Chapter 1: Historical Overview of Climate Change Science

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Table of Contents

Executive Summary

An awareness and 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. Correspondingly, 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 main scientific conclusions from the sequence of IPCC assessments.

1.1 Overview of the Chapter

To better understand the science assessed in this Fourth Assessment Report (AR4), it is helpful to review the long historical perspective that has led to the current state of climate change knowledge. This chapter starts by describing the fundamental nature of earth science. It then describes the history of climate change science through the use of a wide-ranging subset of examples. It ends with a history of the Intergovernmental Panel on Climate Change (IPCC).

The concept of this chapter is new. There is no counterpart in previous IPCC assessment reports for an introductory chapter providing historical context for the remainder of the report. Here, a restricted set of topics has been selected to illustrate key accomplishments and challenges in climate change science. The topics have been chosen for their significance to the IPCC task of assessing information relevant for understanding the risks 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, and we refer to these chapters throughout this first chapter.

1.2 The Nature of Earth Science

Science may be stimulated by argument and debate, but it generally advances through formulating hypotheses clearly and testing them objectively. This testing is the key to science. In fact, one philosopher of science insisted 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 usually submit their research findings to the 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 thus confirmed or rejected in the peer-reviewed literature 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.

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. Sometimes, only certain kinds of questions tend to be asked about a scientific phenomenon 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 majority of scientific insights, even unexpected insights, tend to emerge incrementally as a result of repeated attempts to test hypotheses as thoroughly as possible. Therefore, because almost every new advance is 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. Superficial or amateurish acquaintance with the current state of a scientific research topic is an obstacle to a scientist's progress. Working scientists know that a day in the library can save a year in the laboratory. Even Sir Isaac Newton (1675) wrote that if he had “seen further it is by standing on the shoulders of giants.” Intellectual honesty and professional ethics call for scientists to acknowledge the work of predecessors and colleagues.

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 where appropriate?

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 (Section 1.6). It must be acknowledged, however, that the IPCC also contributes to science by identifying the key uncertainties and 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 which cannot conduct experiments on galaxies or the cosmos. This is an important consideration, because it is precisely such 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 (Chapter 8, Section 8.6) provided key tests of particular aspects of global climate models (Hansen et al., 1992)

Another example is provided by past IPCC projections of future climate change compared to current observations. 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 (Chapter 3, Section 3.2) showed that the evolution of the actual climate system fell midway between the FAR and the SAR best estimated projections and were within or near the upper range of projections from the Third Assessment Report (TAR; IPCC, 2001a)..

[INSERT FIGURE 1.1 HERE]

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 aerosols remain in the atmosphere only a short time compared to 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 (although the peer-review didn’t catch this problem), 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. 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. An important example of this is the additional physics incorporated in climate models over the last several decades as illustrated in Figure 1.2. As a result of the cumulative nature of science, climate science today is an interdisciplinary synthesis of countless tested and proven physical processes and principles painstakingly compiled and verified over several centuries of detailed laboratory measurements, observational experiments and theoretical analyses; and is now far more wide-ranging and physically comprehensive than was the case only a few decades ago.

[INSERT FIGURE 1.2 HERE]

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 documenting our changing atmospheric composition (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, FAQ 7.1). Keeling's measurements on Mauna Loa in Hawaii provide a true measure of the global carbon cycle, an effectively continuous record of the burning of fossil fuel. They also maintain an accuracy and precision that allows us to separate fossil fuel emissions from those due to the natural annual cycle of the biosphere, demonstrating 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. (Chapter 2, Section 2.3; Chapter 7, Sections 7.1 and 7.3)

To place the increase in CO_2 abundance since the late 1950s in perspective, and to compare the magnitude of the anthropogenic increase with natural cycles in the past, a longer-term record of CO_2 and other natural greenhouse gases is needed. This 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 period (Delmas et al., 1980; Berner et al., 1980; Neftel et al., 1982). From 10,000 years before present up to the year 1750, CO_2 abundances have stayed within the range 280 ± 20 ppm (Indermuhle et al., 1999). The CO_2 abundance has risen roughly exponentially during the industrial era to 367 ppm in 1999 (TAR: Neftel et al., 1985; Etheridge et al., 1996) and to 379 ppm in 2005 (Chapter 2, Section 2.3.1). (See Chapter 6, Sections 6.2, 6.3, 6.4)

Direct atmospheric measurements since 1970 (Steele et al., 1996) have also detected the increasing atmospheric abundances of two other major greenhouse gases, CH_4 (methane) and N_2O (nitrous oxide). 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., 1998) with the possible stabilization of CH_4 abundance (Chapter 2, Section 2.3.2). 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 when a steady increase brought CH_4 abundances to 1745 ppb in 1998 (TAR) and 1774 ppb in 2005 (Chapter 2, Section 2.3.2). This peak abundance is much higher than the 400-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 (15%), yet the 1998 abundance of 314 ppb (TAR) rising to 319 ppb in 2005 ((Chapter 2, Section 2.3.3) is also well above the 180-to-260 ppb range of glacial-interglacial cycles (Flückiger 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)

