UNCERTAINTIES IN GREENHOUSE GAS INDUCED CLIMATE CHANGE

Alberta
ENVIRONMENT

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by:

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FOREWORD

The increase in the atmospheric concentration of greenhouse gases is an important global issue because of the risk of climate change. Despite considerable uncertainties in climate change science, the nations of the world have decided on a global effort to reduce the emissions of greenhouse gases. However, for the assessment of future actions and the formulation of an adaptation strategy, an updated knowledge of the developments regarding the uncertain aspects of the science of climate change is essential.

The science of climate change has been advancing in a fast pace. The purpose of this study is to review the recent scientific literature with particular emphasis on the latest development in several key areas of climate science uncertainties. These key areas are noted in the report. Since climate change science has an extensive literature, this allows focus on the more important aspects of the issue.

The report was prepared by Dr. Madhav Khandekar, who is a former Research Scientist from Environment Canada, where he worked for over 25 years. He holds M.S. and Ph.D. degrees in Meteorology from the Florida State University, USA, and has been in the fields of climatology, meteorology, and oceanography for over 42 years. He has published over 75 papers, reports, and book reviews, and has written a book on Ocean Surface Wave Analysis and Modelling, published by Springer-Verlag in 1989. His current research interests are: El Niño/Southern Oscillation, Asian Monsoon, and global weather anomalies.

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ABSTRACT

The purpose of this study was to assess the uncertainty associated with the science of climate change and global warming and determine the present state of our knowledge. The study examines several issues (as defined in the terms of reference) in the light of a large number of publications in the recent literature and describes the present status and uncertainties associated with these issues. The findings of this study are summarized below.

Uncertainties Related to Observational Evidence and Data Analysis

It is now certain that mean global temperature has increased over the last 100 years; however, there is still uncertainty regarding the actual magnitude of this increase. For the recent 20-year period, 1978-1997, the mean surface temperature increase is estimated to be about 0.32°C, or about 0.16°C per decade; however, the impact of urbanization and land-use change, which has not been thoroughly established as yet, could contribute up to 0.1°C (or more) towards the mean surface temperature increase. There is still some uncertainty about the temperature trend at the surface (as measured by surface network of stations) versus the temperature trend in the troposphere (as measured by earth-orbiting satellites and/or by radiosonde data). Based on the available satellite data (1979-1997), the mean temperature trend in the troposphere is now estimated to be about 0.10°C per decade; based on radiosonde data (1958-1998), the mean temperature trend for the troposphere (850-300 mb layer) is about 0.10°C per decade, the trend being stronger in the southern hemisphere than in the northern hemisphere. A causal and unequivocal link between the mean surface temperature increase and the anthropogenic greenhouse gas increase has not yet been established. The most probable cause of the mean surface temperature increase is considered to be a combination of internally and externally forced natural variability and anthropogenic sources. Significant uncertainty still exists relating the total (direct plus indirect) radiative forcing by anthropogenic aerosols (e.g., sulfate, black carbon, dust etc.). Recent studies suggest that the negative total radiative forcing by anthropogenic aerosols may offset the positive forcing by the greenhouse gases. Precipitation trends in different regions of the world do not present conclusive evidence about the intensification of the hydrologic cycle of the atmosphere-ocean system. There is still uncertainty relating trends in storm (tropical as well as extratropical) frequency in different parts of the world. Available climate data do not show any increasing trend in extreme weather events (e.g., extreme precipitation, extreme drought, thunderstorms, winter blizzards) in any part of the world.

Uncertainties Related to Climate Models and Other Issues

Global cloud climatology and its realistic simulation is perhaps the single largest uncertainty in climate models at present. An associated aspect is the modeling of the impact of anthropogenic aerosols on clouds and on the radiation budget. The presence of climate drift in simulations using coupled climate models and the associated flux adjustment problem represents a significant uncertainty regarding (model) climate sensitivity to natural and anthropogenic forcing of various origins. Sea ice cover is not well simulated in most climate models; further, most climate models do not include adequate dynamics in simulating growth and decay of sea ice. This represents a significant weakness in climate models, many of which project excessive depletion of ice cover from the Arctic and Antarctic regions. There is considerable uncertainty in the simulation of mesoscale atmospheric and oceanic features and their impacts on future climate. Finally, the

strongest climatic signal, namely the El Niño southern oscillation (ENSO) phenomenon is still inadequately simulated by most climate models.

Possible Areas for Further Work

In addition to a number of broad areas of research, several research activities on a regional and provincial scale are identified. In particular, it is suggested that a thorough analysis be made of precipitation and temperature trends over western Canada to determine spatial and temporal variability of these trends. It is further suggested that data on extreme events like blizzards, heat waves, intense precipitation, and floods, droughts, etc. be collected and carefully analyzed to establish trends (if any) in these extreme events

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During my attendance at the IUGG (International Union of Geodesy and Geophysics) 1999 General Assembly in Birmingham UK, I held extensive discussions with several scientists who made important presentations at the general assembly. I wish to acknowledge, in particular, fruitful discussions with Dr. Phil Jones (University of East Anglia, Norwich, UK), Dr. Joyce Penner (University of Michigan, Ann Arbor, USA), Dr. V. Ramanathan (University of California, San Diego, USA), and Dr. Vin Saxena (North Carolina State University, Raleigh, USA).

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Finally, I wish to express my gratitude to my wife Shalan for her help on the home computer during the preparation of the report.

1.0 INTRODUCTION

1.1 Historical Notes and Overview

The concept that the earth's atmosphere acts somewhat like the glass of a greenhouse, letting through the sunlight (the shortwave light rays) while retaining a portion of the longwave radiation from the earth's surface was first introduced by French mathematician Joseph Fourier (1827). The idea was further elaborated by Pouillet (1838), Tyndall (1865), and Langley (1890). Tyndall was the first person to propose the "greenhouse" warming hypothesis while Langley calculated the absorption coefficient for carbon dioxide and water vapour, while measuring the intensity of radiation from the moon.

The first estimates as to how changes in global concentration of "carbonic acid" (a primary greenhouse gas, now more commonly referred to as carbon dioxide) might affect mean global surface temperature were made by Swedish chemist Svante Arrhenius more than 100 years ago. Arrhenius' work was motivated by a desire to explain the temperature variation of the earth's surface during the quaternary glaciation cycles; accordingly he showed that an increase in the atmospheric concentration of CO_2 by a factor of two would lead to a heating of the earth's temperature by 5 to 6°C (Arrhenius, 1896). He further addressed the question whether such changes in the atmospheric CO_2 concentration were plausible and made some calculations of the human impact on climate that were published in a couple of papers a few years after his landmark paper of 1896. Arrhenius was influenced by the work of his geologist colleague Arvid Hogbom on the processes and possible changes in the global carbon cycle.

Arrhenius' work was followed by the work of the American geologist T. C. Chamberlin who supported the principal conclusion of Arrhenius and further elaborated on how concentrations of atmospheric CO_2 might change with time. Chamberlin's emphasis was on the processes of CO_2 emissions into the atmosphere from volcanic eruptions, the absorption and outgassing of CO_2 into and out of the world's oceans, and the role of rock formation and weathering in controlling terrestrial carbon reservoirs (Chamberlin, 1899). The studies of Arrhenius and Chamberlin did not receive much support among the atmospheric science community of that time, since the general consensus was that the absorption of longwave radiation (emanating from the earth) by water vapour was so strong that the absorption by carbon dioxide was negligible. This consensus was held in view of the fact that water vapour is the strongest absorber in the spectral region of 6 to 8 μm (10^{-6}m) bands, while in the 15 to 20 μm bands, the absorption by water vapour and carbon dioxide overlapped so much that it was difficult to separate the two effects solely on the basis of surface observations (Ramanathan and Vogelmann, 1997).

In 1938, British engineer G.S. Callendar reintroduced Arrhenius' work and possible impacts of CO_2 on the atmosphere and the earth's climate. On the basis of much improved analyses of absorption spectra for different gases, Callendar (1938, 1940) demonstrated that CO_2 does indeed have important absorption bands outside of those dominated by water vapour and that increased CO_2 concentration could have significant global effects on the surface temperature of the earth. Callendar suggested that the increase in concentrations of atmospheric CO_2 may account for the observed slight rise of average temperature in northern latitudes during recent decades. He also speculated for the first time that humans could have significant influence on the atmospheric CO_2

concentrations, but estimated that it would take several centuries of continued industrial emissions to achieve a doubling of concentration. Callendar's work rekindled interest among atmospheric scientists about the role of CO_2 on past as well as future climates, leading to the publication of several papers linking CO_2 concentration with atmospheric temperature increase. A paper by Plass (1956) suggested that a 10% increase in atmospheric carbon dioxide would increase the average temperature by 0.36°C. In an important paper in 1957, the well-known American geophysicist Roger Revelle proposed that "humans are carrying out a large-scale geophysical experiment through world-wide industrial activity that could lead to a buildup of CO_2 greater than the rate of CO_2 production from volcanoes" (Revelle and Suess, 1957). Revelle was instrumental in establishing the first station for long-term monitoring of atmospheric CO_2 at Mauna Loa (Hawaii) and in launching an accelerated international research program on the potential human influence on the climate system (Hengeveld, 1996). Another CO_2 monitoring station was later established at the south pole and several global CO_2 monitoring networks were established during the 1970s and 1980s. These networks have established the steady buildup of atmospheric CO_2 as can be seen in Figure 1.1, which shows the well-publicized increase in concentration of CO_2 at Mauna Loa and at South Pole during the last 40 years. The two curves (Mauna Loa and South Pole) clearly show seasonal cycles with opposite phases. The much larger amplitude in the Mauna Loa data is attributed to the larger land and vegetation areas of the northern hemisphere.

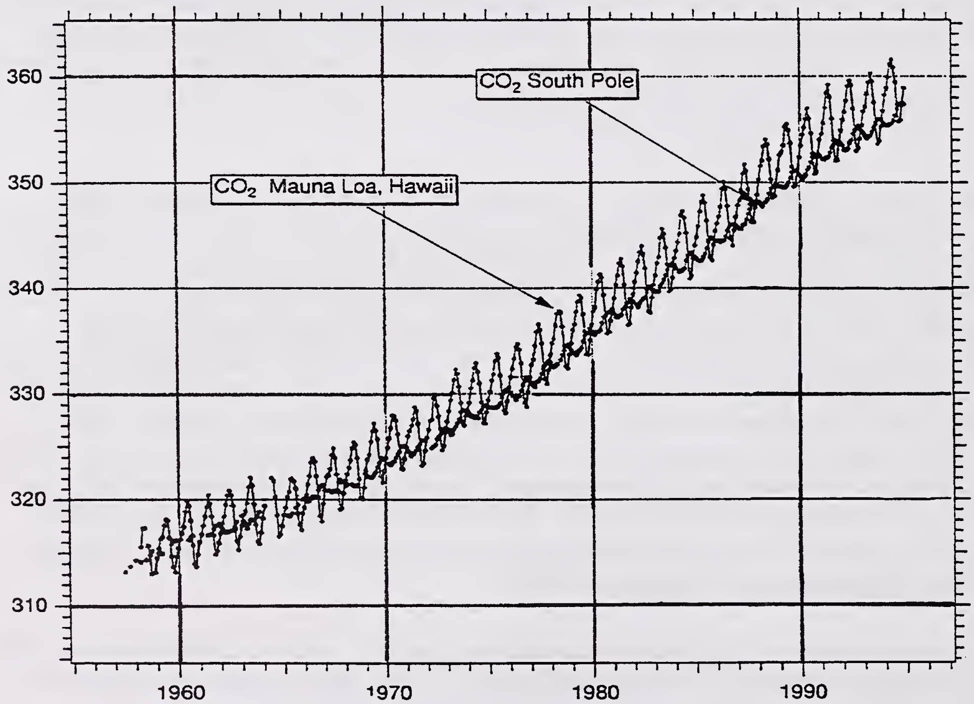


Figure 1.1 Direct atmospheric measurements of CO_2 concentrations at Mauna Loa and South Pole since about 1956. Concentration is in units of ppmv (parts per million, volume basis). Note that seasonal oscillations in the interannual variation at South Pole are in opposite phase to those at Mauna Loa and considerably smaller.

The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) in 1988. The IPCC is now recognized as the prime source of scientific and technical information on climate change and its environmental and socioeconomic impacts. The first assessment report on climate change was completed by the IPCC in 1990. In its second assessment report on climate change (IPCC, 1996), the IPCC identified the increasing concentration of CO_2 and its possible link with the increasing mean surface temperature of the earth with the cautious statement that *the balance of evidence suggests a discernible human influence on global climate.* The IPCC has also recognized other greenhouse gases, namely, methane (CH_4) and nitrous oxide (N_2O). The atmospheric concentrations of these two gases have also grown significantly since pre-industrial times (i.e., since about 1750) by about 145% (methane) and by about 15% (nitrous oxide) based on 1992 values. However, the direct radiative forcing by these two gases is significantly smaller (0.47 $W \cdot m^{-2}$ and 0.14 $W \cdot m^{-2}$) as compared to 1.56 $W \cdot m^{-2}$ for carbon dioxide; consequently, the present emphasis is on the global carbon cycle and the future growth of carbon dioxide in the earth-atmosphere system over the next 50 to 100 years. The sharply increasing concentration of methane and its consequent radiative impact on the future climate has also been emphasized by the IPCC.

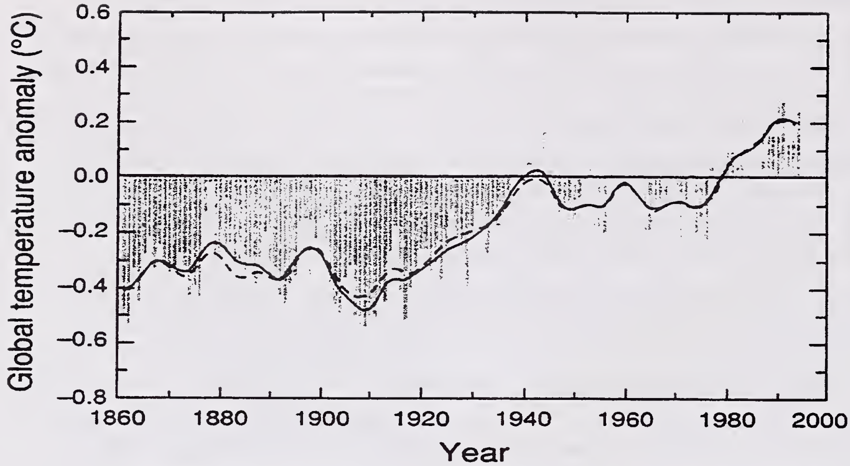
1.2 Global Warming as Evidenced by Mean Temperature Increase

The key question at present is whether the atmosphere-earth system has warmed in recent times and, if so, by how much? The answer to the first part of the question is definitely affirmative, while the answer to the second part of the question is still indeterminate because of a number of uncertainties that will be discussed later.

