on the carbon cycle, atmospheric chemistry, aerosols and radiative forcing. The WGI SAR culminated in the government plenary in Madrid in November 1995. The most cited finding from that plenary, on attribution of climate change, has been consistently reaffirmed by subsequent research: "The balance of evidence suggests a discernible human influence on global climate." (See Chapter 9) The SAR provided key input to the negotiations that led to the adoption in 1997 of the Kyoto Protocol to the UNFCCC.

Uncertainty in the WGI SAR was defined in a number of ways. The carbon-cycle budgets used symmetric ±ranges explicitly defined as 90% confidence intervals; whereas the RF bar chart reported a "midrange" bar along with a ±range that was estimated largely on the spread of published values. The likelihood, or confidence interval, of the spread of published results was not given. This uncertainty was additionally modified by a declaration that the confidence of the RF being within the range was indicated by a stated confidence level that ranged from 'high' (greenhouse gases) to 'very low' (aerosols). Due to the difficulty in getting a long draft, the Summary for Policy Makers (SPM) became a short document with no figures and few numbers. The use of scientific uncertainty in the SPM was thus limited and similar to the FAR: i.e., a range in the mean surface temperature increase since 1900 was given as 0.3 to 0.6°C with no explanation as to likelihood of this range. While the underlying report showed projected future warming for a range of different climate models, the Technical Summary focused on a central estimate.

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." The authors took a uniform approach to assigning and propagating uncertainty in these RF values based on mixed objective/subjective criteria. In addition to a best value, a 2/3 likelihood (67% confidence) interval is given. This interval is similar to a one-sigma (i. e., one standard deviation) normal error distribution, but it was explicitly noted that the probability distribution outside this interval was not evaluated and might not have a normal distribution. A bar chart with "whiskers" (2/3-likelihood range) showing the components and total (except for cirrus clouds) RF for aviation in 1992 appeared in the SPM. (See Chapter 2, Section 2.6; Chapter 10, Section 10.2)

The TAR was approved at the government plenary in Shanghai in 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." (See Chapter 9)

In an effort to promote consistency, a guidance paper on uncertainty (Moss and Schneider, 2000) was distributed to all Working Group authors during the drafting of the TAR. The WGI TAR made some effort at consistency, noting in the SPM that when ranges were given they generally denoted 95% confidence intervals, although the carbon budget uncertainties are specified as ±1 standard deviation (68% likelihood).

The range of 1.5 C to 4.5°C for climate sensitivity to CO_2 doubling was reiterated but with no confidence assigned; however, it was clear that the level of scientific understanding had increased since that same range was first given in the Charney et al. (1979) report. The RF bar chart noted that the RF components could not be summed (except for the long-lived greenhouse gases) and that the "whiskers" on each of these meant something different (e.g., some were the range of models, some were uncertainties). Another failure in dealing with uncertainty was that the projected warming for the 21st century was reported as a range covering 6 SRES emissions scenarios with 9 atmosphere-ocean climate models is reported as two gray envelopes without estimates of likelihood levels. The full range (i.e., scenario plus climate model range) of 1.4°C to 5.8°C is a much cited finding of the WGI TAR but the lack of discussion of associated likelihood in the report makes the interpretation and useful application of this result difficult.

The WGI contribution to AR4 is contained in this volume. As in previous reports, the number of lead authors, reviewers and review cycles makes this publication a far more extensively reviewed and revised document than typical scientific peer-reviewed publications. In renewed efforts to address uncertainties across AR4, a new set of guidance notes was distributed to lead authors at the start (See Box 1.1).

Box 1.1: Treatment of Uncertainties in the Working Group I Assessment

The importance of consistent and transparent treatment of uncertainties is clearly recognized by the IPCC in preparing its assessments of climate change and the increasing attention given to formal treatments of uncertainty in previous assessments is summarised in Section 1.6. To promote consistency in the general treatment of uncertainty across all three Working Groups, authors of the Fourth Assessment Report have agreed to follow a brief set of guidance notes on determining and describing uncertainties in the context of an assessment[1]. This box summarises the way in which those guidelines have been applied by Working Group I and covers some aspects of the treatment of uncertainty specific to material assessed here.