Several synthetic halocarbons (CFCs, HCFCs, PFCs, halons, SF_6) are greenhouse gases with large Greenhouse Warming Potentials (GWPs) (Chapter 2, Section 2.10). 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 the abundance of halocarbons phased out under the Montreal Protocol began to fall (Montzka et al., 1999; Prinn et al., 2000). In the case of synthetic halocarbons (except CF_4), ice-core research has shown that these compounds did not exist in ancient air (Langenfelds et al., 1996) and thus confirms their industrial human origin. (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), and this record now extends back to nearly one million years (Chapter 6, Section 6.3). Given this daunting picture of increasing greenhouse gas abundances in the atmosphere, it is noteworthy that, for simpler challenges but still on a hemispheric or even global scale, humans have shown the ability to undo what they have done: sulfate pollution in Greenland was reversed in the 1980s with the control of acid rain in the North America and Europe (see TAR SPM, IPCC, 2001b); and chlorofluorocarbon abundances are declining globally because of their phase-out taken to protect the ozone layer.

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 (Kington, 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. Its successor, the World Meteorological Organization (WMO), 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 in the presence of substantial gaps.

Köppen (1873, 1880, 1881) was the first scientist to overcome most of these obstacles in his quest to study the effect of changes in sunspots (Chapter 2, Section 2.7). 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, Köppen averaged annual observations into several major latitude belts and then area-averaged into a near-global time series shown in Figure 1.3.

The next global temperature time series was produced by Callendar (1938) expressly to investigate the influence of carbon dioxide on temperature (Chapter 2, Section 2.3). 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, 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 near-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 method to produce large scale time series. Budyko (1969) 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 adjustments to account for discontinuities in 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 major advancements in SST data. The first was adjusting the early observations to make them comparable to current observations (Chapter 3, Section 3.2). 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. This 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 (McPhaden et al., 1998) and have subsequently increased to over a thousand buoys transmitting data at any one time. Since 1982, satellite data, anchored to *in 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 the current global temperature time series (Chapter 3, Section 3.2). To place the current instrumental observations into a longer historical context requires the use of proxy data (Chapter 6, Section 6.2).

[INSERT FIGURE 1.3 HERE]

Figure 1.3 depicts several historical “global” temperature time series, together with the longest of the current global temperature time series, Brohan et al. (2006) (Chapter 3, Section 3.2). While the data and the analysis 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 especially illustrated by the pre-1880 values of Willet’s (1950) time series. Willett notes that his data coverage remained fairly constant after 1885 but dropped 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 changes they are indicating are 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 the 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 (Chapter 3, Section 3.2).

1.3.3 Detection and Attribution

Using our knowledge of past climates to qualify the nature of ongoing changes has become a concern of growing importance during the last decades, as reflected in the successive IPCC reports. While linked together at a technical level, detection and attribution have separate objectives. 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. Using traditional approaches, unequivocal attribution would require controlled experimentation with our climate system. However, with no spare Earth with which to experiment, attribution of anthropogenic climate change must be pursued by: (a) detecting that the climate has changed (as defined above); (b) demonstrating that the detected observed change is consistent with computer model simulations of the climate-change “signal” that is calculated to occur in response to anthropogenic forcing; and (c) demonstrating 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 and model output. In spite of the efforts described in Section 1.3.2, estimates of century-scale natural climate fluctuations remain 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. 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. 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) and Hansen et al, (1981) predicted it would be evident at least within the next two decades. A decade later, Wigley and Raper (1990) 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 analysis of vertical profiles of temperature change in the ocean and atmosphere. Studies with multiple variables make 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 "fingerprint" (i.e., 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 recent 15 years 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) and Weart (2003) provide an overview of the emerging science. 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, Pouillit 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 (1861) identified through laboratory experiments the absorption of thermal radiation by complex molecules (as opposed to the primary bimolecular atmospheric constituents O_2 and N_2). He noted that changes in the amount of any of the radiatively active constituents of the atmosphere such as H_2O or CO_2 could have produced "all the mutations of climate which the researches of geologists reveal." In 1895 Svante Arrhenius (1896) 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 preceded the change in CO_2 but were enhanced by it. (See Chapter 6, Section 6.4)

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 in the North Atlantic sector of the Arctic since the 19th century and mistakenly believed this climate variation could be explained entirely by greenhouse-gas warming. Similar model predictions were echoed by Plass in 1956 (see Fleming, 1998): "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 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 part of the emitted CO_2 is observed to accumulate in the atmosphere rather than being completely absorbed by the oceans. While CO_2 can be mixed rapidly into the upper layers of the ocean, the time to mix with the deep ocean is many centuries. By the time of the TAR, the interaction of climate change with the oceanic circulation and biogeochemistry was projected to reduce the fraction of anthropogenic CO_2 emissions taken up by the oceans in the future, leaving a greater fraction in the atmosphere. (Chapter 7, Sections 7.1 and 7.3; Chapter 10, Section 10.4)

In the 1950s, 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 (Ramanathan, 1975; Wang et al., 1976). (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 (summarized in Charlson et al., 1990) built 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. (Chapter 2, Section 2.4) Thus, the current picture of the atmospheric constituents driving climate change contains a much more diverse mix of greenhouse agents.