Determination of the mean temperature of the combined land/ocean surface of the earth for a given year is perhaps the most difficult and most elusive task. Several land and water surface processes (e.g., urbanization, land-use change, surface and subsurface water circulations in the oceans) can influence and distort mean surface temperature calculations. Nevertheless, painstaking efforts by Phil Jones of the Climate Research Unit, University of East Anglia (UK) and his coworkers, through careful analysis of a vast amount of land-ocean surface data, have helped elucidate mean temperature variations over the last 140 years. These mean temperature calculations published in a series of papers (Jones et al.; 1986a, 1986b, 1999) have now become a benchmark and provide a firm basis for the scientific discourse on climate change. The mean surface temperature changes for the period 1861-1995 as given in IPCC (1996) are shown in Figure 1.2a, while Figure 1.2b shows the mean temperature variations over the northern and southern hemispheres together with global variations based on a more recent paper by Jones et al. (1999). These temperature curves show mean temperature departures (°C) relative to 1961-1990. Some of the important variations in the mean temperature curves may be noted as follows:

1.2.1 The earth's mean temperature shows a steady increase of almost 0.5°C from about 1910 to about 1940. Mean temperature shows a decline of about 0.2°C from about 1950 to 1975. From 1980 through 1995, the mean temperature of the earth shows a relatively steep increase of about 0.25°C; the recent study by Jones et al. indicates a warming of about 0.32°C over the period 1978-1997.

1.2.2 The temperature change over the southern hemisphere is slightly larger than over the northern hemisphere, while the global temperature change over the entire period 1861-1997 is about 0.57°C.



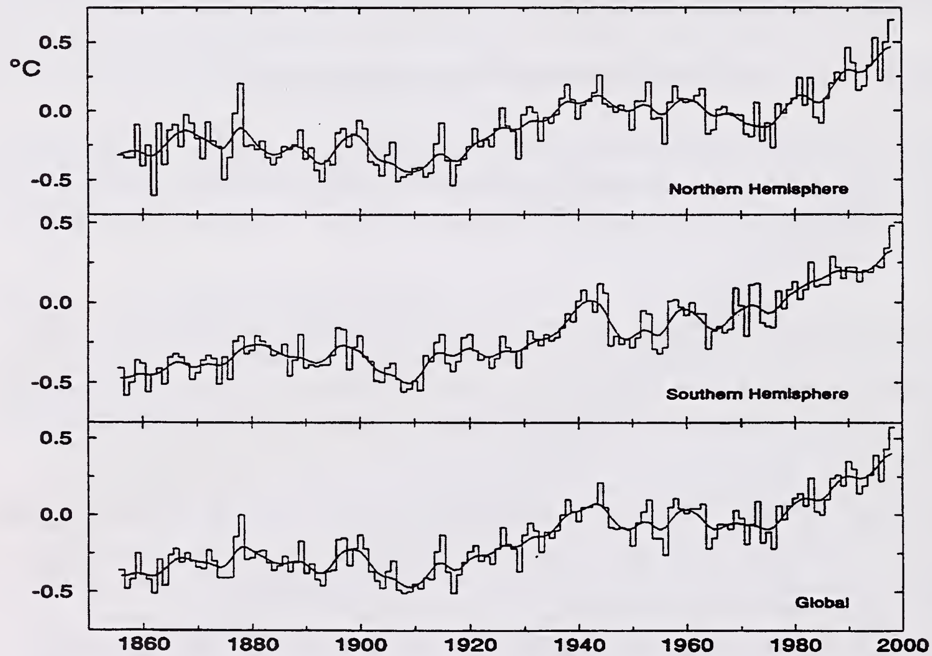


Figure 1.2a (top) Combined land/sea surface temperatures 1869-1990 relative to the 1961-1990 mean. The solid curve represents smoothing of the annual values, shown by the bars, to suppress sub-decadal time-scale variations. The dashed smooth curve is the corresponding result from the IPCC (1992) (from IPCC, 1996).

Figure 1.2b (bottom) Hemispheric and global temperature averages 1856-1998 relative to 1961-1990. The smooth line on the time series highlights variation on the decadal time scale (10-year Gaussian filter) (from Jones et al., 1999).

These temperature changes, although numerically small, are nevertheless significant from the standpoint of radiative equilibrium and warrant a close examination of their possible influence on the earth's climate. The questions facing the scientific community today are:

- **a.** Are these temperature changes caused by anthropogenic greenhouse gases, natural variations in climate, or a combination of the two?
- **b.** Are these temperature changes inducing climate change in terms of increased variability or increased incidence of extreme weather events or both?

This report provides an assessment of uncertainties in greenhouse gas induced climate change based on recent studies and the present state of our knowledge. In the next two chapters, several key issues facing the science of climate change (as defined in the terms of reference of the project) are examined and a detailed analysis and assessment of these issues is presented. The final chapter presents a brief summary and identifies priority areas for further research.

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2.0 ASSESSMENT OF UNCERTAINTIES IN OBSERVATIONS

2.1 Introduction

Since the publication of the Climate Change 1995 report (IPCC, 1996), a large number of studies based on observed data have attempted to verify some of the conclusions regarding present and the future climate by analyzing the available observed data and by examining model simulations of future climate. The thrust of most of the observational studies is to assess if recent weather events and atmospheric data (e.g., precipitation, temperature, tropical and subtropical storms, etc.) indicate any variability that can be associated with possible climate change that, in turn, can be linked to global warming. Many of these studies have identified areas where observations do not support projections of future climate made by computer models. There have also been studies reported in recent literature questioning the magnitude of the warming as well as the validity of the mean surface temperature calculations and associated impacts on future climate. (Lindzen, 1990; Michaels and Stookebury, 1992). The global warming debate began in the early 1980s, well before the publication of the IPCC Climate Change 1995 report. The IPCC report brought the debate into sharper focus and has led to publication of reports by a group of scientists (e.g., ESEF Report, 1996) or commentaries (e.g., Singer et al., 1997, Kondratyev, 1997) and books like "Hot Talk, Cold Science" by Singer (1997). These publications have prompted many scientists and researchers to take a closer look at the available data to determine if the perceived climate variability should be attributed to warming due to greenhouse gas increases, natural climate variability, or a combination of both.

In this chapter, several issues related to observational uncertainties (as defined in the terms of reference) are analyzed in detail. The various issues are first stated *in italics* and then analyzed in the light of recent studies and the present state of our knowledge:

2.2 Cooling in Extratropical North Atlantic Ocean

Cooling has been observed in the North Atlantic and parts of eastern Canada for the last 25-30 years, while most coupled models do not simulate this cooling very well.

The spatial distribution of mean surface temperature relative to the 1961-1990 period shows considerable variation in the magnitude of warming as well as cooling in different geographical regions of the earth (see Figure 2.1a,b). Three significant areas of cooling are: north central Pacific, northwest Atlantic, eastern Canada, and parts of central and eastern Europe. The most notable among these regions is the northwest Atlantic together with eastern Canada, which show significant cooling in the winter months (Figure 2.1b), and another region extending from southeastern USA to the Caribbean Sea and thence southward (Figure 2.1a). Many of the earlier climate models (e.g., Washington and Meehl, 1989; Manabe et al., 1991,1992) do not reproduce this cooling in the northwest Atlantic very well (in fact some of the climate models show a warming of up to 2 to 4°C in this region). A recent model developed at the Max Planck Institute for Meteorology, Hamburg (Germany) by Roeckner et al., (1995, 1998) shows a large area of cooling over the Canadian sector of the North Atlantic, in agreement with the observed temperature

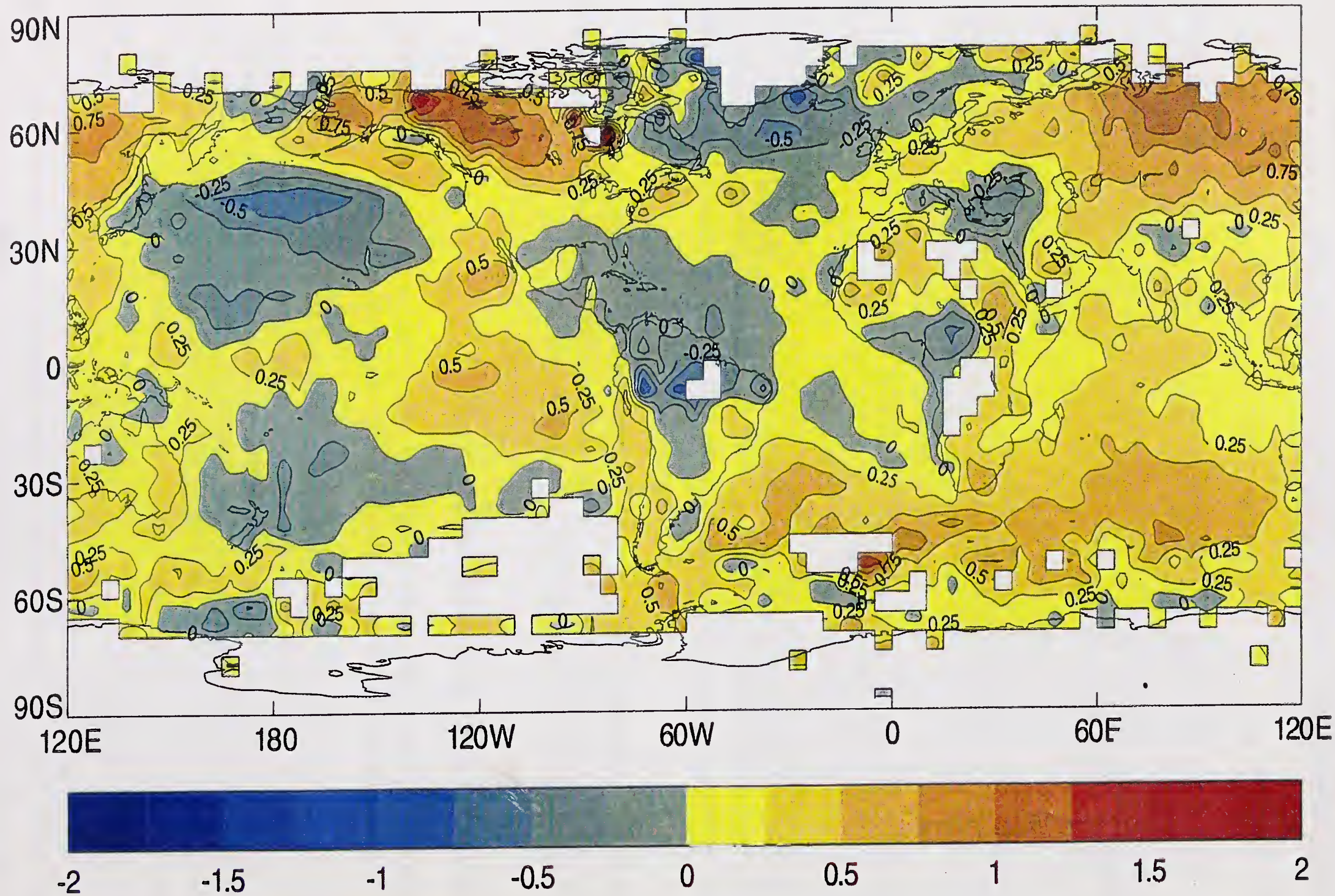


Figure 2.1a Changes (from 1955-74 to 1975-94) of annual land-surface air temperature and sea surface temperature (from IPCC, 1996)

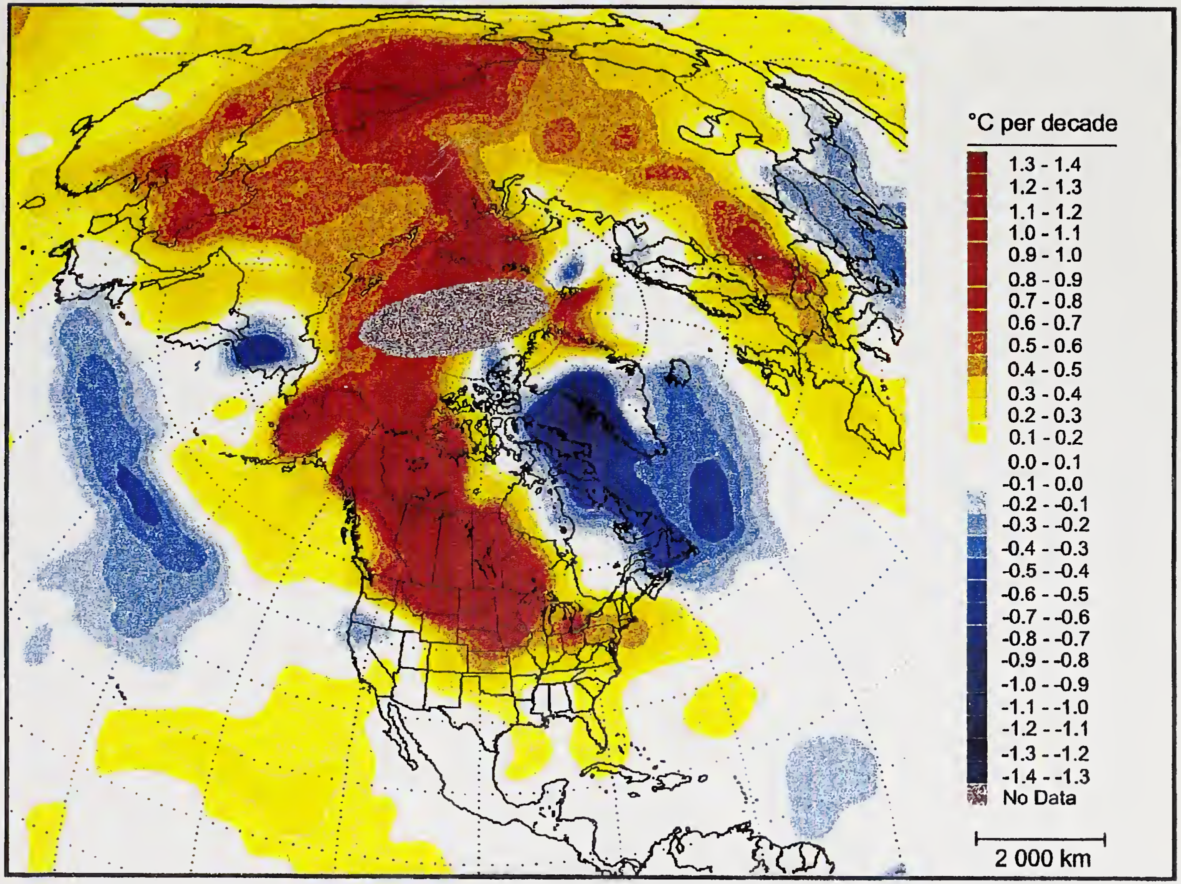


Figure 2.1b Winter (DJF) surface temperature trends 1961-1990 for the period 1961-1990 expressed as degrees Celsius per decade (from Shabbar et al., 1997)

distribution shown in Figure 2.1b. This improvement is attributed to improved simulation of the natural climatic variability by the model (see Bengtsson, 1997).