It is useful to recognize two different types of uncertainty, although in some cases these are closely linked. *Value uncertainty* arises from the incomplete determination of particular values or results, e.g., because data are never 100% accurate nor fully representative of the phenomenon of interest. *Structural uncertainty* arises from an incomplete understanding of the processes that control particular values or results, e.g., when the conceptual framework or model used for analysis does not include all the relevant processes or relationships. In both cases estimating uncertainties is intrinsically about describing the limits to scientific knowledge and for this reason involves expert judgment about the state of that knowledge.

Value uncertainties are generally estimated using statistical techniques and expressed probabilistically. Structural uncertainties are generally described by giving the authors' collective judgment of their confidence in the correctness of a result. The uncertainty guidance used in the Fourth Assessment Report draws, for the first time, a careful distinction between levels of confidence and likelihood of results. This is necessary to express situations where there is high confidence that an event is very unlikely (e.g., rolling a die to show six three times in a row), or that an event is about as likely as not (tossing a coin once to show heads). While confidence and likelihood used in this sense are distinct concepts they are linked, because it does not make sense to express a low confidence that an event is very likely.

The standard terms used to define levels of confidence in this report are as given in the Uncertainty Guidance Note:

Terminology	**Degree of confidence in being correct**
Very High confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

Chapter 2 of this report uses a related term "level of scientific understanding" when describing uncertainties in different contributions to radiative forcing. This terminology is used for consistency with the Third

[1] See http://www.ipcc.ch/activity/uncertaintyguidancenote.pdf

Assessment Report and the basis on which the authors have determined particular levels of scientific understanding uses a combination of approaches defined in the uncertainty guidance note as explained in detail in section 2.9 and table 2.9.2.

The standard terms used in this report to define the likelihood of an outcome or result where this can be estimated probabilistically are:

Terminology	**Likelihood of the occurrence/ outcome**
Virtually certain	> 99% probability of occurrence
Very likely	> 90% probability
Likely	> 66% probability
About as likely as not	33 to 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Exceptionally unlikely	< 1% probability

Where values are specified in this report as a central estimate with a plus/minus range, then by default the range represents a 95% (two standard deviations, or 2-σ) confidence interval. Exceptions are explained in the text.

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Question 1.1: What Factors Determine Earth's Climate?

The climate system is the highly complex system consisting of five components, atmosphere, hydrosphere, cryosphere, land surface and biosphere, as well as the interactions among these. For most people, it is the atmospheric component of the climate system that characterizes climate; in a narrow sense climate is often defined as the "average weather". The climate is usually described in terms of the mean and variability of quantities such as temperature, precipitation and wind over a period of time, ranging from months to millions of years (the classical period is 30 years). The climate system evolves in time under the influence of its own internal dynamics and because of changes in external forcings. The external forcings are those that are not affected by changes in the climate system, such as volcanic eruptions, solar variations and human-induced changes in atmospheric composition. Solar radiation is the driving force of the climate system. There are three fundamental ways to change the radiation balance of the Earth: 1) by changing the incoming solar radiation (e.g., by changes in Earth's orbit or in the sun itself), 2) by changing the fraction of solar radiation that is reflected (the albedo; e.g., by changes in cloud cover, aerosols land cover), and 3) by altering the long-wave back radiation (e.g., by changing the greenhouse gas concentration). Climate, in turn, responds directly to such changes, as well as indirectly, through a range of feedback mechanisms.

[INSERT QUESTION 1.1, FIGURE 1 HERE]

Outside the atmosphere, the amount of energy reaching the Earth each second on a surface area of one square meter facing the sun is about 1370 W, and the average amount of energy incident on a level surface is one quarter of this (see Question 1.1, Figure 1). 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: aerosols. 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 sulphate containing gases far above the highest cloud, these aerosols typically influence the climate for about a year or two before falling into the troposphere and being removed by precipitation. Major volcanic eruptions can cause a drop in mean global surface temperature of about half a degree C that can last for months or even years. Also human activities affect the level of reflectivity of sunlight, for instance through industrial releases of aerosols and through land-use changes.