1.4.2 Past Climate Observations, Astronomical Theory and Abrupt Climate Changes

Throughout the 19th and 20th centuries, a wide range of geomorphology and paleontology studies has provided new insight into the Earth's past climates, covering periods of hundreds of millions of years. The Palaeozoic Era, beginning 600 million years before present (BP), displayed evidence of both warmer and colder climatic conditions than the present, the Tertiary Period (65 million to 2.6 million years BP) was generally warmer, whereas the Quaternary Period (2.6 million years BP to present, the ice ages) showed oscillations between glacial and interglacial conditions. Louis Agassiz (1837) developed the hypothesis that Europe had experienced past glacial ages, and there has since been a growing awareness that long-term climate observations can advance the understanding of the physical mechanisms affecting climate change. The scientific study of one such mechanism – 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 this astronomical theory of climate change are widely known, and the historical review of Imbrie and Imbrie (1979) calls attention to much earlier contributions, such as those of James Croll, originating in 1864.

The pace of paleoclimatic research has accelerated over recent 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). 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 theory (Hays et al., 1976).

Ice cores provide key information about past climates, including surface temperatures and atmospheric chemical composition. The bubbles sealed in the ice are the only available samples of these past atmospheres. 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 the past 400,000 years (Petit et al., 1999) and now extends to almost one million years. 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 fluctuations of rapid ice-age terminations preceded by longer cycles of glaciations.

The importance of other sources of climate variability was heightened by the discovery of abrupt climate changes. In this context, abrupt designates events of large amplitude regionally, typically a few °C, that occurred within several decades, much 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, particularly in the North Atlantic regions 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). With no obvious external forcing, these changes are thought to be manifestations of the internal variability of the climate system.

The importance of internal variability and processes was reinforced in the early 1990s with analysis of records with high temporal resolution. New ice cores (Greenland Ice Core Project, Johnsen et al., 1992; Greenland Ice Sheet Project 2, Grootes et al., 1993), new ocean cores with high sedimentation rates, as well as lacustrine sediments and cave stalagmites produced additional evidence for unforced climate changes, and revealed a large number of abrupt changes in many regions throughout the last glacial cycle. Long sediment cores from the deep ocean were used to reconstruct the thermohaline circulation connecting deep and surface waters (Bond et al., 1992; Broecker, 1997) and to demonstrate the participation of the ocean in these abrupt climate changes during glacial periods.

By the end of the 1990s, paleoclimate proxies for a range of climate observations had expanded greatly. The analysis of deep corals provided indicators for nutrient content and surface-to-deep water mass exchange (Adkins et al., 1998), showing 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 of the dating 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.

Abrupt changes are often regional, for example, severe droughts lasting for many years have changed civilizations, and have occurred during the last 10,000 years of stable warm climate (deMenocal, 2001). This result has altered the notion of a stable climate during warm epochs, as previously suggested by the polar ice cores. The emerging picture of an unstable ocean-atmosphere system has opened the debate of whether human interference through greenhouse gases and aerosols could trigger such events (Broecker, 1997).

Paleoclimate reconstructions cited in the FAR were based on various data, including pollen records, insect and animal remains, oxygen isotopes and other geological data from lake varves, loess, ocean sediments, ice cores, and glacier termini. These records provided estimates of climate variability on time scales up to millions of years. A climate proxy is a local quantitative record (e.g., thickness and chemical properties of tree rings, pollen of different species) 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, including tree rings (Fritts, 1962), corals (Weber and Woodhead, 1972; Dunbar and Wellington, 1981), and ice cores (Dansgaard et al., 1984; Jouzel et al., 1987). Phenological and historical 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; Zhu, 1973; 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). Most of these reconstructions were at single sites and only loose efforts had been made to consolidate records. A notable advance in the use of proxy data was made by Mann et al. (1998) who, for the first time, took care to ensure that the dating of different records lined up. Thus the true spatial patterns of temperature variability and change could be derived, and estimates of northern hemispheric average surface temperatures were obtained.

The WGI FAR noted that past climates could provide analogues. Fifteen years of research since has identified a range of variations and instabilities in the climate system that occurred during the last two million years of glacial-interglacial cycles and in the super-warm period of 50 million years ago. These past climates do not appear to be analogues of the immediate future, yet they do reveal a wide range of climate processes that need to be understood when projecting 21st century climate change. (See Chapter 6).

1.4.3 Solar Variability and the Total Solar Irradiance

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. 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}, which encompasses the current estimate of 1365 W m^{-2}. Foukal et al. (1977) deduced from Abbot’s daily observations that higher values of TSI were associated with more solar faculae, e.g. Abbot (1910).