Further discussion on climate model performance and weaknesses will be deferred to the next chapter; suffice it to say here that the cooling over the northwest Atlantic and over eastern Canada is now attributed to the positive phase of the NAO (North Atlantic oscillation), according to recent studies by Hurrell (1995, 1998) and others. Another recent study by Shabbar et al., (1997) has developed an index called the BWA (Baffin Bay–west Atlantic) index to explain the cooling over eastern Canada; this BWA index is a reflection of the western structure of the NAO and is more closely related to the negative temperature anomalies over the northwest Atlantic. The NAO and other large-scale oscillations, for example, the recently identified Arctic oscillation (Thompson and Wallace, 1998; Kerr,1999) are not yet well simulated by many climate models. The cooling over southeastern USA in the Atlantic seaboard states is now attributed to negative radiative forcing by sulfate aerosols (e.g., Saxena and Yu, 1998; Saxena and Menon, 1999). A large number of studies on the important topic of climate forcing by anthropogenic aerosols have been reported in the recent literature; a detailed discussion on this appears in the next chapter.

2.3 Satellite and Land-Based Temperature Records

Satellite records show a slight cooling instead of warming during their past 19 years of existence. Recent analysis shows that the falling altitude of the satellites can be a reason for the apparent cooling trend. However, the results show great uncertainty about the impact of this effect on the satellite records. Land-based temperature records are also compared with satellite data. Uncertainties in land-based records include the effect of urbanization and uneven distribution of stations. These have impacts on mean surface temperature calculations.

As mentioned in the first chapter, calculation of the mean surface temperature of the earth, free of sampling error associated with urbanization and other effects, is perhaps the most difficult task. The mean surface temperature calculation and its upward trend are being increasingly questioned because of strong disagreements with mean tropospheric temperature trends calculated using satellite-based radiometric data from the past 19 years (1979-1997). Several important and painstaking studies, notably by Spencer and Christy (1990, 1992) and Christy et al. (1995, 1998) have merged MSU (microwave sounding unit) data from several satellites to produce a mean daily temperature value for the troposphere and its trend over the years for which satellite data have been available. These studies show a small cooling trend for the mean tropospheric temperature, inconsistent with the warming trend for the mean surface temperature documented in several papers by Jones and his coworkers. This inconsistency in temperature trends has been analyzed by Hurrell and Trenberth (1996, 1998) and by Jones et al. (1997), among others. The difference in temperature trends has been attributed to a number of factors, such as merging of data from different satellites, uncertainties regarding the level and character of natural differential variability between the surface and lower troposphere, uncertainties in differential response to anthropogenic and/or natural (e.g., volcanic) forcing, and errors due to satellite drift from original local-equator crossing time (LCT). The recent paper by Christy et al. (1998) recalculates the mean temperature trend for the troposphere applying several corrections and using improved techniques for merging data from different satellites. The revised calculations yield a smaller cooling trend (~ -0.046°C per decade) for the mean tropospheric temperature, still at odds with the surface temperature trend of +0.15°C per decade. Hansen et al. (1995) made a comprehensive analysis of the differences between surface and tropospheric temperature trends and have attributed part of the difference to stratospheric ozone depletion, which cools the troposphere more than the surface. Hansen et al. further suggest that urbanization would influence the mean surface temperature calculation by at least 0.1°C over 100 years. The satellite-based MSU data have been reanalyzed by Prabhakara et al. (1998) and a mean temperature trend of about +0.11°C per decade during the period 1980-1996 has been estimated for the troposphere; this trend is in better agreement with the surface temperature trend. Another recent study by Angell (1999) calculated the mean temperature trend for the troposphere (850-300 mb layer) using a 63-station radiosonde network and obtained a mean tropospheric temperature trend of +0.10°C per decade during the 41-year period (1958-1998). This value appears to be in very good agreement with the temperature trend calculated by Prabhakara et al. for the period 1980-1996.

Assessing the impacts of urbanization and land-use change on the mean surface temperature calculation is a challenging task. The classical studies of Mitchell (1961) and Oke (1973) suggest that the urban heat island effect could be significant even for towns with populations of few thousand people. For large cities with populations of two million or more, Oke's study estimates the urbanization impact could increase the surface air temperature at urban sites by 10°C or more. According to the IPCC (1990), the urban heat island (and its potential impact on surface air temperature) is probably the most serious source of systematic error in land surface climatological measurements. Several studies published in the last 15 years or so have attempted to assess the effects of urbanization on local and regional climate (e.g., Cayan and Douglas, 1984; Balling and Idso, 1989; Karl et al.,1988; Goodrich, 1992; Portman,1993). In the context of global warming there have been several studies, notably by Karl and Jones (1989) and Jones et al. (1990) to assess the impact of urbanization on the calculation of the mean surface temperature of the earth as a whole and to estimate a numerical value for it. According to Jones et al. (1990), the impact of urbanization on the mean surface temperature would be no more than 0.05°C over 100 years. This value appears to be too small in view of similar calculations for individual large cities or local regions. For example, Fujibe (1995) obtains an average rising trend of 2-5°C per 100 years in the minimum temperature at several large cities in Japan, while Hingane (1996) estimates rising trends of 0.84°C and 1.39°C per 100 years in the mean surface temperatures calculated for Bombay and Calcutta, two of the largest cities in India. It is now recognized that urbanization and changing land use influence minimum temperature, which, in the last 100 years has risen faster than maximum temperature at most locations. The more rapid increase in minimum temperature (than maximum temperature) has led to a decrease in the diurnal temperature range (DTR) at most locations on a worldwide basis (Karl, 1993) and an increase in the mean surface temperature, estimated to be up to 0.25°C or more (Easterling et al. 1997), thus accounting for up to half of the global warming estimated by Jones and coworkers. In a more recent study (Gallo et al., 1999), over 1200 weather observing stations in USA were designated as either urban, sub-urban, or rural using a night-light index from a satellite-based device, and temperature trends at rural and urban sites were determined for the period 1950-1996. The study found that the decreasing trend in DTR (primarily associated with increases in minimum temperature) was smaller at rural stations than at urban stations by about 0.45°C per 100 years. This value, although not statistically significant, suggests that urbanization (e.g., increased humidity and cloud cover) tends to increase the minimum temperature more than the maximum temperature, thus reducing DTR and boosting mean temperature. Another recent study (Hansen et al., 1999) makes a comprehensive analysis of surface temperature change and estimates the anthropogenic urban contribution to the global mean temperature curve for the past century to be about 0.1°C.

In summary, the satellite-based MSU data, when suitably corrected for decay of satellite altitude (Wentz and Schabel, 1998) and other corrections as mentioned above show a small but definite warming trend in mean temperature of the troposphere over the last 19 years (1979-1997); the actual magnitude of the warming trend is still a subject of study (C. Prabhakara, personal communication). The MSU data and the mean surface temperature data appear to be reconciling towards a small but a definite increasing trend throughout the tropospheric depths of the atmosphere (Hansen et al., 1998).

2.4 Solar Irradiance Change Affecting Last 100 Years

The influence of solar activities may contribute to the warming observed in the ground-level temperature record. This may be significant in the post-1900 period. What are the recent findings on the solar contribution to observed warming?

The IPCC 1996 report did consider solar irradiance change over the last 100 years and its possible impact on the global warming. However, it was concluded that the solar irradiance variations of the past century are likely to have been considerably smaller than the anthropogenic radiative forcing, and hence its impact on climate was considered to be insignificant. Several recent studies (e.g., Hoyt and Schatten,1993; Lean et al., 1995a, 1995b; Solanki and Fligge, 1998) have attempted to reconstruct the solar irradiance variations over the last 300 years or more and these reconstructed solar irradiance values have been studied in conjunction with variations in the earth's mean surface temperature by Lean et al. (1995) and Lean and Rind (1998), among others. These studies now suggest that solar forcing can be significant and may have contributed to some of the recent observed global warming. According to Lean et al.(1995), solar forcing may have contributed about half of the observed 0.55°C surface warming since 1860 and about one third of the warming since 1970. In a recent comprehensive study, Lean and Rind (1998) correlated the reconstructed solar irradiance values with the northern hemisphere surface temperature anomalies and found a correlation of 0.86 over the preindustrial period from 1610 to 1800, implying a predominant solar influence on the preindustrial climate. Extending this correlation analysis to the industrial era from about 1850 to about 1960, during which the solar activity has generally increased, it is possible to attribute up to half of the observed global warming to the increased solar output. Since about 1970, greenhouse gas radiative forcing has been significantly larger than solar irradiance-change forcing. Consequently the solar forcing signal in the global warming data cannot be easily isolated; nevertheless, Lean and Rind attribute up to one third of the recent warming to increasing solar irradiance output.

In summary, recent studies on reconstruction of solar irradiance and its possible impact on the earth's climate has added a new dimension to the global warming debate. Further, these studies strongly suggest that at least part of the observed global warming can be explained due to increased solar irradiance during the last 100 years.

2.5 Change in Intensity or Frequency of Extreme Weather Events

Extreme weather is expected to increase in frequency and intensity with global warming. Recent analyses of extreme weather intensities and frequencies show conflicting results. What are the major findings for drought, storms, and floods? What do GCMs say about extreme weather? A related aspect is the relationship between El Niño and warming. Are there new developments regarding the linkages between El Niño and warmer climate?

There are several aspects of this issue that require careful assessment. The projections of future climate according to the IPCC 1996 report suggest

- **a.** increased frequency and intensity of storms (tropical as well as extratropical),
- **b.** increase in the area of the globe affected by droughts and floods, and
- **c.** intensification of the global hydrologic cycle (e.g., vigorous Indian/Asian monsoon).

Let us consider these points separately:

Storms: An analysis of tropical storms (hurricanes, tropical cyclones, typhoons, etc.) and their interannual variability indicates that these storms do not show any increasing trend in terms of frequency or intensity. The North Atlantic tropical storms (or hurricanes as they are popularly known) have been studied extensively by Gray (Colorado State University, USA) and his coworkers, and the results of their studies have been reported in a number of papers (e.g., Gray, 1984a, 1984b; Gray et al., 1994; Landsea, 1993; Landsea et al., 1999). Based on these and other studies it is now well established that the Atlantic hurricane frequency and intensity are governed by several large-scale features, including the phase of the ENSO, Caribbean basin sea level pressure and 200-mb zonal winds, west Sahel (Africa) rainfall, and Atlantic sea surface temperature and its variation. According to Landsea et al. (1999), the Atlantic hurricane variability can be characterized as lacking strong linear trends, but is comprised of robust multidecadal variations. In particular, intense hurricanes—those reaching sustained winds of 50 m/s^{-1} were very common in the 1940s through the 1960s, and were much reduced in occurrence from the 1970s through the early 1990s. The years 1995 and 1996 showed a dramatic increase in hurricane activity, most likely because of the La Niña (cold) phase of the ENSO. The 1997 hurricane season was remarkably quiet (Rappaport, 1999) with only six tropical storms formed in the Atlantic basin, compared to the long-term average of ten. For ready reference, interannual variation of hurricanes, hurricane days, strongest Atlantic hurricanes, and hurricane wind speed are shown in Figure 2.2a,b. These figures underscore the conclusion of Landsea et al., as stated earlier. In the central Pacific, the total number of tropical cyclones and typhoons shows a decreasing trend from 1959 till the mid-1970s, followed by an increasing trend during recent years (Figure 2.3a). In the Australian region, there was a distinct reduction in the total number of tropical cyclones in recent years while a small increase is seen in the number of intense cyclones (Figure 2.3b). No study has been reported so far on the interannual variability of tropical cyclones in the Indian Ocean area, while the tropical cyclones (and depressions) in the Bay of Bengal show no discernible trend. In summary, there is no increasing trend in the tropical cyclone frequency or intensity in any of the three ocean basins, and the interannual variability appears to be primarily governed by the ENSO phase and other large-scale features of the atmosphere-ocean system.

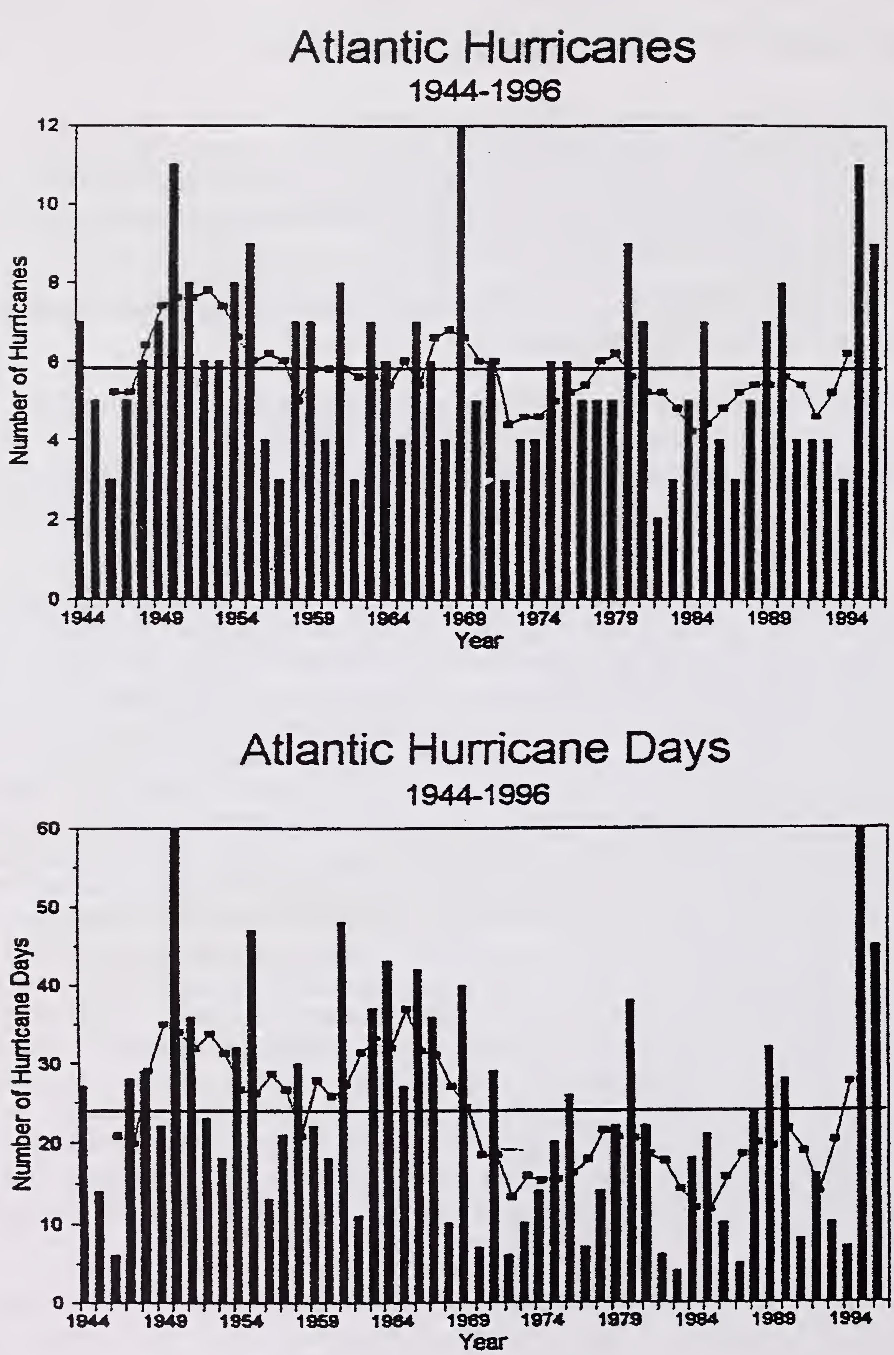


Figure 2.2a Interannual variation of Atlantic hurricanes and hurricane days (from Landsea et al., 1999)

