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CO$_2$/ CLIMATE REPORT

A PERIODICAL NEWSLETTER DEVOTED TO THE REVIEW OF CLIMATE CHANGE RESEARCH

1998 IN REVIEW
AN ASSESSMENT OF NEW RESEARCH DEVELOPMENTS RELEVANT TO THE SCIENCE OF CLIMATE CHANGE

1.0 INTRODUCTION

As part of an ongoing literature review and assessment process within the Science Assessment and Integration Branch of the Meteorological Service of Canada (MSC), this issue of CO$_2$/Climate Report provides a synthesis of more than 1000 scientific papers and reports relevant to climate change that have appeared within the international peer-reviewed literature in 1998. As for past reviews, this synthesis is not intended to be a full assessment of the state of scientific knowledge on climate change, but rather a brief summary of recent, incremental research results. For a more comprehensive assessment of the science of climate change, readers are referred to the 1995 Second Assessment Report (SAR) prepared by the Intergovernmental Panel on Climate Change (IPCC) and to subsequent special IPCC reports (1-5). Earlier issues of the CO$_2$/Climate Report can also be consulted for summaries of research papers published subsequent to the SAR but prior to 1998. Recent issues can be accessed on the MSC science assessment web site at www.tor.ec.gc.ca/apac/climate/ccsci_e.cfm.

In the interests of brevity and utility, the 1998 literature review is very concise, but fully referenced. Readers should consult the relevant papers identified for further details on the various topics and results discussed. Undoubtedly some important papers will have been missed in this review, either through oversight or lack of ready access to the relevant journals in which they appeared. Any related annoyance to the authors of such papers, and inconvenience to the reader is unintended and regretted.

2.0 CHANGES IN ATMOSPHERIC COMPOSITION

2.1 Carbon Dioxide

Atmospheric Concentrations: Data from some 40 monitoring stations around the world indicate that, by 1997, average atmospheric concentrations of carbon dioxide had reached 364 part per million by volume (ppmv), about 1.3 and 3.1 ppmv higher than in 1996 and 1995, respectively. This rate of increase is similar to the average annual increase since 1980 of 1.5 ppmv. Measurements from ice cores show supporting evidence for continued increases. However, while there is good agreement amongst various analyses of ice cores records undertaken (regardless of extraction processes used), there continues to be concern about the accuracy of CO$_2$ concentration reconstructions in older sections of some of these cores, particularly for those from Greenland[6-8].

Spring 2000 Issue

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Issued by the Science Assessment & Integration Branch • Meteorological Service of Canada (with Support from the Panel of Energy R&D)
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Understanding the Global Carbon Budget: Analyses of the large regional and temporal variations in atmospheric CO_2 concentrations can help identify and quantify specific sources and sinks of carbon dioxide, and can be used to test atmospheric transport models. However, such analyses must consider the influence of horizontal advection processes, boundary layer depths, local thermal factors and the position of monitoring stations relative to both human and natural sources and sinks. Related studies indicate that seasonal, interannual and interdecadal climate variability can also have a significant influence on changes in ocean upwelling behaviour and on terrestrial vegetation growth, and hence on the variability of CO_2 concentrations[9-19].

Recent analyses suggest that the global carbon flux between the atmosphere and terrestrial biosphere is now in near equilibrium, with net ecosystem uptake now approximately offsetting deforestation sources. Most of the biospheric uptake appears to be occurring in North America, particularly in the southern temperate regions, although other areas of apparent uptake include Eurasia, northern Africa and mature tropical forest regions of South America. Land erosion and biological processes within lake and river systems may also be transporting as much as 0.7 GtC from terrestrial systems into the oceans each year. Satellite mapping techniques and a proposed network of tall monitoring towers may help to significantly improve estimates of these regional fluxes of CO_2 in the future[20-26].

Advanced measurements and modelling techniques have also helped to significantly reduce the uncertainty in estimating the magnitude of net ocean carbon uptake. Related studies suggest that about 35% of industrial emissions from the 1980s have been taken up by the oceans, and that, if the global carbon budget were to come to a new equilibrium over the next several thousand years, 85% of current emissions would end up in the ocean, while most of the other 15% would remain in the atmosphere. Much of the excess deep ocean carbon would be neutralized over time by sediments, while the anthropogenic carbon remaining in the atmosphere would slowly be neutralized over eons by silicate rocks. However, such estimates are sensitive to how ocean processes, such as the thermohaline circulation system, will change in a warmer world[27-31].

Analyses of changes in isotopes of atmospheric carbon and oxygen can also be useful in studying past and current behaviour of the global carbon cycle. For example, isotopic trends within atmospheric carbon dioxide, collected both from ice cores and observing network samples, indicate that the terrestrial biosphere was a net source of carbon dioxide until the mid 20th century, then became a sink estimated at 0.9 GtC/year by 1970-90 period. Related estimates for current ocean sinks are about 1.1 GtC/year (which is lower than estimates obtained by other techniques). However, isotopic analysis techniques continue to be complex and subject to considerable uncertainty[32-36].