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.

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 0.2 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 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 the changes in solar radiation could cause surface temperature changes on the order of a few tenths of a degree centigrade Celsius.

For the time before satellite measurements became available, the solar radiation variations can be inferred from cosmogenic isotopes (^{10}Be, ^{14}C) and 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 routinely monitor 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, 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 that of the surrounding photosphere. He concluded that they would block the emission of radiation and estimated that at sunspot cycle 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.

These satellite data have been used in combination with the historically recorded sun spot number, cosmogenic isotopic records and the characteristics of other, sun-like stars 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 indicated quasi-periodic changes in solar radiation of 0.24–0.30% on the centennial time scale. These values have recently been re-assessed (c. f. Chapter 2).

The TAR states that the changes in solar irradiance are not the major cause of the temperature changes in the second half of the twentieth century unless those changes can induce unknown large feedbacks in the climate system. The effects of galactic cosmic rays on the atmosphere (via cloud nucleation) and those due to shifts in the solar spectrum towards the UV range, at times of high solar activity, are largely unknow. The latter may produce changes in tropospheric circulation via changes in static stability resulting from the interaction of the increased UV with stratospheric ozone. 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 (see Sections 1.3.1, 1.4.1), the publication of generally accepted quantitative results coincides with, and was driven in part by the questions being asked by the IPCC, beginning in 1988. Thus, it is instructive to view the evolution of this topic as it has been treated in the successive IPCC reports.

The WGI FAR codified the key physical and biogeochemical processes in the Earth system which relate a changing climate to respectively 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. (Chapters 2, 7, 10)

The concept of radiative forcing (RF) as the radiative imbalance (W m^{-2}) to the climate system 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 projected chemical feedbacks were limited to short-lived increases in tropospheric ozone. By 1990, it was clear that the RF from tropospheric ozone had increased over the 20th century and stratospheric ozone had decreased since 1980 (e.g., Lacis et al., 1990), but the associated RFs were not evaluated in the assessments. 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). (Chapters 2, 7, 10)

The cases for more complex chemical and aerosol effects were becoming clear, but 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 and application 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 '+', '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 causing 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 altered CH_4 and N_2O fluxes from natural systems; however, in terms of a community assessment it remained qualitative

By 1994 with work on SAR progressing, the Special Report on Radiative Forcing (IPCC, 1995) reported significant breakthroughs in a set of chapters limited to assessment of 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 highlighted 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 Special Report 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 (e.g., 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 lifetime of a perturbation (and hence climate impact and GWP) of CH_4 emissions was about 50% greater than reported in the FAR. There was still no consensus on quantifying the past or future changes in tropospheric O_3 or OH (the primary sink for CH_4). (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 sulfate aerosol indirect effects on cloud properties and hence RF 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 direct 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. (Chapters 2 and 7; Chapter 8, Section 8.2; Chapter 9, Section 9.2)

Throughout the 1990s there were concerted research programs in the USA and EU 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. (Chapter 2, Sections 2.6 and 2.8; 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). (Chapter s 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, snow, sea ice, river and lake ice, permafrost and seasonally frozen ground, is an important component of the climate system. 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 gases (through changes in the permafrost). (Chapter 4)

Studies of the cryospheric albedo feedback have a long history. The albedo is the fraction of solar energy reflected back to space. Over snow and ice the albedo (about 0.7 to 0.9) is large compared to that over the oceans (<0.1). 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 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. For instance, it is not clear whether this mechanism is the main reason for the high latitude amplification of the warming signal.

The potential cryospheric impact on ocean circulation and sea level are of particular importance. There may be "large-scale discontinuities" (TAR) through both the shutdown of the large-scale meridional circulation of the world oceans (see Section 1.4.6) 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 (10% of the Antarctic ice volume) would lose its land connection and come afloat, causing a sea level rise of about 5 meters.

The importance of permafrost-climate feedbacks 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 to 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 with 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.

In 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 (1644–1912). Records of glacial length go back to the mid-1500s. 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. Systematic measurements of permafrost (thermal state and active layer) began in earnest around 1950 and were 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 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) and enabled 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). The number of cryospheric elements now routinely monitored from space is growing, and one of the more challenging elements, variability of ice volume, is now being addressed with current satellites.

Climate modelling results have pointed to high-latitude regions as areas of particular importance and ecological vulnerability to global climate change. 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. 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 representation of the cryosphere in climate models is still an area of intense research and continuing progress. (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; Holton, 1992).

A comprehensive description of these circulations was 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 20th century that the strength of the deep circulation might be varying over time, or that the ocean's Meridional Overturning Circulation (MOC; often loosely 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 subsurface 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). Nevertheless, routine observations of the subsurface ocean remain scarce compared to that of the atmosphere.