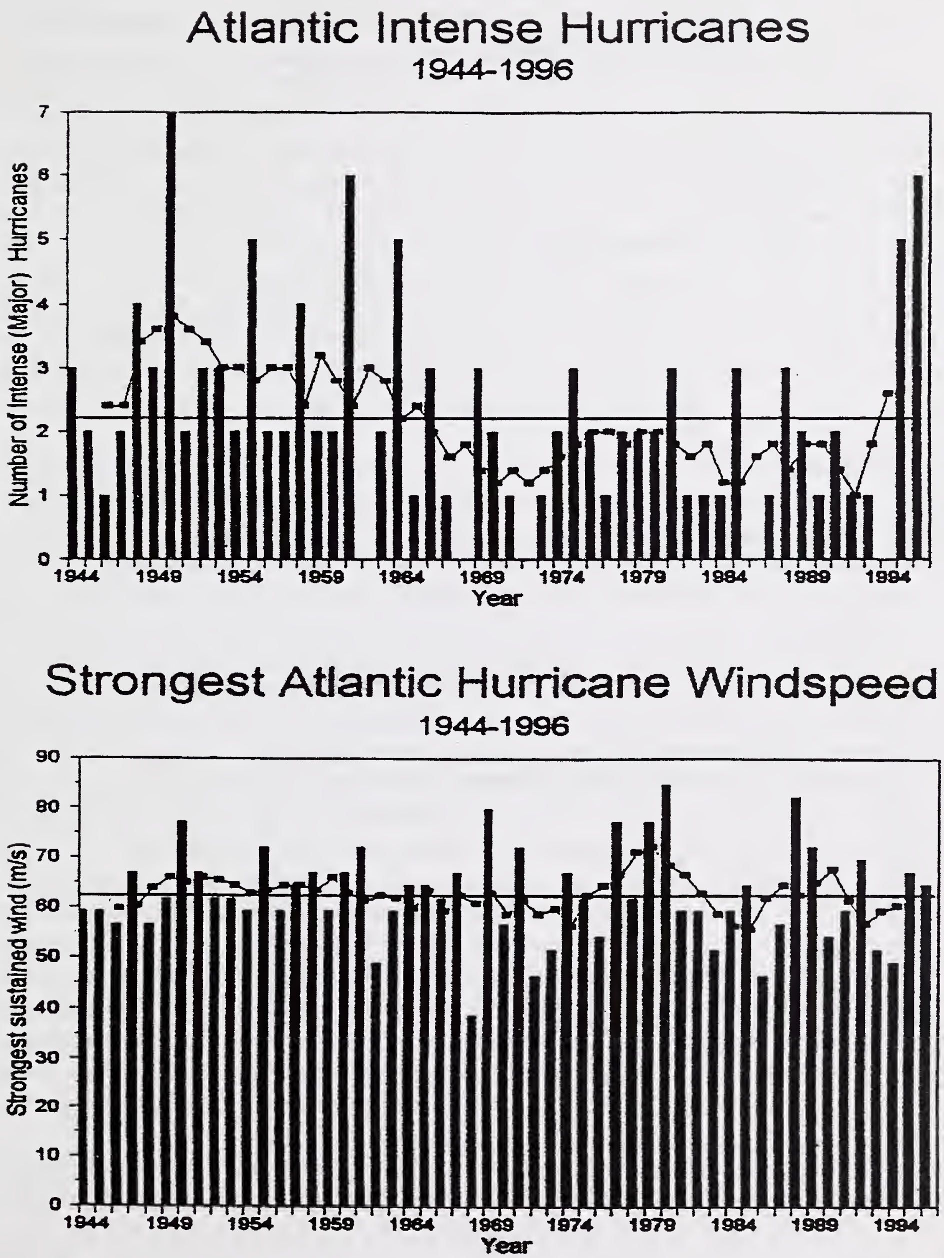
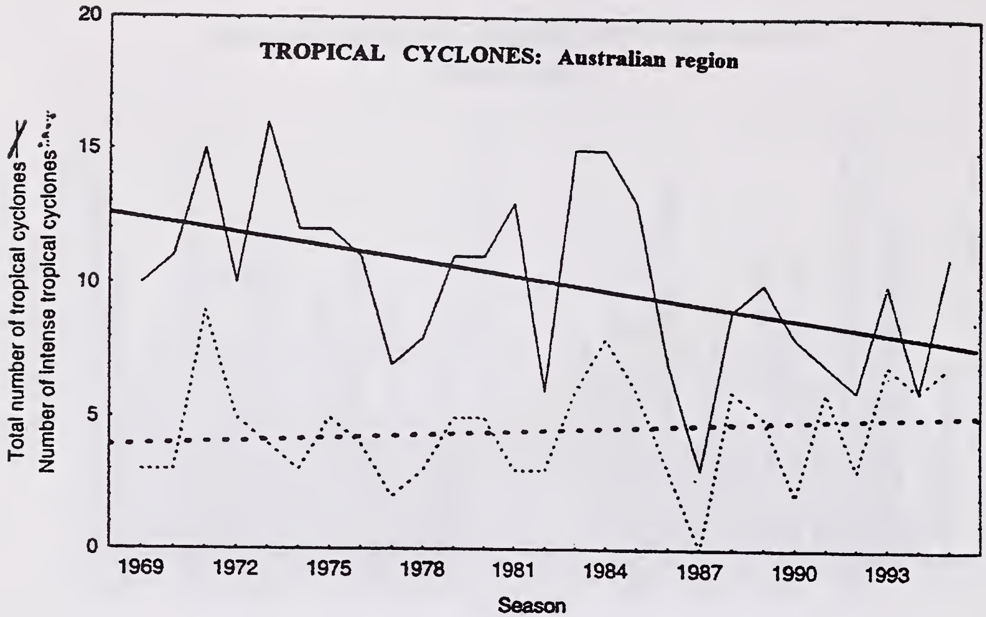


Figure 2.2b Intense Atlantic hurricanes and strongest Atlantic hurricane wind speeds (from Landsea et al., 1999)



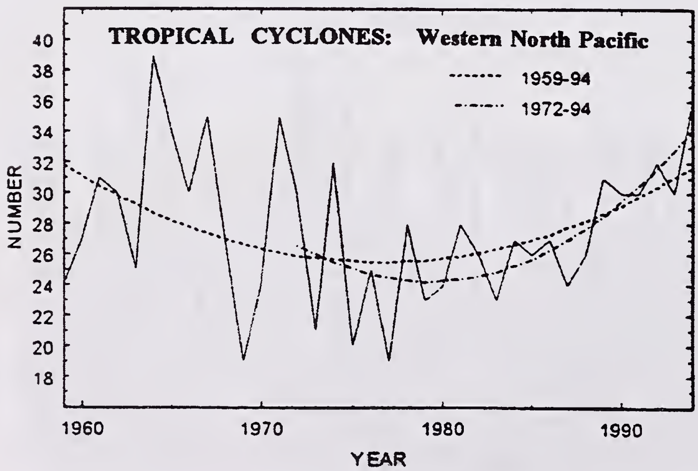


Figure 2.3a (top) Total number of tropical cyclones (solid lines) and number of intense systems (dotted lines) in Australian region (105-160°E) 1969-1995

Figure 2.3b (bottom) Annual number of tropical storms and typhoons over western North Pacific. Two second-order polynomial fits to the series are also shown (from Shan and Shi, 1996).

The interannual variability of extratropical storms appears to show an increasing trend but the results are conflicting. An earlier study by von Storch (1993) concludes that there was no observational evidence of systematic change in either the frequency or the severity of extratropical storms in the North Atlantic over the past 100 years. Lambert (1996) analyzed intense cyclones in the North Pacific and North Atlantic and found evidence to support an increase in intensity during the past several decades. A more recent study by Bijl et al. (1999) analyzes long-term observational sea-level data sets in the context of a possible change in storminess over northwest Europe. The study concludes that, for sea-level stations in the southern North Sea, there has been a tendency towards a small weakening of the storm climate over the past 100 years. For the more northern stations, there was no indication of a weakening of the storm climate; a small but insignificant increasing trend was indicated. In another recent study (Hirsch et al., 1999), an analysis of winter storms climatology (based on 1951-1997 data) reveals a decreasing trend in the frequency of winter storms for the east coast of North America. Thus there is no increasing trend emerging out of the studies reported so far.

Floods and droughts: A study by Balling Jr. (1996) analyzes over 100 years of excellent drought records in the USA during a period of substantial buildup of greenhouse gases and concludes that there is no evidence of a drying trend in any climatological region of the USA. A similar study on drought in Canada (Maybank et al. 1995) finds that the Palmer Drought Severity Index (PDSI, a commonly used drought index) shows no significant trend during the last 80 years over the Canadian prairies, the most drought-prone region in Canada. A more recent study by Dai et al. (1998) calculates the PDSI on a global scale using gridded monthly air temperature and precipitation data over the period 1900-1995. The study finds large multi-year to decadal variations in the percentage areas in severe drought (PDSI < -3.0) and severe moisture surplus (PDSI $> +3.0$) over many land areas, but no significant secular trends. Since the late 1970s, there have been some increases in the combined percentage areas in severe drought and severe moisture surpluses, however, these recent changes are attributed to the shift in the ENSO phase towards a warmer phase, which has resulted in more frequent El Niño events during the last 25 years or so. Another recent study (Plummer et al., 1999) on changes in climate extremes over the Australian region reveals that the percentage area of Australia experiencing extreme wet conditions has increased slightly while the area of extreme dryness has decreased slightly since 1910. A comprehensive study on interannual variability of seasonal rainfall over various subdivisions of India (Parthasarathy et al., 1995) based on over 125 years of excellent data sets shows no increasing or decreasing trend in rainfall amounts over any of the subdivisions, including the desert region of Rajasthan in northwest India. The studies reported so far do not reveal any increase or decrease in the total areas of floods and droughts worldwide.

Intensification of global hydrologic cycle: This is perhaps the most contentious aspect of climate change as a result of global warming. Several recent studies have made detailed analyses of precipitation data on local, regional, and continental scales attempts to find an increasing trend in either the total precipitation or in the frequency of "heavy precipitation" events; the results appear to be conflicting at this time. Among the often-quoted studies is the painstaking analysis by Karl and Knight (1998) showing an increasing trend in the percentage contribution of the upper 10th percentile of daily precipitation events to the total annual precipitation, area-averaged across the conterminous USA. However, such an analysis for Canada does not show any definite increasing trend. According to Mekis and Hogg (1999), the fraction of annual precipitation falling in heavy

(90th percentile) events has decreased by over 4% since 1910 in southern regions of Canada. At more northern stations (north of 55°N), this fraction has increased by 5%, but this trend is based on a shorter data set (1940-1995). Another recent study on precipitation trends on the Canadian prairies (Akinremi et al., 1999) finds an increase in the number of precipitation events on the Canadian prairies, but this increase is mainly due to increase in the number of low-intensity events (precipitation amounts in the 0.5 to 5.0 mm range); the study further concludes that "precipitation events are not getting more intense on the Canadian prairies". Outside of North America, precipitation trend studies show inconclusive results. Over the Australian region, heavy rainfall has increased in some areas (based on data period 1910-1995), but this increase is not significant. The study by Zhai et al. (1999) on climate extremes in China concludes that, for China as a whole, there were no significant trends in much greater than normal amounts of annual precipitation either in 1-day or 3-day maximum rainfall or in rainfalls derived from daily precipitation amounts greater than 10, 50, or 100 mm. For the monsoonal climate of India, Rakhecha and Soman (1994) analyzed annual extreme rainfall time series of 1 to 3 days duration at 316 rainfall stations, well-distributed over India. Only 14 of the 316 stations showed significant trends in all the three durations—stations on the west coast of peninsular India (north of 12°N) showing an increasing trend while stations in the southern peninsula showing a decreasing trend. *It may be noted that several of the highest 3-day rainfall amounts were more than 500 mm, well over annual precipitation amounts at many Canadian stations!* Another comprehensive study by Groisman et al., (1999) applies a statistical model of daily precipitation based on the gamma distribution and obtains a 20% increase in the probability of summer daily precipitation amounts over 25.4 mm in a few northern European countries (e.g., Russia, Norway, and Poland); however, this increasing trend has not been reported elsewhere in Europe. Further, the precipitation amounts for some of the northern European countries are much too small to be of any real significance; for example, the increased number of days with summer precipitation in Norway is based on threshold values of 0.2 mm and 1.0 mm per day, much too small compared to daily values in the monsoonal climate of south Asia. No studies have been reported so far on increasing trends in "heavy" precipitation over southeast Asia. A few studies on interannual variability of rainfall over southeast Asia (Khandekar et al., 1999; Kriplani and Kulkarni,1997) indicate that seasonal rainfall over Indonesia/Malaysia and vicinity is primarily governed by the ENSO phase and does not reveal any increasing tendency in recent years. In summary, the hydrologic cycle, while showing variability over different regions, does not reveal any intensification on a global or continental scale. Over the tropical monsoon regions where the hydrologic cycle is the strongest, the annual and seasonal rainfalls appear to be primarily governed by ENSO and other local and regional features.

A brief mention about the GCM (General Circulation Model) simulation of extreme climate in a warmer world: Typically GCM simulations obtain changes in mean temperature, daily precipitation, and wind speed in a doubled CO_2 environment and examine these changes (against a "control" climate) in terms of increased/decreased probability of certain threshold values of these weather parameters being exceeded. Recent GCM simulation studies (e.g., Jones et al., 1997; Hennessy et al., 1997; Zwiers and Kharin, 1998) indicate an increase in global average precipitation by 10% or more and increased frequency of heavy precipitation, especially over the south Asian monsoon zone. According to Zwiers and Kharin (1998), strongest increase in precipitation probability (precipitation over 50 mm/day) is found over northwest and central India, due to intensification of the Asian summer monsoon under a doubled CO_2 atmosphere. Recent observational studies of the Indian/Asian monsoon (reported earlier) do not support the findings of

Zwiers and Kharin. Further, the global warming projected by Zwiers and Kharin is much larger than expected on the basis of recent and improved model projections (this will be discussed in the next chapter). Another study (Bhaskaran and Mitchell, 1998) simulates monsoon precipitation change over the Indian subcontinent in a doubled CO_2 environment and obtains (with both greenhouse gas and aerosol forcing included) a 12% decrease in precipitation in the western region of India, and an increase of 20% in the eastern and northeastern regions of India. Once again, there is no observational support for these simulations (see Rupa Kumar et al., 1992).