The energy that is not reflected back to space is absorbed by the Earth's surface and atmosphere. This amount is roughly 240 W m^{-2}. To balance the incoming energy, the Earth itself must radiate on average the same amount of energy back to space. The Earth does this by emitting outgoing long-wave radiation. Everything on Earth emits long-wave 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. To emit 240 W m^{-2}, a surface would have to have a temperature of around –19°C. This is much colder than the conditions that actually exist at the Earth's surface (the global mean surface temperature is more like 14°C). Instead, the necessary –19°C is found at an altitude of around 5 km above the surface.

The reason why the Earth's surface is so much warmer is the presence of greenhouse gases, which act as a partial blanket for the long-wave radiation from the surface. This blanketing is known as the natural greenhouse effect. The most important greenhouse gases are water vapour and carbon dioxide. The two main constituents of the atmosphere – nitrogen and oxygen – have no such effect. Clouds, on the other hand, do have a blanketing effect similar to that of the greenhouse gases; however, this effect is offset by their reflectivity, such that on average clouds tend to have a cooling effect on climate (although locally one can definitely feel the warming effect: cloudy nights tend not to cool as much as clear nights because they radiate long-wave energy back down to the surface). Human activities influence and enhance the blanketing effect through the release of greenhouse gases. For instance, the amount of carbon dioxide has increased by more than 25% in the past century, and this increase is known to be in part due to combustion of fossil fuels and removal of forests.

Because the Earth is a sphere, more solar energy arrives for a given surface area in the tropics than at higher latitudes, where sunlight strikes the atmosphere at a lower angle. Energy is transported from the equatorial areas to higher latitudes via atmospheric and ocean circulations, including storm systems. Atmospheric circulation is primarily driven by the release of latent heat. Energy is required to evaporate water from the sea or land surface and this latent heat is released when water vapour condenses in clouds (see Figure 1). 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 ocean's surface temperature and salinity through precipitation and evaporation.

Due to the rotation of the Earth, the circulation patterns tend to be directed east-west more than north-south. Embedded in the mid-latitude westerlies are large-scale weather systems which act to transport heat poleward. These weather systems are the familiar migrating low and high pressure systems and their associated cold and warm fronts. Because of land-ocean contrasts and obstacles such as mountain ranges and ice sheets, the circulation system's planetary-scale waves tend to be geographically anchored although their amplitude can change with time. Because of the wave patterns, a particularly cold winter for instance over North America may be associated with a particularly warm winter elsewhere in the hemisphere. Changes in the climate system, such as the size of ice sheets, the type of vegetation or the temperature of the atmosphere or ocean will influence the large-scale circulation features of the atmosphere and oceans.

The number of feedback mechanisms within the components of the climate system that enhance (a positive feedback) or diminish (a negative feedback) a change in climate forcing is very large. For example, the concentration of water vapour in the atmosphere is projected to increase in a warming climate because warmer air can contain more water vapour. Because water vapour is an important greenhouse gas, it will amplify the warming. As illustrated throughout Chapter 1 and indeed the entire Fourth Assessment Report, detecting, understanding and accurately quantifying the main mechanisms underlying observed climate variability and change have been the focus of a great deal of research by scientists unravelling the secrets of the rich and complex nature of Earth's climate.

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

Climate in a narrow sense is usually defined as average weather. Since climate is made up of weather, there are multiple inter-relationships between climate change and weather. Climate change is an indication that there have been changes in weather, and it is the statistical descriptions of changes in the weather that are identified as climate change. The term climate is also commonly used to encompass a description of the boundary conditions that influence the time-averaged weather such as the amounts of sea and glacial ice, the state of the biosphere, and, depending on the context, ocean surface temperatures and soil moisture of the ground as shown in Figure 1. Conversely, the total effect of weather is a vital part of climate as the instability in storm systems are crucial for transporting energy poleward.

[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 1960s, 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, 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 the background conditions. More precisely, climate can be viewed as the status of the Earth-atmosphere-hydrosphere-cryosphere-biosphere (see Question 1.2, Figure 1) that serves as the global background conditions that determine the concurrent array of weather patterns. An example of this would be an El Niño 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 and 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. The march of the seasons is due to changes in the geographical patterns of energy absorbed and radiated away by the atmosphere-land-ocean-biosphere-cryosphere system. Likewise, projections of future climate are shaped by fundamental changes in radiation, especially the intensity of the downward longwave radiation caused by greenhouse gas concentrations. Projecting 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, forced variations through changes in the boundary conditions of the atmosphere can be more predictable than individual events. As an example, the date of the death of a specific person who starts or gives up smoking is not predictable, but changes in the life expectancy for large populations that start or give up smoking are predictable.