In parallel with the technological developments yielding new insights through observations, theoretical and numerical explorations of multiple (stable or unstable) equilibria began. Already in 1906, Chamberlin (1906) suggested that deep ocean currents could reverse in direction, and might impact climate. The idea didn't gain momentum until fifty years later, when Stommel (1961) presented a mechanism, based on the opposing effects that temperature and salinity have on density, by which ocean circulation can fluctuate between states. Numerical climate models incorporating models of the ocean circulation were 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 feel the attraction of different equilibrium states, gained further 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 noticed 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 (1897) noted large-scale relationships between interannual trends in pressure data from a world-wide network of 68 weather stations, and how Lockyer and Lockyer (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 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 involved 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 has similarly been known by the people of Northern Europe for a long time. 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 as a north-south oscillation in atmospheric mass with centers of action near Iceland and Portugal.

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 (Hurrell, 1995) 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. Understanding the physical processes involved in producing low frequency variability is crucial for improving our ability to accurately predict climate change and for allowing the separation of anthropogenic and natural variability, thereby improving our ability to detect and attribute anthropogenic climate change. 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 enabled 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). At the same time the physical content of the models has become more comprehensive(see in Section 1.5.2 the example of clouds). 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. This example alone shows 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, many of the key processes that control climate sensitivity or abrupt climate changes (such as clouds, vegetation, oceanic convection) depend on very small spatial scales. They cannot be represented in full detail in the context of global models, and their scientific understanding 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; on the contrary a stronger emphasis has been given to the concept of a “hierarchy of models”, as the only way to provide a linkage between theoretical understanding and the complexity of realistic models (Held, 2005)

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 by Pierrehumbert (1995) who introduced a separate representation of the areas with ascending and subsiding circulation in the Tropics, has significantly improved the understanding of the feedbacks which control climate. Simple linearized models of the atmospheric circulation have been used to investigate potential new feedback effects. Ocean box models have played an important role in improving the understanding of the possible slowing down of the Atlantic thermohaline circulation (Birchfield et al., 1990), 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 ensembles 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 been modified most continuously to take into account increasingly complex physical processes. On the other hand, clouds were still considered at the time of the TAR a major source of uncertainty in the simulation of climate changes. (Of course this role is not unique: changes in the atmospheric water vapour content constitute the largest positive feedback in most models, as comprehensively reviewed in Chapter 7 of the TAR).

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 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 Sundqvist (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 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 emission scenario. This cannot be regarded as a surprise: that the sensitivity of the Earth's climate to changing atmospheric greenhouse gas concentrations must depend strongly on cloud feedbacks, can be illustrated on the simplest theoretical grounds, using data which have been available for a long time. Satellite measurements have indeed provided meaningful 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 up to two-thirds of the planetary albedo, which is about 30%. An albedo change of only 1%, bringing the Earth's albedo from 30% to 31% or 29%, would then cause a change in the black-body radiative equilibrium temperature of about 1°C, a highly significant value, roughly equivalent to the direct radiative effect of a CO_2 doubling. Simultaneously clouds contribute importantly to the planetary greenhouse effect. Also changes in cloud cover constitute only one of the many parameters that affect cloud radiative interactions: 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 simulated cloud feedbacks was revealed by the analysis of model results (Manabe and Wetherald, 1975; Hansen et al, 1984), and the first extensive model intercomparisons (Cess et al., 1989) also showed a substantial 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 radiative 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), which differed from the approach of Senior and Mitchell (1993) through the treatment of partial cloudiness or mixed-phase properties. The model intercomparisons presented in the TAR showed no clear resolution of this unsatisfactory situation.

The scientific community realized long ago that using adequate data to constrain models was the only possible way out this problem. Using climate changes in the distant past to constrain the amplitude of cloud feedback has definite limitations (Ramstein et al., 1998). The study of cloud changes at decadal, interannual or seasonal time scales therefore remains a necessary path to constrain models. 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 and analyzed 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 as the High Resolution Infrared Radiation Sounder (HIRS) (Susskind et al., 1987), and with microwave absorption, as used by the Special Sensor Microwave/Imager (SSM/I). Chapter 8 provides an update of this ongoing observational effort.

A parallel effort has been carried out to develop 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. Recent progress in this area is assessed in Chapter 8.

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 comparison 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 changes in 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 leaps forward in climate modelling during the last 20 years (Trenberth, 1993), although both the atmospheric and oceanic components themselves have undergone highly significant improvements. This advance has led to significant modifications in the patterns of simulated climate change, particularly in oceanic regions. It has also 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, momentum 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 (Manabe and Stouffer, 1988; 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 still 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 even then necessary. One argument brought forward is that "non-adjusted" models made use of ad-hoc tuning of radiative parameters, i.e. an implicit flux adjustment.

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 actual 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. Originally it was thought that predictions of the second kind do not at all 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. However, ensemble simulations show that the projections tend to form clusters around a number of attractors as function of their initial state (see Chapter 10).

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 comparison of models is provided by Cess et al. (1989) who compared results of documented differences among model simulations in their representation of cloud feedback, to show 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 under the auspices of WCRP to undertake controlled conditions for model evaluation. One of the first 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 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 (See Box 1.1).