Linkages between El Niño and warmer climate: The tendency for more frequent El Niño events and fewer La Niña events since the late 1970s has prompted a question whether El Niño events are being influenced by the warmer climate due to increasing greenhouse gas concentration. The El Niño event of 1990-1995 is considered to be the longest on record and this has prompted Trenberth and Hoar (1996) to link El Niño events to decadal changes throughout the Pacific basin. Using a simple ARMA (autoregressive moving average) model to a measure of the southern oscillation index, Trenberth and Hoar obtain the probability of occurrence of a prolonged El Niño (like the 1990-95 El Niño) to be extremely small; this has led to the suggestion that such a prolonged ENSO and the associated changes may have been partly caused by the observed increase in greenhouse gas concentrations. The suggestion of Trenberth and Hoar was closely examined by Rajgopalan et al., (1997) who used a nonparametric statistical technique to analyze 114 years of continuous data on Darwin sea-level pressure (a good measure of the southern oscillation index) and demonstrated that the probability of occurrence of an El Niño event like that in 1990-95 is much higher than that suggested by Trenberth and Hoar. According to Rajgopal et al., such a prolonged (and unusual) El Niño event could occur through natural climatic variation. Nevertheless, the suggestion that El Niño events could become more frequent in a warmer world is intriguing and has caught the attention of many atmospheric scientists. It is not clear at this time whether El Niño events are becoming more frequent. Following the intense El Niño of 1997-98 (from March 1997 to about May 1998), the SST (sea surface temperature) anomalies in the equatorial eastern and central Pacific have remained negative (La Niña phase) for the past 16 months or so, and may remain negative until March 2000 according to recent projections (Climate Diagnostics Bulletin, 1999). More studies are needed to investigate interannual and decadal variability in the Pacific basin before we can link El Niño events to warmer climate.

2.6 Mean Temperature Increase and its Link to Greenhouse Gas Increase

The relationship between mean global temperature increase and greenhouse gas increase has not been unequivocally established. What are the uncertainties in the relationship?

The increase in greenhouse gas concentration in the atmosphere over the last 100 years has been well established as discussed earlier. The increased concentration has led to an increase in the mean radiative forcing of 2.45 $W \cdot m^{-2}$ and this has also been well established by the IPCC (1996) and several other studies. What is not unequivocally established is the direct link between the mean surface temperature increase and the increase in the radiative forcing by the greenhouse gas increase. There are several other processes in the complex earth-atmosphere-ocean system that make this unequivocal link difficult to establish. Some of these processes have already been mentioned and discussed, for example, the role of large-scale atmospheric circulation features like ENSO and NAO in influencing the mean surface temperature patterns over different areas of landmasses and oceans. Considering the radiative equilibrium of the earth-atmosphere system, the uncertainty stems from several factors, including the role of increasing solar irradiance, the direct and indirect impact of aerosols and carbonaceous particles, and the role of cloud microphysics and fractional cloudiness on radiation balance and ultimately on mean surface temperature. A recent paper by Solanki and Fligge (1998) estimates an increase of 2-5 $W \cdot m^{-2}$ in solar irradiance over the past 100 years and suggests a possible link between solar irradiance increase and mean surface temperature. Further, direct and indirect negative radiative forcing by sulfate aerosols are now estimated to be comparable in magnitude to positive forcing by increased greenhouse gas concentrations. Consequently, a simple and direct link between the increasing concentration of CO_2 (the most important of the greenhouse gases) and mean surface temperature increase is not easy to establish. This point is illustrated in Figure 2.4, which shows estimated changes in annual global-mean temperature together with changes in CO_2 concentration over the past 138 years relative to the1961-1990 average. The variation in CO_2 concentration is shown by a steadily increasing (smoothed) curve, whereas the mean temperature curve shows irregular variations with several time periods (each several years long) during which the mean global temperature has increased or decreased, either steadily or abruptly. Such increases and decreases of the mean temperature cannot be easily explained by a more-or-less linear increase in CO_2 concentration. In particular, the steep increase in the mean temperature from 1910 to 1940 cannot be explained by anthropogenic forcing alone (see Wigley, 1999). Thus, an unequivocal and direct link between the mean temperature increase and the increase in greenhouse gas concentration remains elusive at this time. The most probable cause of the observed warming now appears to be a combination of internally and externally forced natural variability and anthropogenic sources. In a recent comprehensive study, Barnett et al. (1999) concludes that, due to uncertainties in climate models and limitations in observed data, "*a reliable weighting of the different factors contributing to the observed climate (temperature) change cannot currently be given*".

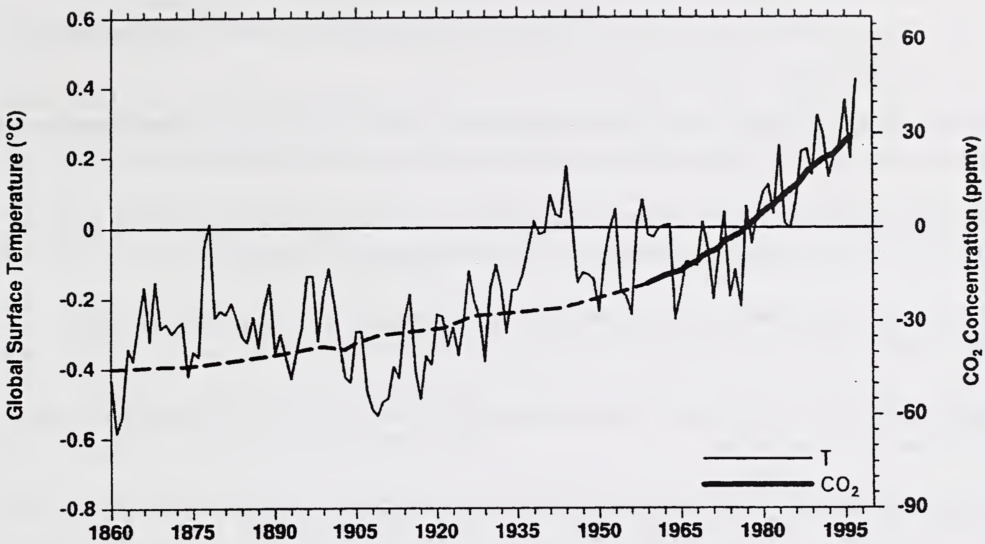


Figure 2.4 Changes in annual global-mean temperature (thin line) and carbon dioxide (thick line) over the past 138 years relative to the 1961-1990 average. Carbon dioxide values for 1959-1996 are from direct measurements at Mauna Loa, Hawaii; earlier values are estimated from ice core data (dashed line). The scale for carbon dioxide is in ppmv (parts per million, volume basis) relative to a mean value of 333.7 (from Hurrell, 1998).

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3.0 ASSESSMENT OF UNCERTAINTIES RELATED TO CLIMATE MODELS AND OTHER ISSUES

3.1 Introduction

Attempts at estimating the impact of increasing greenhouse gas concentration on climate using numerical general circulation models of the atmosphere have been going on for almost 30 years. One of the first such studies was made almost a quarter of a century ago by Manabe and Weatherald (1975). The model they used was very simple with a limited computational domain, nine vertical levels in the atmosphere, a model ocean represented by an area of wet land (an area possessing an infinite source of soil moisture for evaporation), no heat transport by ocean currents, an idealized land topography, and fixed cloudiness. Despite these simplifications, the model produced results that are remarkably similar, in some ways, to some of the recent simulation studies. Specifically, the model obtained mean temperature changes (due to doubling of CO_2 concentration) of between 2 and 3°C in the troposphere from equator to about 60°N, a pronounced warming of several degrees at high latitudes in the lower troposphere, cooling in the stratosphere from about 18 km to 30 km, and a more active hydrologic cycle as indicated by the greater rates of total precipitation and evaporation computed by the model. The pronounced warming at high latitudes was attributed to decrease in the area of snow/ice cover due to increased downward radiation from increased CO_2 and consequently a pronounced warming due to a net increase in the amount of solar radiation absorbed by the earth. Similar high-latitude warming in the lower troposphere has been predicted by other climate models and reported in recent literature (e.g., Washington and Meehl, 1989; Boer et al., 1992). Since the 1975 study, Manabe and coworkers have produced a series of papers in the recent literature detailing a variety of simulations of climate change using coupled atmosphere-ocean models of increasing complexity; some of these papers will be discussed later in this chapter.

Coupled atmosphere-ocean models are a powerful tool for assessing the impact of increasing greenhouse gas concentrations on present and future climate. Typically, these models, which consist of several vertical levels in the atmosphere as well as in the depths of the ocean, generate changes in mean values of weather elements like pressure, temperature, and precipitation over the next 50 to 100 years by allowing the concentration of greenhouse gases to increase to two or more times their present value. With the availability of better and faster computer technology, GCMs have become more comprehensive and are able to include in their computations a variety of atmosphere-ocean processes such as heat transport by ocean currents, a number land/ocean surface processes, clouds and their spatial and temporal variation, and a detailed atmospheric chemistry involving changes in concentration of carbon dioxide, methane, nitrous oxide, ozone, etc. Despite these advances, the present GCMs cannot realistically include or simulate all the atmosphere-ocean processes and their future changes. There are several weaknesses in the GCMs, some of which are examined below.

3.2 Specific Modeling Uncertainties

3.2.1 Transient modeling: *The gradual inclusion of CO_2 as the model integrates is the latest approach to climate modeling. What are the advantages and disadvantages?*

The model by Manabe and Weatherald (referred to earlier) first simulated the present climate by integrating the model equations for several hundred days using the present concentration of CO_2. A doubled amount of CO_2 was then introduced in the model, which was integrated again for several hundred days until an equilibrium stage was reached. The differences between the two climate states were analyzed to assess the climate change. This instantaneous doubling of CO_2 concentration in the model is, of course, unrealistic and has, in general, produced relatively large increases in predicted surface air temperature. Since about 1990 most climate models have been simulating climate change by gradually increasing the greenhouse gas concentrations (e.g., Manabe et al.,1990, 1991, 1992; Manabe and Stouffer, 1996; Washington and Meehl, 1989; Murphy, 1995, Murphy and Mitchell, 1995). Some of these studies (e.g., Washington and Meehl, 1989) have reported climate change results using two parallel runs, one in which the CO_2 concentration was doubled instantaneously and the other in which CO_2 concentration was increased gradually at the rate of 1% per year. The rate of 1% per year has been chosen for most climate models investigating the transient response because the total CO_2-equivalent radiative forcing of various greenhouse gases other than water vapour is currently increasing at the rate of approximately 1% per year (Hansen et al., 1988). According to Washington and Meehl (1989) the transient response (gradual increase of CO_2) produces an increase in mean surface temperature of 0.7°C, while the equilibrium response (instantaneous doubling of CO_2) produces an increase of 1.6°C in the mean temperature. The difference in transient and equilibrium response has been analyzed by Manabe and Weatherald who find that the equilibrium response produces much larger increases in the mean surface temperature over higher-latitude land areas and over circumpolar oceans of the southern hemisphere. Over the northern hemispheric land areas at higher latitudes, the reduction in sea ice and snow in response to increased greenhouse gas concentrations leads to increased exchange of heat between oceanic water surfaces and overlying air and this results in larger increases in mean temperature over land areas. Over the northern regions of the North Atlantic and the circumpolar southern oceans, the transient response produces very little warming because of the location of the sinking branches of the thermohaline circulation, which carries large amount of heat (trapped by increasing atmospheric CO_2) to greater depths in the oceans. The equilibrium response to doubling of CO_2 is particularly large (as much as +9°C) along the coast of Antarctica due to poleward retreat of sea ice, which has high surface albedo. The changes in precipitation rates due to enhanced CO_2 concentration are generally larger at high latitudes than at low latitudes because of increased poleward transport of water vapour, the equilibrium response simulating a larger poleward transport than the transient response. Consequently, the precipitation rate change at higher latitudes is larger for the equilibrium response than for the transient response.

In summary, the equilibrium response (with instantaneous doubling of CO_2) produces greater temperature increases than the transient response, as well as greater precipitation rates in high-latitude land areas of the northern hemisphere. These changes are not realistic when compared with observed temperature and precipitation changes of recent years. On the plus side, the equilibrium response experiment is simpler to design and is less computer-intensive than the transient response experiment. Most climate models at present use the procedure of gradual increase in CO_2 concentration to predict the climate change response.

3.2.2 Cloud feedback and aerosols: *The modeling of clouds has been a major uncertainty in climate modeling. What are the latest results in this respect? What kinds of aerosol modeling have been included in the current GCMs? What are the strengths and weaknesses?*

These two aspects will be analyzed and discussed in tandem since the two are intimately connected in the context of climate modeling. The appropriate representation of clouds and their spatial and temporal distribution in climate models is perhaps the single most challenging task for the climate modeling community at present. The presence of clouds, even at a single level, complicates the radiation budget of the earth-atmosphere system. With the presence of multilevel clouds, absorption and transmission of solar radiation at various levels can complicate the radiation budget considerably. Further, the presence of anthropogenic aerosols is now recognized as causing a significant perturbation on the atmospheric radiation field through direct and indirect interaction with solar radiation. There is considerable uncertainty associated with each of these effects, making the radiation budget calculation extremely complex and often indeterminate.

In climate modeling, the simulated cloudiness field, because of its simple dependence on relative humidity, reflects the broad features of the simulated moisture field. However, accurate simulation of the moisture field depends on the model's ability to simulate general circulation patterns in the atmosphere. Most climate models are able to simulate general circulation patterns in a broad sense only. Accordingly, they simulate large-scale cloud features like maximum cloudiness at the ITCZ (inter-tropical convergence zone at around 10-12°N) and maximum mid-latitude cloudiness at around 60°N during the boreal summer. Many regional and local features of cloud climatology are not well estimated by climate models. For example, the Canadian Climate Centre second-generation GCM (McFarlane et al., 1992) underpredicts cloudiness in the polar regions of both hemispheres and does not produce relative maxima associated with coastal stratus clouds near the western coasts of South America and Africa in the southern hemisphere and near the California coast in the northern hemisphere. These differences in the simulation of cloud climatology can affect regional and global radiation balances. In an important short communication, Albrecht (1989) discusses the effects of increasing aerosol concentrations (natural or man-made) on low-level cloudiness and on global albedo. It is estimated that marine stratocumulus clouds contribute about a third of the earth's global albedo (Charlson et al., 1987). Inaccurate simulation of marine stratocumulus clouds can significantly alter future climate projections by GCMs; for example, Randall et al. (1984) argue that a 4% change in the amount of marine stratocumulus could offset the warming resulting from a doubling of CO_2 concentration. Further, the impact of Arctic cloud cover on the radiation budget and consequently on regional and global climate is poorly understood because of the sparsity of observations. In a comprehensive study, Curry et al. (1996) concluded that basic annual cycles of clouds and radiation characteristics in the Arctic remain uncertain enough that the precise role of cloud feedbacks cannot be determined. An analysis of several GCM products over the Arctic (Tao et al., 1995; Chen et al., 1995) reveals several discrepancies in modeled cloud cover and surface temperatures. Incomplete knowledge of cloud climatology in the Arctic (as well as in the Antarctic) is a source of major uncertainty in climate modeling at present.

Do clouds heat or cool the planet earth? This seemingly simple question has been a challenge to climate modelers and was settled only recently through a comprehensive analysis of satellite data from ERBE (Earth Radiation Budget Experiment). The ERBE data separated the clear-sky radiation budget from the radiation budget of average cloudy skies and the difference in the two budgets is attributed to cloud radiative forcing which, according to Ramanathan (1998) is about -18 W·m^{-2}, much larger than the 2.45 W·m^{-2} forcing from greenhouse gases. For ready reference, the global radiation balance for the annual mean condition together with average clear-sky and cloudy-sky radiation balances are shown in Figure 3.1a,b. It is not known at this time how this net forcing of -18 W·m^{-2} (shown in Fig.3.1b) would change in response to global warming. Further, the cloud radiative forcing effects are concentrated regionally along storm-track cloud systems, over mid-latitude oceans, and in deep convective cloud systems associated with the ITCZ in the tropics and its seasonal migration (Ramanathan et al., 1998). Multilevel cloudiness and changing cloud types can reduce solar radiation significantly on a regional scale, as observed by Abakumova et al., (1996) and Leipert and Kukla (1997).