Scientists have determined that human activities can be agents of climatic change. Human-caused, or anthropogenic, climate change results from 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. 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 frequent and others 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 Greenhouse Effect?

Solar radiation is the driving force of the Earth's climate system. The sun radiates energy at very short wavelengths, predominately in the visible or near-visible (e.g., ultraviolet) part of the spectrum. Roughly one third of the solar radiation that reaches our planet is reflected directly back to space. The remaining two thirds are absorbed by the surface and, to a lesser extent, the atmosphere. To balance the absorbed incoming energy, the Earth must, on average, radiate the same amount of energy back to space. Because the Earth is much colder than the sun, it radiates at much longer wavelengths, primarily in the infrared part of the spectrum as shown in Figure 1. Much of this thermal radiation emitted by the land and ocean is absorbed by the atmosphere, including clouds, and reradiated back to Earth. This is called the greenhouse effect. The glass walls in a conventional greenhouse reduce air flow and increases the temperature of the air inside to benefit the growth of plants. Analogously, but through a different physical process, the Earth's greenhouse effect warms the surface of the planet.

[INSERT QUESTION 1.3, FIGURE 1 HERE]

One of the most interesting aspects of the greenhouse effect is that the two most abundant gases in the atmosphere, nitrogen (N_2 comprising 78% of the dry atmosphere) and oxygen (O_2 comprising 21%), have almost no greenhouse effect. Instead the greenhouse effect comes from more complex molecules that are much less common. Globally averaged, the relative importance of the main greenhouse gases to the clear-sky greenhouse effect currently are roughly: water vapour (H_2O) 60%, carbon dioxide (CO_2) 26%, and ozone (O_3) 8%, with methane (CH_4) and nitrous oxide (N_2O) contributing most of the remaining 6%. In the humid equatorial regions, where there is so much water vapour in the air that the greenhouse effect is very large, adding a small additional amount of carbon dioxide or water vapour will have only a small direct impact on downward infrared radiation. However, in the cold, dry polar regions, the effect of a small increase in CO_2 or water vapour will be much greater. The same is true for the cold, dry upper atmosphere where a small increase in water vapour has a greater influence on the greenhouse effect than the same change in water vapour would have if it were near the surface.

Several components of the climate system, such as the hydrosphere and the biosphere, provide a regulatory effect on greenhouse gases. The prime example of this is plants taking CO_2 out of the atmosphere and converting it (and water) into carbohydrates via photosynthesis. Humans, on the other hand, add greenhouse gases to the atmosphere through the burning of fossil fuels and a variety of other activities. The terms *enhanced* greenhouse effect and *natural* greenhouse effect distinguish the impact of man-made inputs from those that would exist without human activities. But in reality, the greenhouse effect from a molecule of CO_2 released by the burning of fossil fuel is exactly the same as that from a molecule of CO_2 released by the respiration of a hummingbird. The IPCC focus on anthropogenic sources of greenhouse gases is due to their role in the rapid growth of the greenhouse gas content of the atmosphere.

The qualitative effect of adding more of a greenhouse gas, such as carbon dioxide, to the atmosphere is to strengthen the greenhouse effect and thus to warm the Earth's climate. But the quantitative effect of such a change depends on various feedback mechanisms. For example, as the atmosphere warms it will be able to contain more water vapour. If the atmosphere has more water vapour then the greenhouse effect is strengthened. This in turn would cause more warming. Quantitatively, the positive water vapour feedback may be strong enough to approximately double the change in the greenhouse effect due to the added carbon dioxide alone.

Another major feedback mechanism is that of clouds. Clouds are very effective at absorbing infrared radiation and therefore have a very large greenhouse effect, thus warming the Earth. Clouds also are very effective at reflecting incoming solar radiation, thus cooling the Earth. A change in almost any aspect of clouds, such as type, location, droplet size or lifetimes, will affect the radiation budget of the Earth. Some changes cause positive feedbacks and some changes cause negative feedbacks. Much research is in progress to better understand cloud changes in response to climate warming and their feedbacks on the climate system.