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) of WGI. 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 WGI FAR was completed under the leadership of Bert Bolin (IPCC Chair) and John Houghton (WGI Chair) in a plenary at Windsor in May 1990. In a mere 365 pages with 8 color plates, it 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, under Bert Bolin (IPCC Chair) and John Houghton and Gylvan Meira Filho (WGI Co-chairs), 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. These uncertainties were 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 (without cirrus effects) RF for aviation in 1992 appeared in the SPM. (See Chapter 2, Section 2.6; Chapter 10, Section 10.2)

The TAR, under Robert Watson (IPCC Chair) and John Houghton and Ding YiHui (WGI Co-chairs), 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 the RF bars each of these meant something different (e.g., some were the range of models, some were uncertainties). Another failure in dealing with uncertainty was the projection of 21st century warming: it was reported as a range covering (i) 6 SRES emissions scenarios and (ii) 9 atmosphere-ocean climate models using 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.

1.7 Summary

As this chapter shows, the history of the centuries-long effort to document and understand climate change is often complex, marked by successes and failures, and has followed a very uneven pace. Testing scientific findings and openly discussing the test results have been the key to the remarkable progress which is now accelerating in all domains, in spite of inherent limitations to predictive capacity. Climate change science is now contributing to the foundation of a new interdisciplinary approach to understanding our environment. Consequently, much published research and many notable scientific advances have occurred since the TAR, including advances in the understanding and treatment of uncertainty. Key aspects of recent climate change research are assessed in Chapters 2-11 of this report.

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. The increasing attention given to formal treatments of uncertainty in previous assessments is addressed 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 been asked 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.

Uncertainties can be classified in several different ways according to their origin. Two primary types are *value uncertainties* and *structural uncertainties*. Value uncertainties arise from the incomplete determination of particular values or results, e.g., when data are inaccurate or not fully representative of the phenomenon of interest. *Structural uncertainties* arise 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. 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. In both cases estimating uncertainties is intrinsically about describing the limits to knowledge and for this reason involves expert judgment about the state of that knowledge. A different type of uncertainty arises in systems that are either chaotic or not fully deterministic in nature and this also limits our ability to project all aspects of climate change.

The scientific literature assessed here uses a variety of other generic ways of categorizing uncertainties. Uncertainties associated with *random errors* have the characteristic of decreasing as additional measurements are accumulated, whereas those associated with *systematic errors* do not. In dealing with climate records considerable attention has been given to the identification of systematic errors or unintended biases arising from data sampling issues and methods of analysing and combining data. Specialized statistical methods based on quantitative analysis have been developed for the detection and attribution of climate change and for producing probabilistic projections of future climate parameters. These are summarised in the relevant chapters.

The uncertainty guidance provided for the Fourth Assessment Report draws, for the first time, a careful distinction between levels of confidence in our scientific understanding and the likelihoods of specific results. This allows authors to express high confidence that an event is extremely unlikely (e.g., rolling a dice twice and getting a six both times), as well as high confidence that an event is about as likely as not (e.g., a tossed coin coming up heads). Confidence and likelihood as used here are distinct concepts but are often linked in practice.

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

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

Confidence 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

Note that *low* and *very low confidence* are only used for areas of major concern and where a risk based perspective is justified.

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 Assessment Report and the basis on which the authors have determined particular levels of scientific understanding uses a combination of approaches consistent with the uncertainty guidance note as explained in detail in Section 2.9.2 and Table 2.11.

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

Likelihood Terminology	**Likelihood of the occurrence/ outcome**
Virtually certain	> 99% probability of occurrence
Extremely likely	> 95% probability
Very likely	> 90% probability
Likely	> 66% probability
More likely than not	> 50% probability
About as likely as not	33 to 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Extremely unlikely	< 5% probability
Exceptionally unlikely	< 1% probability

The terms *"Extremely likely/unlikely"* and *"More likely than not"* as defined above have been added to those given in the IPCC Uncertainty Guidance Note in order to provide a more specific assessment of the detection and attribution of key aspects of climate change.

Unless noted otherwise, values given in this report are assessed best estimates and their uncertainty ranges are 90% confidence intervals, i.e., there is an estimated 5% likelihood of the value being below the lower end of the range or above the upper end of the range. Note that in some cases the nature of the constraints on a value, or other information available, may indicate an asymmetric distribution of the uncertainty range around a best estimate. In such cases the uncertainty range is given in square brackets following the best estimate.

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Frequently Asked Question 1.1: What Factors Determine Earth's Climate?

The climate system is a complex, interactive system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water, and living things. The atmospheric component of the climate system most obviously characterizes climate; climate is often defined as "average weather". Climate is usually described in terms of the mean and variability of 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 due to changes in external factors that affect climate (called "forcings"). External forcings include natural phenomena such as volcanic eruptions and solar variations, as well as human-induced changes in atmospheric composition. Solar radiation powers 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 (called "albedo"; e.g., by changes in cloud cover, atmospheric particles, or vegetation), and 3) by altering the long-wave radiation from Earth back toward space (e.g., by changing greenhouse gas concentrations). Climate, in turn, responds directly to such changes, as well as indirectly, through a variety of feedback mechanisms.