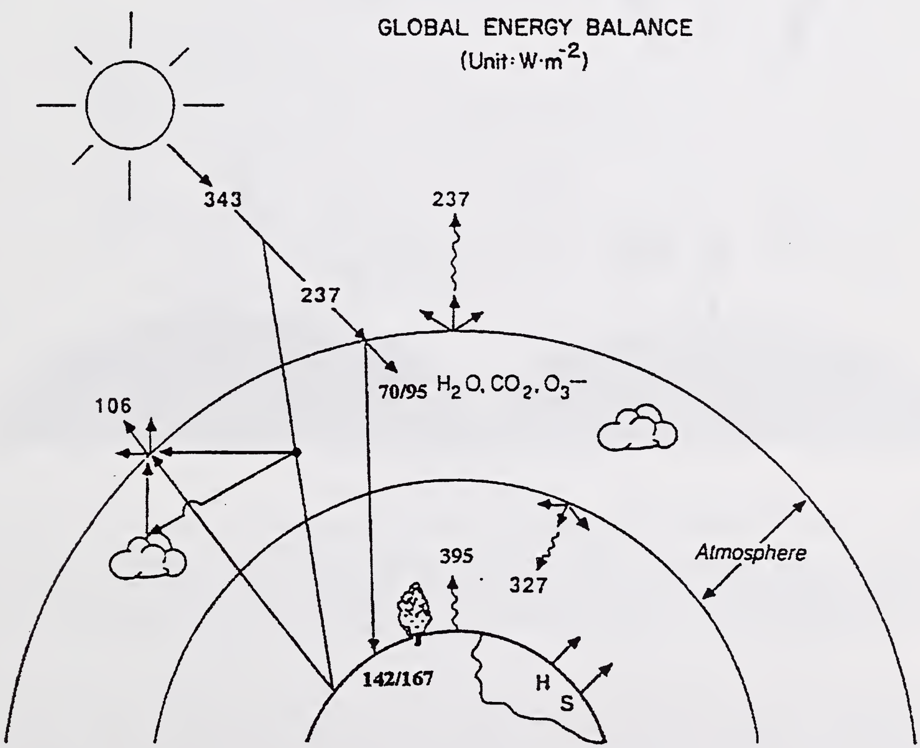

Figure 3.1a Global energy balance for annual mean conditions. The top-of-the-atmosphere estimates of solar insolation (343±2 W·m^{-2}) reflected solar radiation (106±3 W·m^{-2}), and outgoing longwave radiation (237±3 W·m^{-2}) are obtained from satellite data. The other quantities include atmospheric absorption of solar radiation (70-95 W·m^{-2}), surface absorption of solar radiation (142-167 W·m^{-2}), downward longwave emission by the atmosphere (327±15 W·m^{-2}), upward longwave emission by the surface (390±15 W·m^{-2}), and latent (H) and sensible (S) fluxes from the surface (from Ramanathan, 1998).

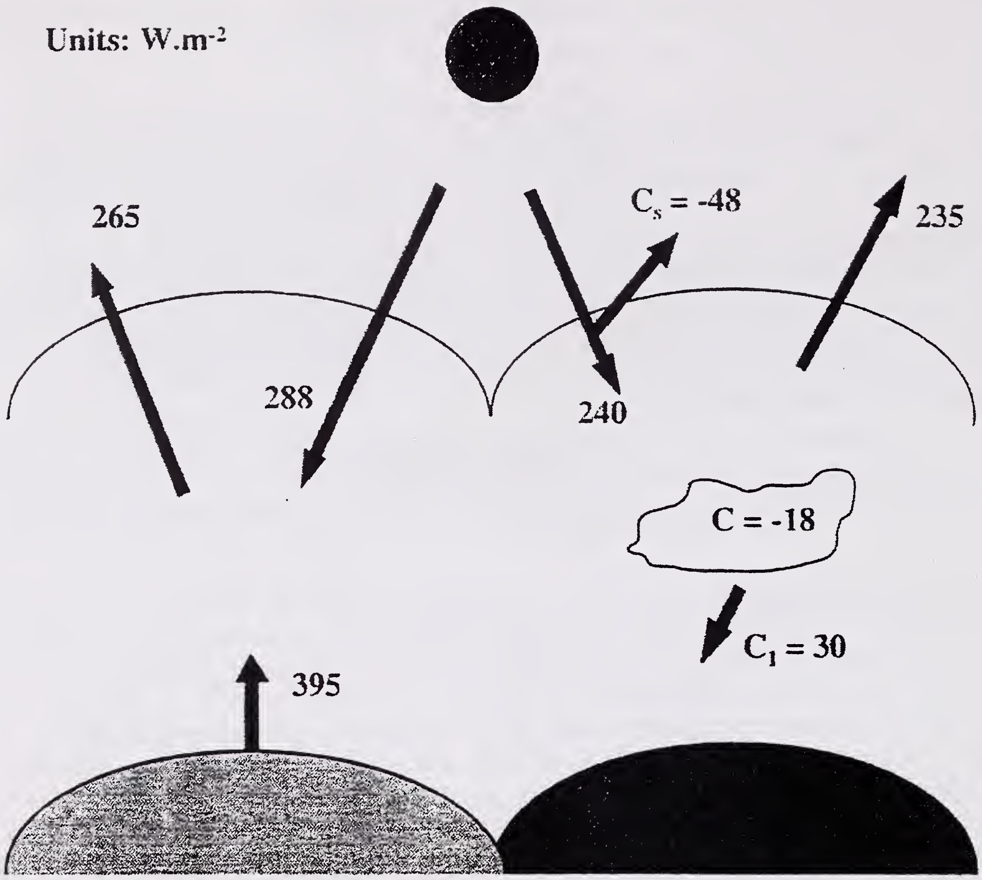

Figure 3.1b Global average clear-sky radiation budget (left panel) and average cloudy fluxes and cloud radiative forcing (right panel) from ERBE data. Outgoing arrows denote outgoing longwave radiation and incoming arrows denote net incoming solar radiation. Uncertainties in these fluxes are ±5 $W{\cdot}m^{-2}$ and the values are for 5-year averages between 1985 and 1989 (from Ramanathan et al., 1989).

The anthropogenic aerosols (sulfate, black carbon, dust, etc.) are now recognized as providing a significant and yet uncertain perturbation on the global radiation balance in terms of an overall cooling effect (Charlson et al., 1990, 1992; Boucher and Lohmann, 1995). Through the direct effect, aerosols can scatter and absorb solar radiation in cloud-free air. In terms of indirect effect, an increase in concentrations of aerosols composed of soluble substances that act as cloud condensation nuclei (CCN) would increase the cloud droplet number density, thereby reducing average cloud droplet size. This, in turn, would enhance cloud albedo (Twomey, 1977) and could suppress drizzle production and increase cloud cover and persistence (Albrecht, 1989; Leaitch et al.,1992; Gultepe et al., 1996). There is considerable uncertainty in quantifying the impact of indirect forcing of anthropogenic aerosols because of the uncertainty in the relationship between aerosol number distribution and anthropogenic pollution (Charlson et al., 1992; Penner et al., 1994). The IPCC 1996 report assigns "low" to "very low" confidence levels in the estimates of radiative forcing (direct as well as indirect) by aerosols as shown in the schematic reproduced in Figure 3.2. Several recent studies have attempted to reduce the uncertainty associated with the estimates of these forcings (Penner et al., 1998, 1999). These and other studies (Lohman and Feichter, 1997) have now provided estimates that are significantly higher than the IPCC estimates. These new values have significant implications in the global warming debate with regard to radiation balance. A few observational studies reported recently (Saxena and Yu, 1998; Saxena and Menon, 1999) have assessed these forcings to be as high as -4.8 and -4.0 W·m^{-2} for the southeastern USA, a region where the effect of anthropogenic aerosols could supersede that of anthropogenic greenhouse gases (IPCC, 1996) and could even produce a (small) cooling effect on a regional scale. Such a cooling effect has been documented in recent studies by Saxena and his coworkers

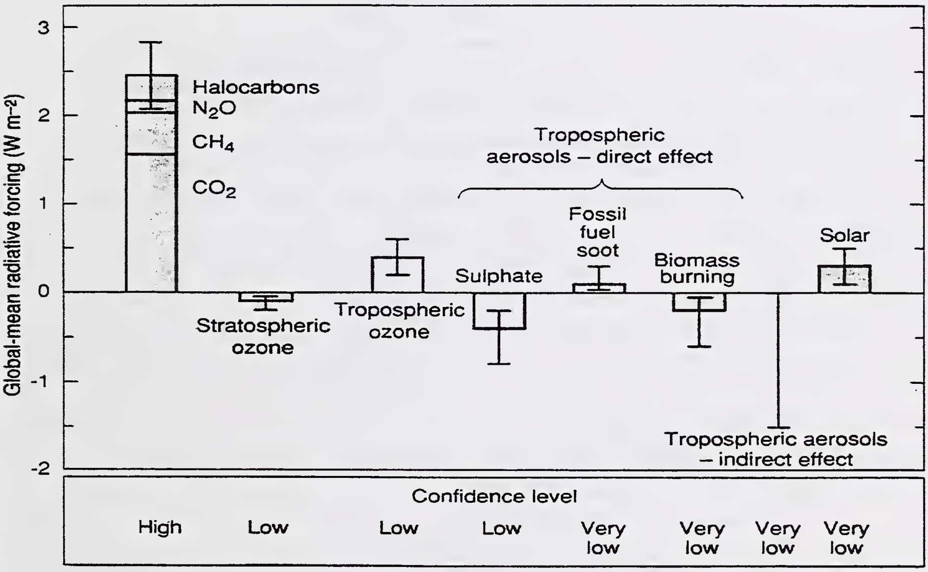

Figure 3.2 Estimates of globally and annually averaged anthropogenic radiative forcing (W·m^{-2}) due to changes in concentrations of greenhouse gases and aerosols since pre-industrial times and to natural changes in solar output since 1850. The height of the rectangular bar indicates a mid-range estimate of the forcing while the error bars show an estimate of the uncertainty range. Contributions of individual gases to direct greenhouse forcing are indicated in the first bar. Indirect forcing associated with depletion of stratospheric ozone and increased concentration of tropospheric ozone are shown in the second and third bars. The next three bars indicate the direct contributions of individual tropospheric aerosol components. Indirect effects are shown in the second last bar and the last bar shows an estimate of changes in radiative forcing due to variation in solar output. Confidence levels are indicated below each bar. The value and confidence level of indirect forcing has increased significantly according to recent studies (from IPCC, 1996).

(referenced above). At this time, the best estimate for aerosol direct forcing on a global scale appears to be somewhere between -0.5 and -0.9 $W \cdot m^{-2}$ (Penner et al., 1998). The estimate for indirect aerosol forcing still appears to be associated with considerable uncertainty because of cloud dynamics and the impact of aerosols on cloud microphysics. The most recent estimate for indirect aerosol forcing on a global scale is about -1.6 $W \cdot m^{-2}$ (Penner et al., 1999).

Several modelers have attempted to include aerosols in climate modeling in the last few years. One of the first attempts appears to have been by Mitchell et al. (1995a, 1995b) who included the radiative effects of both greenhouse gases and sulfate aerosols in their model. The concentrations of greenhouse gases and sulfate aerosols used by Mitchell et al. in their model was based on the IPCC scenario IS92a (see IPCC 1996), which assumes a slow reduction in the rate of world economic growth and a gradual increase in conservation measures. Mitchell et al. included only the direct radiative forcing of sulfate aerosol by increasing surface albedo. The resulting simulation produces significantly reduced global warming, about 0.2°C per decade compared to about 0.3°C per decade with only greenhouse gas (CO_2) inclusion. Simulated mean surface temperature increase as modeled by Mitchell et al. (1995a) using the UKMO (United Kingdom Meteorological Office) model is shown in Figure 3.3a, together with similar projections using the MPI (Max Planck Institute) model. With the inclusion of direct forcing due to sulfate aerosol, the simulated global warming for the period 1900-1990 appears to be closer to observed mean warming as per the data of Jones et al. The projected future warming for the year 2050 is about 1.9°C, which is smaller by almost 1°C than the projected global warming in the presence of CO_2 only. In a more recent study, Roeckner et al., (1999) used the ECHAM4 model, which is an upgraded version of the MPI model referred to in Figure 3.3a, to simulate future global warming in an experiment that included direct as well as indirect radiative forcing of sulfate aerosol. The ECHAM4 model experiment includes the direct radiative forcing (by sulfate aerosol) as was done by Mitchell et al., while, for the indirect effect, the cloud albedo is recalculated using empirical relationships between the cloud droplet number concentration and the sulfate aerosol mass mixing ratio. The model obtains future warming under three scenarios: **1.** inclusion of GHG (CO_2, CH_4, N_2O plus other industrial gases) only, **2.** Inclusion of GHG plus sulfur cycle with direct effects only, and **3.** Inclusion of GHG plus sulfur cycle with direct as well as indirect effects. Projected global warming for the year 2050 and beyond under the three scenarios (GHG, GSD, and GSDIO) is shown in Figure 3.3b. It can be seen that the projected warming under scenario GSDIO is in closest agreement with observed warming from 1900 to the present time. This scenario projects additional warming over the next 50 years of about 1°C, a value presently considered to be probable. It may be noted that the GSDIO scenario does not include the impact of sulfate aerosol on cloud lifetime, which is likely to increase the cloud albedo further and may lead to further reduction in the projected global warming.

In summary, the impact of anthropogenic aerosols on present and future climate is still fraught with considerable uncertainty and this uncertainty has a direct impact on cloud representation in climate models. Present observational and theoretical studies may help reduce some of the uncertainties as discussed above and this may help produce more realistic simulations of future global warming and associated climate change. Inclusion of additional aerosol and cloud processes in climate models is likely to reduce the projected global warming. Further, if the hydrologic cycle is expected to intensify in a warmer world, the global cloud cover is expected to increase producing additional (negative) forcing in general.