[INSERT FAQ 1.1, FIGURE 1 HERE]

The amount of energy reaching the top of Earth's atmosphere each second on a surface area of one square meter facing the sun during daytime is about 1370 Watts, and the amount of energy per square meter per second averaged over the entire planet is one quarter of this (see FAQ 1.1, Figure 1). About thirty percent of the sunlight that reaches the top of the atmosphere is reflected back to space. Roughly two-thirds of this reflectivity is due to clouds and small particles in the atmosphere known as "aerosols". Light-colored areas of Earth's surface – mainly snow, ice, and deserts – reflect the remaining third of the sunlight. The most dramatic change in aerosol-produced reflectivity comes when major volcanic eruptions eject material very high into the atmosphere. Rain typically clears aerosols out of the atmosphere in a week or two, but when material from a violent volcanic eruption is projected far above the highest cloud, these aerosols typically influence the climate for about a year or two before falling into the troposphere and being carried to the surface by precipitation. Major volcanic eruptions can thus cause a drop in mean global surface temperature of about half a degree C that can last for months or even years. Some manmade aerosols also significantly reflect sunlight.

The energy that is not reflected back to space is absorbed by the Earth's surface and atmosphere. This amount is approximately 240 Watts per square meter (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. That is the heat energy one feels radiating out from a fire; the warmer an object, the more heat energy it radiates. 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 about 14°C). Instead, the necessary –19°C is found at an altitude about 5 km above the surface.

The reason the Earth's surface is this warm is the presence of greenhouse gases, which act as a partial blanket for the long-wave radiation coming 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 most abundant constituents of the atmosphere – nitrogen and oxygen – have no such effect. Clouds, on the other hand, do exert 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 feel the warming effect: cloudy nights tend to remain warmer than clear nights because the clouds radiate long-wave energy back down to the surface). Human activities intensify the blanketing effect through the release of greenhouse gases. For instance, the amount of carbon dioxide in the atmosphere has increased by about 35% in the industrial era, and this increase is known to be due to human activities, primarily the combustion of fossil fuels and removal of forests. Thus, humankind has dramatically altered the chemical composition of the global atmosphere with substantial implications for climate.

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 oceanic circulations, including storm systems. Energy is also required to evaporate water from the sea or land surface, and this energy, called latent heat, is released when water vapour condenses in clouds (see Figure 1). Atmospheric circulation is primarily driven by the release of this latent heat. 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 atmospheric circulation patterns tend to be more east-west than north-south. Embedded in the mid-latitude westerly winds are large-scale weather systems that act to transport heat toward the poles. These weather systems are the familiar migrating low- and high-pressure systems and their associated cold and warm fronts. Because of land-ocean temperature contrasts and obstacles such as mountain ranges and ice sheets, the circulation system's planetary-scale atmospheric waves tend to be geographically anchored by continents and mountains although their amplitude can change with time. Because of the wave patterns, a particularly cold winter over North America may be associated with a particularly warm winter elsewhere in the hemisphere. Changes in various aspects of the climate system, such as the size of ice sheets, the type and distribution of vegetation, or the temperature of the atmosphere or ocean will influence the large-scale circulation features of the atmosphere and oceans.

There are many feedback mechanisms in the climate system that can either amplify ("positive feedback") or diminish ("negative feedback") the effects of a change in climate forcing. For example, as rising concentrations of greenhouse gases warm Earth's climate, snow and ice begin to melt. This melting reveals darker land and water surfaces that were beneath the snow and ice, and these darker surfaces absorb more of the sun's heat, causing more warming, which causes more melting, and so on, in a self-reinforcing cycle. This feedback loop, known as the "ice-albedo feedback" amplifies the initial warming caused by rising levels of greenhouse gases. Detecting, understanding and accurately quantifying climate feedbacks have been the focus of a great deal of research by scientists unravelling the complexities of Earth's climate.

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

Climate is generally defined as average weather, and as such, climate change and weather are intertwined. Observations can show that there have been changes in weather, and it is the statistics of changes in weather over time that identify climate change. While weather and climate are closely related, there are important differences. A common confusion between weather and climate arises when scientists are asked how they can predict climate 50 years from now when they can't predict the weather a few weeks from now. The chaotic nature of weather makes it unpredictable beyond a few days. Projecting changes in climate (that is, long-term average weather) due to changes in atmospheric composition or other factors is a very different and much more manageable issue. As an analogy, while it is impossible to predict the age at which any particular man will die, we can say with high confidence that the average age of death for men in industrialized countries is about 75. Another common confusion of these issues is thinking that a cold winter or a cooling spot on the globe is evidence against global warming. There are always extremes of hot and cold, (though their frequency and intensity change as climate changes). But when weather is averaged over space and time, the fact that the globe is warming emerges clearly from the data.