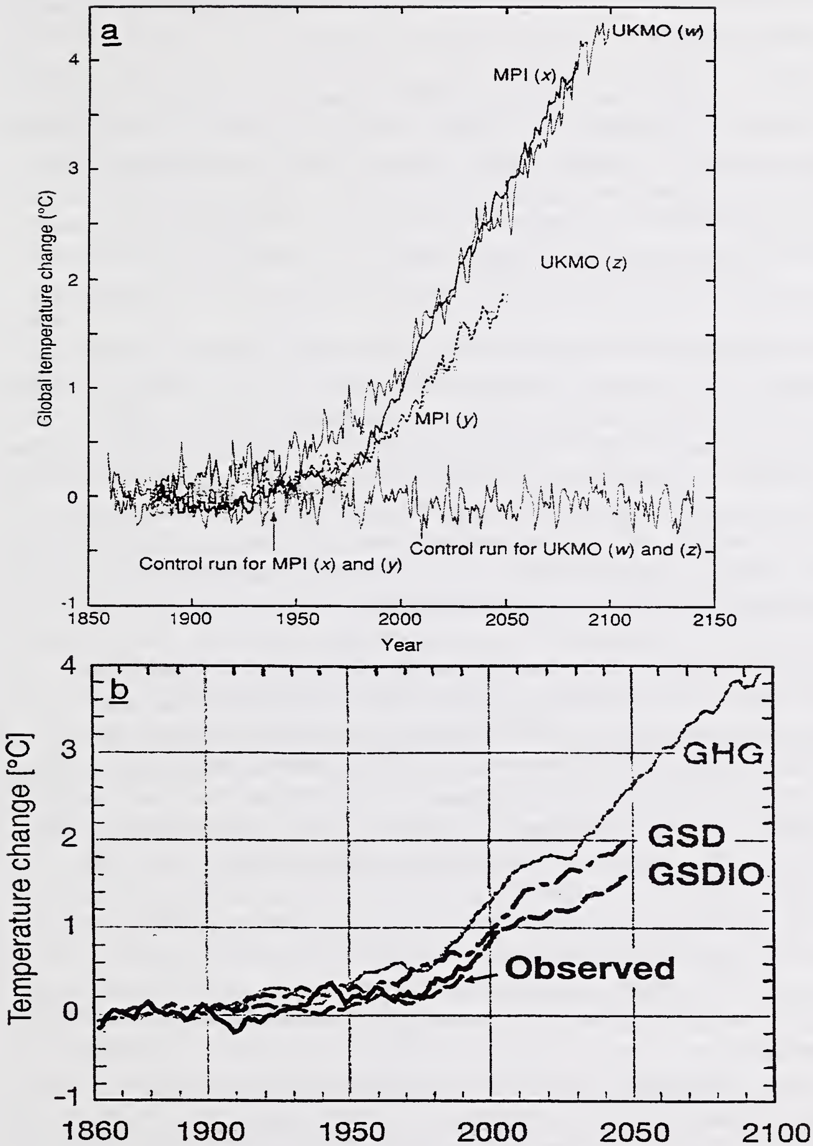

Figure 3.3a Simulated global annual mean warming from 1880 in two simulations with GHG forcing only (MPI(x) and UKMO(w)) and two simulations that include both GHG and direct sulfate aerosol forcing (MPI(y) and UKMO(z)) (from IPCC, 1996)

Figure 3.3b Evolution of changes in annual global mean surface air temperature compared to the mean for observations (1860-1990). Simulations are shown for three experiments: GHG, GSD, and GSDIO. See text for details (from Roeckner et al., 1999).

3.2.3 Oceans and sea ice: *What are the major difficulties in incorporating oceans and sea ice in GCM's? What are the latest findings?*

A variety of oceanic processes ranging from turbulent transfer of heat, momentum, and water vapour at the air-sea interface to the thermohaline circulation through the depths of the oceans are now identified as important controls of present and future climate of the earth. Also, interannual variations of sea ice over the Arctic and Antarctic regions are identified as having a significant influence on present and future climate. A comprehensive discussion on each of these processes and their inclusion in GCMs is beyond the scope of the present report. A brief discussion on some of the important processes as they relate to the issue of uncertainty is presented in the following:

One of the earliest GCMs (Manabe and Weatherald, 1975) represented the ocean by an area of wet land or an area possessing an infinite source of soil moisture for evaporation. According to Manabe and Weatherald, their model ocean resembles an actual ocean in the sense that it is wet but it lacks the effects of heat transport by ocean currents. This highly simplified model ocean (often known as "swamp ocean model") was later replaced by a mixed-layer ocean, which was represented by a slab of sea water 50 m thick over which various fluxes based on climatological (or seasonal) values were prescribed. Some of the first-generation climate models developed in the mid-1980s and early 1990s (e.g., Washington and Meehl, 1984; McFarlane et al., 1992) used a mixed-layer model ocean over which various fluxes were prescribed. These fluxes were further adjusted so as to yield a realistic simulation of observed climatological SST (sea surface temperature) field over the oceanic regions of the climate model. Such a mixed-layer model ocean could not generate deep water circulation in the northern oceans of the subarctic region nor in the circumpolar oceans of the southern hemisphere. The models of Manabe et al., (1991, 1992) were among the first to use several levels in the vertical for their model ocean which was coupled with an atmospheric model consisting of several vertical levels through the troposphere and lower stratosphere. Such coupled models were able to generate deep-water circulation, which helped extract a large amount of heat (trapped by increased CO_2) from the Arctic as well as Antarctic regions and thus were able to produce a much smaller temperature increase in the higher latitudes in a doubled CO_2 scenario. Most climate models today include several vertical levels for their model ocean and also consider the impact of ocean bottom topography. A climate model coupled with an ocean consisting of several vertical levels presents a formidable challenge from a computational point of view. Due to different time scales for the atmosphere and ocean (few weeks for the atmosphere versus hundreds of years for the ocean, because of its thermal inertia), the atmosphere and the ocean models are separately "spun-up" for initialization before they can be coupled using prescribed fluxes and a flux adjustment procedure. The "spin-up" of ocean models for initialization presents special computational problems requiring special "acceleration" techniques as described by Manabe et al., (1991). As the two components (atmosphere and ocean) of the climate models are coupled, the coupled system is found to drift into a new climate equilibrium state that is far removed from the observed climate. The model climate drift is a sensitive indicator of model imperfections (Sausen et al., 1988) and has to be fixed by a flux adjustment process which is briefly discussed below:

The flux adjustment problem (called a "modeling dilemma" by the IPCC 1996) arises because the values of various exchange coefficients (momentum, heat, and moisture) and their temporal and spatial variations are not completely known. The problem is further compounded because of cloud parameterization in the mid-latitudes where shortwave planetary albedo is too high in the storm track region (Murphy, 1995). The flux adjustment terms are calculated from the difference between the modeled surface fluxes and those required to keep the model close to current climate. After running the model for a period suitable for the calculation of average flux adjustments, these terms are applied throughout the control and the anomaly (increased GHG concentration) experiment. The main purpose of the flux adjustment is to ensure that any perturbation (due to increased CO_2 for example) is applied to a realistic reference climate so that distortion of the major climate feedback process is minimized. Strictly speaking, the flux adjustment should be relatively small in comparison to the magnitude of the flux terms; however, the flux adjustment terms in some models are almost as large as the flux terms. In the tropical and subtropical latitudes, the flux terms are of the order of about 50 $W \cdot m^{-2}$; however, values in excess of 100 $W \cdot m^{-2}$ occur in many extratropical regions, especially over the North Atlantic where many climate models reveal deficiencies in terms of insufficient heat transport by the Gulf Stream. The need for flux adjustment is expected to decrease in the future as the climate models are further improved. In a recent paper, Janssen and Viterbo (1996) investigate the role of ocean surface waves and associated momentum transfer on the atmospheric circulation. The paper further documents the impact of enhanced sea surface roughness caused by young wind seas (growing wind waves) on the mid-tropospheric atmosphere and on the storm track in the southern hemisphere in particular. The authors (Janssen and Viterbo) suggest the use of a coupled wind-wave model to ameliorate the flux adjustment problem in climate models. Another technique of applying small zonally averaged flux terms to eliminate drift of the thermohaline circulation has been suggested by Weaver and Hughes (1996).

The presence of sea ice in the Arctic and Antarctic regions and its evolution and interannual variation presents another challenging problem for climate modelers. The initial formation of sea ice depends upon the ocean surface temperature and most climate models employ the thermodynamic sea ice growth algorithm of Semtner (1976). The evolution of sea ice (growth and decay of ice mass) in most climate models is governed primarily by a thermodynamic process and is based on a surface energy budget and heat conduction through the ice mass. The simulation of sea ice cover in the initialization and control experiment of many climate models is found to be significantly less than observed sea ice cover and distribution (IPCC, 1996). Also the sea ice thickness is significantly underestimated by many climate models. For example, the CCC (Canadian Climate Centre) model described by McFarlane et al., (1992) obtains maximum sea ice thickness of only about 2.5 m as compared to observed thicknesses of 5 m, and greater than 5 m in the Canadian archipelago (Flato, 1995). This underestimation of sea ice thickness in climate models is attributed to the exclusion of sea ice dynamics (e.g., advection and deformation) and internal mechanics, which have a significant impacts on the sea ice distribution, ice thickness, and formation of ridges and leads. Several studies on sea ice dynamics have been reported in literature in the last 20 years (e.g., Hibler, 1979, 1980; Lemke et al., 1990; Pollard and Thompson, 1994). The study by Pollard and Thompson (1994) showed that inclusion of sea ice dynamics produced a more realistic simulation of ice extent and that the ice cover was less sensitive to CO_2-induced warming in the higher latitudes. The recent study by Roeckner et al., (1999) employs a sea ice model that includes ice dynamics and a viscous-plastic rheology to parameterize the stress tensor. Their simulation of the evolution of sea ice area is much more realistic than other models (see Figure 3.4).

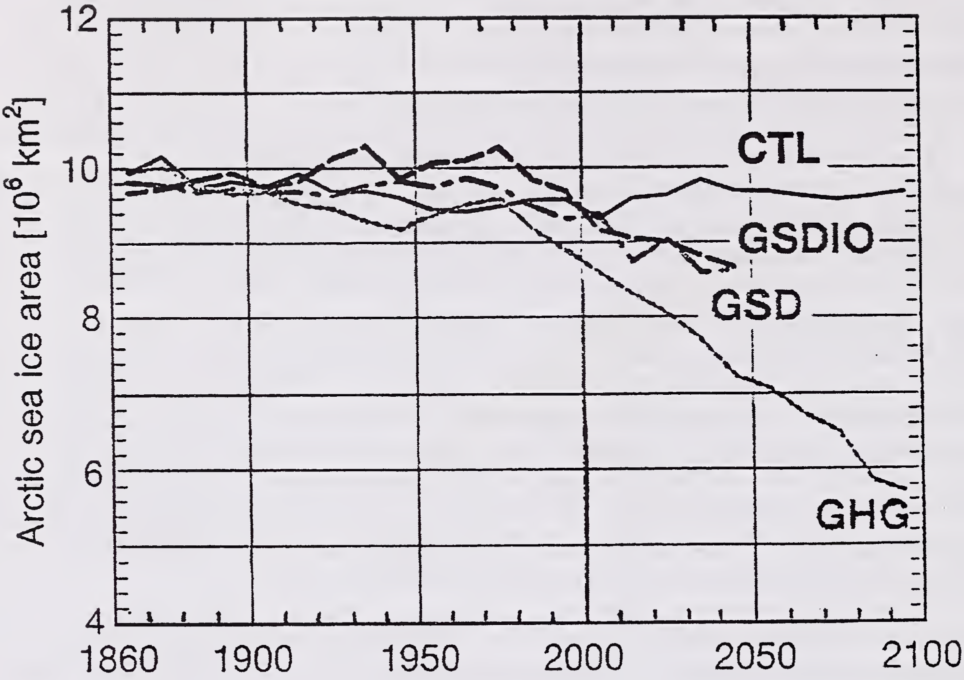

Figure 3.4 Evolution of decadal mean Arctic sea ice area for three experiments: GHG, GSD, and GSDIO. The evolution of sea ice area from the control experiment is denoted by CTL (from Roeckner et al., 1999).

In summary, the atmospheric and oceanic components of climate models have been coupled with considerable success in recent years in terms of more realistic simulations of present climate; however, there are still a number of areas of uncertainty that remain unresolved at this time. The most important issue appears to be the large flux adjustment in the North Atlantic and insufficient transport of heat from southern latitudes. These two aspects are intimately linked to the thermohaline circulation in the North Atlantic and its possible breakdown (Rahmstorf, 1997; Weaver, 1993) as a result of increased GHG concentrations and associated warming. Another area of major uncertainty appears to be in the inadequate simulation of sea ice cover and, in particular, its thickness, which is significantly undersimulated. Developing appropriate numerical techniques for coupling the atmospheric and oceanic components of the climate models is also an area that needs further attention.

3.2.4 Interactive biology and chemistry: *These have not been incorporated in the GCMs but are considered potential areas of refinement for future climate models. What do we know about the relationship of these to climate processes?*

The impact of increasing concentrations of CO_2 on vegetation growth has been discussed in a number of studies by Idso and others (Idso and Kimball, 1993; ESEF, 1996). A recent study (Tian et al., 1998) analyzes the effect of interannual climate variability on carbon storage in Amazonian ecosystems. The study finds that during El Niño years, the Amazon ecosystems act as a source of carbon to the atmosphere, while in other years these ecosystems act as a carbon sink. These carbon fluxes are comparable in magnitude to the fluxes associated with deforestation in the Amazon basin in the early 1990s. The increasing growth of vegetation and its interannual variability could very well influence the carbon cycle and this, in turn, could influence global warming potential and projections of future climate change. The future role of the terrestrial biosphere in controlling atmospheric CO_2 is difficult to predict at this time. No modeling studies that include interactive biology appear to have been reported so far.

In a recent study, Roeckner et al. (1999) include in their atmospheric chemistry model the three main GHGs, namely, CO_2, CH_4, and N_2O plus several industrial gases such as chlorofluorocarbons (CFC-11, 12, 113, 114, and 115) and hydrochlorofluorocarbons (HCFC-22, 123, and 141b). The evolution of these gases is based on simple chemistry and the IS92a scenario as defined by IPCC 1996. None of the models reported so far incorporates interactive chemistry.

3.2.5 Regional climate: *There have been various attempts to do climatic downscaling to estimate climate change scenarios on a regional scale. Some are statistical downscaling techniques and some are regional climate models. How much confidence can we place in the results? What are the limitations in doing this?*

In recent years a number of studies have been reported using regional climate models developed on a relatively smaller computational domain covering a regional area over which climate change studies may have special particular socio-economic relevance or benefit. A review paper by Giorgi and Mearns (1991) discusses various approaches to the simulation of regional climate change while a recent paper by Hewitson and Crane (1996) discusses techniques and applications of downscaling. These regional models, often identified as RCM (regional climate models) are typically developed as nested models so that the lateral boundary conditions for these models are obtained from large-scale GCMs. Such a procedure can be computationally very expensive, hence a statistical downscaling approach is often used in which the local values of weather elements like temperature and precipitation are inferred from either observed atmospheric predictor variables or by dynamical downscaling techniques in which the temperature and precipitation simulated at the nearest grid point of a GCM are used. There are several issues regarding the downscaling and the regional climate that are beyond the scope of this report. A very brief assessment on the utility and the limitations of downscaling will be presented here:

A recent comprehensive paper (Murphy, 1999) evaluates statistical and dynamical techniques for downscaling of local climate(temperature and precipitation) at over 900 European stations. The dynamical and statistical methods are compared in terms of correlation between the estimated and observed time series of monthly anomalies. According to Murphy, a high degree of skill is found for estimates of temperature, especially over western, central, and northern Europe; for precipitation the skill is lower with average correlation ranging from 0.4 in summer to 0.7 in winter. Overall, the dynamical and statistical methods show similar levels of skill, although the statistical method is better for summertime estimates of temperature while the dynamical method gives slightly better estimates of wintertime precipitation. In another recent paper (Charles et al., 1999), a non-homogeneous hidden Markov model was used for downscaling of precipitation (from a limited-area model) for southwestern Australia. The statistical technique was found to provide a credible downscaling procedure for assessing climate change in that region (southwest Australia) provided a variable characterizing the absolute moisture content is included in the predictor set. The results further highlight that the validation of a statistical downscaling technique for present-day conditions does not necessarily imply validity for changed climate conditions. A statistical downscaling approach for estimating local changes in surface climate in the central Argentina region (South America) has been reported in another recent paper by Solman and Nunez (1999). The statistical approach appears to provide reasonable results, however, the prediction skill varied between the station and the season. A paper by Laprise et al. (1998) reports on the development of a regional climate model (with grid spacing of 45 km) that is nested with a second-generation Canadian Global Climate Model (GCMII). The current climate simulation by this regional climate model appears to show some improvement over the large-scale GCMII; however, validating the current climate simulation presents difficulty due to lack of available climatology on the comparable regional scale. Further, the model simulation cannot be given too much credence because of several problems with the physical parameterization at the mesoscale.

In summary, the statistical downscaling approach appears to provide reasonable skill for assessing climate change on a regional or a local scale. The statistical approach is certainly cost-effective as it does not involve costly development of a regional model. The utility of a regional climate model appears to be limited at this time due to the problems noted by Laprise et al. (1998).

3.2.6 Additional modeling issues: There are a couple of additional issues regarding climate models that are not defined in the terms of reference of this project but have relevance in the present discussion. Most climate models at present are not able to adequately simulate the ENSO phenomenon and associated global weather anomalies. A recent simulation study (Timmermann et al., 1999) using the ECHAM3/LSG model obtains an ENSO-like oscillation with a characteristics period of 5 to 8 years. However, the ENSO amplitude in the model simulation is considerably underestimated. Simulating the ENSO phenomenon in all its detail is still a major challenge for the climate modeling community. Another aspect of climate modeling that has not been discussed is the adequate representation of mesoscale oceanic and atmospheric features. Most climate models use a grid spacing that is much too coarse for simulating oceanic features like mesoscale eddies or atmospheric features like squall lines and associated convective clouds. These mesoscale features can have a significant impact on the energy and radiation budget of the atmosphere and inadequate representation of these features in a model atmosphere could lead to inaccurate projections of future climate.

3.3 Other Issues

3.3.1 Heat from fuel combustion: *Burning of fossil fuel produces heat. David Taylor, an emeritus professor of chemistry in England calculated that the heat produced from the burning of fossil fuel may heat the atmosphere significantly. What are the latest developments on this issue?*

This issue does not seem to be of serious concern to the climate change science community at this time. Only a few studies appear to have been reported in recent literature. A study by Fischer (1990) makes an interesting calculation of the amount of heat generated by worldwide human activity and its relative importance with respect to global warming due to CO_2. Fischer obtains a value of about 13.8 TW (1 TW= 10^{12} W), which is equivalent to about 0.027 $W{\cdot}m^{-2}$ over the earth's surface. In a doubled CO_2 scenario, Fischer obtains a reduction of about 0.57 $W{\cdot}m^{-2}$ in net outgoing radiation due to absorption of longwave radiation by increased concentration of CO_2 (an assumption of half-cloudy sky is used here to allow for absorption by water vapour). The heat generated directly by human activity at the time of doubled CO_2 is estimated to be between 0.034 to 0.053 $W{\cdot}m^{-2}$ over the earth's surface. Fischer concludes that the heat pollution by combustion of fossil fuel, biomass burning etc. can be significant compared to the CO_2 absorption and should be taken into account in the global warming debate. In a similar study by Kaufman et al. (1991), the heating from burning of fossil fuel and biomass (associated with deforestation) is analyzed relative to the cooling due to anthropogenic aerosols. The study concluded that the cooling effect from coal and oil burning may presently range from 0.4 to 8 times the heating effect. Within this large uncertainty, Fraser and Mahoney hypothesize that it is presently more likely that the fossil fuel burning causes cooling of the atmosphere rather than heating. A recent paper by Stanhill and Kalma (1995) analyzes the solar radiation depletion at Hong Kong over the last 35 years in relation to anthropogenic heating (due to explosive population growth and associated human activity) and compare the impact of this anthropogenic or urban heating on the mean annual minimum temperature increase at Hong Kong, which is about 0.6°C. Stanhill and Kalma further analyze the urbanization impact on other large cities in North America and conclude that the increase in minimum temperature (of 0.6°C) was about half the urban-rural temperature difference at other similar large cities and that this was due to solar depletion at Hong Kong because of increased cloudiness and interaction of anthropogenic aerosols with clouds.

In summary, the impact of anthropogenic heating due to fossil fuel burning appears to be more than offset by anthropogenic aerosol cooling at present time. According to Fraser and Mahoney (1991), future increase in coal and oil burning and the resulting increase in concentration of cloud condensation nuclei, which may saturate the cooling effect, may allow the (fossil fuel) heating effect to dominate. The evolution of clouds and associated radiation budget may be critical in determining the impact of fossil fuel burning in a future climate.

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4.0 SUMMARY OF FINDINGS AND PRIORITY AREAS OF RESEARCH

The present report examines a large number of publications reported in literature since the IPCC 1996 study, and attempts to assess the present status of several key areas of uncertainty in the science of global warming and climate change.

4.1 Summary of Important Findings

4.1.1 The annual global mean surface temperature warmed by 0.57°C over the period 1861-1997 and by 0.62°C over 1901-1997. For the recent 20-year period (1978-1997), the mean surface temperature increase is estimated to be about 0.32°C or about 0.16°C per decade. The spatial distribution of the temperature change also reveals a cooling of between 0.5 to 1.0°C during the last 30 years over the northwest Atlantic, parts of eastern Canada and southeastern United States, and a sizable area over central/eastern Europe and western Russia.

4.1.2 The mean temperature trend of the troposphere as determined by the satellite-based radiometric data over the last 19 years (1979-1997) is now estimated to be about 0.1°C per decade. Recent studies attempt to explain the difference in mean temperature trend between surface and troposphere in terms of cooling of the troposphere due to stratospheric ozone depletion and warming of the surface due to urbanization and land-use change.

4.1.3 The increase in mean surface temperature of the earth is attributable to a number of factors according to several recent studies. Differential changes in daily maximum and minimum temperatures and associated narrowing of the diurnal temperature range (DTR) appear to provide at least a partial explanation for the mean temperature increase. Mean maximum temperature has increased over most areas of the earth with the notable exception of eastern Canada, the southern United States, portions of eastern Europe, southern China, and parts of southern South America. Mean minimum temperature has increased almost everywhere, except over eastern Canada and small areas of eastern Europe, the Middle East, and at most locations over India. Since daily minimum temperature has been increasing at a higher rate (or decreasing at a lower rate) than daily maximum temperature, DTR has decreased in most areas and mean temperature has increased, by 0.3°C or more.

4.1.4 Slowly varying large-scale atmospheric oscillations like the SO (southern oscillation) and the NAO (North Atlantic oscillation), which were first identified by Sir Gilbert Walker in the 1920s, and the more recently identified Arctic oscillation (AO) can explain part of the observed increase in the mean surface temperature of the earth. The SO and the associated El Niño phenomenon have contributed to positive surface temperature anomalies over western Canada and the northwestern United States, while the strong positive phase of the NAO has, since 1980, contributed to the positive temperature anomalies over western Europe and parts of Eurasia.

4.1.5 Changing solar radiation since 1900 and its forcing on the earth's climate may have contributed to about half of the observed warming at the earth's surface during the last 100 years.

4.1.6 No studies reported so far have directly and unequivocally linked increased concentration of greenhouse gases to the recent increase of the mean surface temperature of the earth. The most probable cause of the mean surface temperature increase is now considered to be a combination of internally and externally forced natural variability and anthropogenic sources.

4.1.7 Radiative forcing by anthropogenic aerosols (sulfate in particular) is now identified as an important perturbation that can significantly influence present and future climate. The direct and indirect (cloud-mediated) radiative forcing effects due to sulfate aerosols are presently assessed to be between about -4.8 and -4.0 $W \cdot m^{-2}$ over the southeastern USA. A few recent studies have identified a small cooling trend in the surface temperature records of the southeastern USA.

4.1.8 An analysis of precipitation data (1910-1995) over the conterminous United States shows an increasing trend in percent contribution of the upper ten percentile of daily precipitation events to the total annual precipitation, thus suggesting an intensification of the hydrologic cycle as per the IPCC 1996 conclusion. However, a similar analysis for Canada shows a decreasing trend from 1910 through 1995 for stations located in southern Canada; for stations located north of 55°N in Canada, there is a 10% increase in precipitation based on a shorter (1940-1995) data set. Over the Canadian prairies, there is no increase in heavy precipitation events. Elsewhere, an analysis of summer (June-September) monsoon rainfall over China and India does not show any increasing trend in extreme precipitation events. Over Indonesia/Malaysia, available data do not reveal any increasing trend in precipitation. For Australia, the percentage area of the land mass experiencing extreme wet conditions appears to have increased slightly while the area of extreme dryness has decreased slightly since 1910; however, this variability in extreme climate appears to be governed primarily by the frequency of El Niño and La Niña events. On a global or continental scale, there is no evidence of intensification of the hydrologic cycle in recent years.

4.1.9 There is no increasing trend in the total number of hurricanes occurring in the North Atlantic, nor is there any increasing trend in the intensity of the Atlantic hurricanes as measured by the wind speed. The central Pacific region appears to show an increase in the total number of hurricanes while the Australian region shows a distinct reduction in the total number of tropical cyclones in recent years. The interannual variation of hurricanes in the Atlantic as well as in the Pacific is found to be primarily governed by the phase of the ENSO (El Niño southern oscillation) phenomenon.

4.1.10 Recent studies using sea-level data sets over northwest Europe indicate a small weakening of the storm climate in the southern North Sea, while, for the northern North Sea region, a small (but insignificant) increasing trend in the storm climate is indicated.

4.1.11 There is no evidence of an increased frequency of El Niño (warm phase of SO) events in the equatorial central and eastern Pacific. The present La Niña (or the cold phase) of SO, which began in June 1998, is expected to continue until March 2000 according to recent analysis.

4.1.12 The predicted impact of global warming in terms of increased frequency of extreme weather events (e.g., extreme precipitation, extreme drought, increased number of tropical and extratropical storms) is not borne out by recent observational studies at this time.

4.1.13 There are some issues related to future scenarios that have not been discussed so far. The IPCC 1996 report developed a number of scenarios based on a wide range of assumptions regarding future economic development, population growth, and energy usage. From these scenarios, projected future atmospheric concentrations of GHG are calculated and are then used in climate models to develop projections of future climate. A recent paper by Gray (1998) makes a critical analysis of these scenarios and concludes that the IPCC scenarios exaggerate the extent of one or more factors determining future emissions. The paper further shows that the inaccuracies involved in calculating future atmospheric concentrations of GHG are so great as to render the calculations highly unreliable. This study, once again, points towards the uncertainty involved in projecting the future evolution of atmospheric chemistry and its possible impact on future climate.

4.2 Priority Areas of Research

Based on the discussion and analysis in Chapters 2 and 3, several areas of research relating modeling and observational aspects of the science of global warming and climate change can be identified. From an observational perspective, there are still large gaps in our observations of the atmosphere-ocean system. The Arctic and the Antarctic are probably the two best locations to exemplify the observational gaps and the uncertainty in appropriately defining the atmosphere-ocean system in these regions (see Curry et al., 1996). Other regions with observational gaps are land areas of tropical Africa and South America, tropical southeast Asia with particular reference to the maritime continent of Indonesia, and vast areas of open ocean in the southern hemisphere. From a modeling perspective, several uncertainties exist in adequate simulation of the ENSO phenomenon and in suitable coupling of atmosphere and ocean components of the climate models. Taking into account all these uncertainties, the following priority areas of research are identified:

4.2.1 A cooperative effort to build a data base and to construct temperature and precipitation trends on a regional, national, continental, and global basis. A detailed analysis of these trends to identify and remove any local and/or regional bias. An excellent example is a recent study (Skinner and Majorowicz,1999) on regional climatic warming and associated land-cover changes in northwest North America. The study finds an interesting correlation between the surface air temperature increase and ground surface temperature (as determined from well data) and further assesses the impact of land-cover changes on these temperatures. It would be useful to make such detailed analyses of temperature and precipitation trends in regions where local and regional influences are known to exist.

4.2.2 Improving the observational network, especially in the high-latitude regions (Arctic and Antarctic) and over tropical oceans and land areas. The recent GCOS (Global Climate Observing System) program, launched through the WMO, should help define climate and its variability in a more precise manner. This program should enable more precise detection of future climate change and more accurate attribution to natural and/or anthropogenic forcing. In a comprehensive paper Barry (1995) emphasizes the need for an observing system and data sets related to the cryosphere in Canada. Barry further describes the cryospheric data and its geographical variety and extent in Canada as providing a valuable window on the stability of climate in the Arctic and in middle latitudes. In a recent study on climate extremes, Karl and Easterling (1999) emphasized the need for an improved data set to establish a link between climate extremes and GHG-induced climate change. As Karl and Easterling have succinctly summarized, *There are a* *number of impediments preventing us from more effectively understanding the linkages between changes in climate extremes and natural hazards to anthropogenically induced climate change. Certainly model deficiencies are high on the list, but just as important is our lack of reliable long-term climatic data. Time and time again, we find that our observing systems and data sets often have large systematic biases of uncertain magnitude casting doubt on our ability to detect multi-decadal changes. This is why efforts like the GCOS are so critical.*

4.2.3 While acknowledging significant progress in climate modeling, it must be realized that most climate models have grid spacing that is too coarse to adequately represent mesoscale oceanic and atmospheric features. There is a definite need to develop finer-resolution models and develop suitable parameterization techniques to represent mesoscale features in the models. An associated problem will be to develop revised calculations of radiative forcing from natural and anthropogenic aerosols and their interaction with mesoscale features.

4.2.4 The ENSO phenomenon is now identified as the strongest climatic signal in the coupled atmosphere-ocean system outside of the diurnal cycle. It is imperative that climate models must be improved to realistically simulate the ENSO cycle and the associated global weather anomalies. Climate models with inadequate simulation of the ENSO cycle are unlikely to produce a realistic response to perturbations from increasing GHG concentration. An associated aspect is the inadequate simulation of summer monsoons from Africa to Indonesia (Gadgil and Sajnani, 1998). The ENSO-monsoon connection has been amply demonstrated in several recent studies (e.g., Webster and Yang, 1992; Khandekar, 1996). The summer monsoon and ENSO are two important features of the atmosphere-ocean system that must be adequately simulated in future climate models.

4.2.5 Finally, a few research areas that can be identified on a regional (provincial) scale as described in the terms of reference of this project:

- **a.** Thoroughly analyze precipitation and temperature trends over western Canada with particular reference to Alberta and determine spatial and temporal variability of these trends.
- **b.** Collect and carefully analyze data on extreme events (e.g., blizzards, heat waves, intense precipitation and associated floods, thunderstorms, and tornadoes) over western Canada and determine if any trends exist.
- **c.** Collect data on local and regional land-use and land-cover changes and assess their influence on precipitation and temperature in particular.

4.3 References

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