[INSERT FAQ 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 physics-based concepts that govern 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 beyond several days is a fundamental dynamical property of the atmosphere. 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 (or some other small phenomenon) in one place can, in principle, alter the subsequent weather pattern in a distant place. At the core of this effect is chaos theory, which deals with how small changes in certain variables can cause apparent randomness in complex systems.

Nevertheless, 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 and precipitation (that is, climate) would still be about the same for that region and that period of time. Because a significant problem facing weather forecasting is knowing all the conditions at the start of the forecast period, it can be useful to think of climate as dealing with the background conditions for weather. More precisely, climate can be viewed as concerning the status of the entire Earth system, including the atmosphere, land, oceans, snow and ice, and living things (see FAQ 1.2, Figure 1) that serve as the global background conditions that determine weather patterns. An example of this would be an El Niño affecting the weather in coastal Peru. The El Niño sets limits on the probable evolution of weather patterns that random effects can produce. A La Niña would set different limits.

Another example is found in the familiar contrast between summer and winter. The march of the seasons is due to changes in the geographical patterns of energy absorbed and radiated away by the Earth system that is composed of the atmosphere, land, oceans, snow and ice, and living things. Likewise, projections of future climate are shaped by fundamental changes in heat energy in the Earth system, in particular the increasing intensity of the greenhouse effect that traps heat near Earth's surface, determined by the amount of carbon dioxide and other greenhouse gases in the atmosphere. Projecting changes in climate due to changes in greenhouse gases 50 years from now is a very different and much more easily solved problem than forecasting weather patterns just weeks from now. To put it another way, long-term variations brought about by changes in the composition of the atmosphere are much more predictable than individual weather events. As an example, while we cannot predict the outcome of a single coin toss or roll of the dice, we can predict the statistical behaviour of a large number of such trials.

While many factors continue to influence climate, scientists have determined that human activities have become a dominant force, and are responsible for most of the warming observed over the past 50 years. Human-caused climate change has resulted primarily from changes in the amounts of greenhouse gases in the atmosphere, but also from changes in small particles (aerosols), as well as from changes in land use, for example. As climate changes, the probabilities of certain types of weather events are affected. For example, as Earth's average temperature has increased, some weather phenomena have become more frequent and intense (e.g., heat waves and heavy downpours), while others have become less frequent and intense (e.g., extreme cold events).

Frequently Asked Question 1.3: What is the Greenhouse Effect?

The sun powers Earth’s climate, radiating 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 energy that reaches the top of Earth’s atmosphere is reflected directly back to space. The remaining two thirds is absorbed by the surface and, to a lesser extent, by 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 (see 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 greenhouse reduce air flow and increase the temperature of the air inside. Analogously, but through a different physical process, the Earth’s greenhouse effect warms the surface of the planet. Without the natural greenhouse effect, the average temperature at Earth’s surface would be below the freezing point of water. Thus, Earth’s natural greenhouse effect makes life as we know it possible. However, human activities, primarily the burning of fossil fuels and clearing of forests, have greatly intensified the natural greenhouse effect, causing global warming.

[INSERT FAQ 1.3, FIGURE 1 HERE]

The two most abundant gases in the atmosphere, nitrogen (N_2 comprising 78% of the dry atmosphere) and oxygen (O_2 comprising 21%), exert almost no greenhouse effect. Instead the greenhouse effect comes from more complex molecules that are much less common. Water vapour is the most important greenhouse gas, and carbon dioxide (CO_2) is the second-most important one. Methane, nitrous oxide, ozone, and several other gases present in the atmosphere in small amounts also contribute to the greenhouse effect. 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 has 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 is 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 near the surface.

Several components of the climate system, notably the oceans and living things, affect atmospheric concentrations of greenhouse gases. A prime example of this is plants taking CO_2 out of the atmosphere and converting it (and water) into carbohydrates via photosynthesis. In the industrial era, human activities have added greenhouse gases to the atmosphere, primarily through the burning of fossil fuels and clearing of forests.

Adding more of a greenhouse gas, such as carbon dioxide, to the atmosphere intensifies the greenhouse effect, thus warming Earth’s climate. The amount of warming depends on various feedback mechanisms. For example, as the atmosphere warms due to rising levels of greenhouse gases, its concentration of water vapour increases, further intensifying the greenhouse effect. This in turn causes more warming, which causes an additional increase in water vapour, in a self-reinforcing cycle. This water vapour feedback may be strong enough to approximately double the increase in the greenhouse effect due to the added carbon dioxide alone.

Additional important feedback mechanisms involve clouds. Clouds are effective at absorbing infrared radiation and therefore exert a large greenhouse effect, thus warming the Earth. Clouds are also effective at reflecting away incoming solar radiation, thus cooling the Earth. A change in almost any aspect of clouds, such as their type, location, water content, cloud altitude, particle size and shape, or lifetimes, affects the degree to which clouds warm or cool the Earth. Some changes amplify warming while others diminish it. Much research is in progress to better understand how clouds change in response to climate warming, and how these changes affect climate through various feedback mechanisms.