Terrestrial carbon flux processes: Changes in carbon reservoirs within global terrestrial ecosystems appear to have played an important role in long-term changes in atmospheric CO_2 concentrations. On very long time scales, these variations may have been constrained by interactions between atmospheric CO_2 and continental weathering rates, which provide a significant negative feedback. Paleo data over the past glacial cycle, however, indicate that current global carbon content in these reservoirs may be between 900 and 1900 GtC higher than that of the last glacial maximum. Similar studies using biospheric models suggest somewhat more modest changes. Increased CO_2 fertilization effects appear to contribute substantially to this carbon build-up during deglaciation, but also tend to reduce the fraction of C4 plants within ecosystems. In regions such as the sub-Sahara, enhanced biomass burning may also have been a factor in maintaining low carbon concentrations during glacial periods. The warm climates of the interglacials contributed to particularly high carbon accumulation rates in high latitude regions such as the peatlands and plains of Russia[37-45].

Currently, forest clear cutting processes have once again reverted many terrestrial regions to smaller carbon reservoirs, both by removal of above ground biomass and the continued CO_2 emissions from the denuded soils in subsequent decades. In tropical Africa, for example, such activities have reduced regional total terrestrial carbon pools by an estimated 10% or more during the 1980s alone[46-47].

Satellite data and on site measurements have been very useful in developing and calibrating the carbon flux models needed to properly assess the relationships between vegetation characteristics and regional carbon fluxes, although scaling up from local measurements (which can vary considerably in space and time) to the landscape and ecosystem levels used in these models continues to be a challenge. Carbon flux models are important in improving the understanding of the processes that control changes in carbon reservoirs with time. Inclusion of factors such as phenological processes, land use change and fire have helped to significantly enhance performance of such models, but significant inaccuracies are still evident[48-53].

Both observations and studies with these models suggest a number of factors that influence ecosystem-carbon flux relationships from region to region. For example, the fraction of below ground carbon within an ecosystem can vary from less that 50% of total ecosystem carbon in tropical forests such as those in Brazil to as high as 86% in Russian boreal forests. Likewise, the fraction of regional soils that exist as peatlands also vary dramatically. Climate variables such as temperature, soil moisture and water table levels can also be key factors in controlling the balance between regional ecosystem biological uptake and ecosystem respiration, thus causing large seasonal and interannual variability in carbon fluxes. In some regions, nutrient supply and other biological constraints can be more important than climate variables. The result is a large regional variability in current terrestrial carbon fluxes and in how these fluxes respond to environmental change. For example, boreal forest stands in regions such as central Canada, Scandinavia and eastern Siberia are usually modest carbon sinks during summer, but become sources in winter and particularly during spring thaw due to continued soil respiration. However, during some years these forests can become a significant net annual source. Grasslands, on the other hand, function primarily as net sinks, although the magnitude is subject to management strategies[54-62].

Understanding and modelling the soil processes that affect carbon fluxes can be particularly problematic because of the multiple variables and feedbacks involved. In general, the carbon to nitrogen (C:N) ratios in soils across most ecosystems appear to decrease with warmer temperatures, contrary to theories that a temperature rise will provide a negative feedback by mineralizing more nitrogen as nutrients for plant growth. Increased nitrogen deposition by atmospheric transport can help relieve nitrogen stress providing the supply of other nutrients are non-limiting. Furthermore, some plants such as certain boreal species, may also be able to utilize organic as well as mineralized nitrogen, further complicating the understanding of ecosystem response to change. Rapid temperature rises may also enhance soil respiration more rapidly that plant growth. Microbial processes appear to be very important in soil response to both elevated CO_2 and changing climates. Under certain circumstances, litter accumulation rates in forests may serve as a proxy for the root biomass activity component of these soil processes. At the soil surface, litter decomposition, which can be a significant source of atmospheric carbon, appears to be most sensitive to both carbon structure within the litter and to moisture content[63-70].

In the soils of northern and upland peatlands and tundra, carbon fluxes vary substantially with season, snow cover, location and vegetation characteristics. Some thin vegetation types, for example, allow increased soil exposure to sunlight and hence enhanced oxidation, while others like lichens, mosses and shrubs often have lower soil respiration and hence can have twice the net carbon uptake. Water table height, thaw depth, and nutrient supply are other important controlling factors. These are all expected to change under future climate scenarios, although the net effect on carbon fluxes is as yet hard to project. For example, a number of studies indicate that enhanced respiration could cause some of these ecosystems to become significant sources under future climate regimes. Others imply that enhanced release of nitrogen, from soils due to enhanced decomposition, together with the added influence of higher CO_2 concentrations could both accelerate ecosystem carbon turnover and significantly increase ecosystem net primary productivity and regional carbon sink capacity[71-80].

Ocean Fluxes: During the last ice age, regional factors such as ice cover and iron fertilization due to dust transport from land may have provided significant regional variability in the role of oceans as sources and sinks of atmospheric carbon. For example, while low atmospheric concentrations imply significant average ocean sinks, evidence from Indian Ocean sediments suggest that region may have been a significant source. However, the rise in atmospheric concentrations of CO_2 during the deglaciation that followed was likely caused by a global scale reduction in ocean carbon uptake, rather than regional phenomena[81-82].

Air-sea flux measurements data since 1982 indicate that, although current regional fluxes also can vary considerably from day to day and year to year, globally averaged air-sea fluxes vary annually by only about 0.4 GtC/year. Hence (despite possibly significant measurement errors), large interannual variability in increases in atmospheric concentrations appears to be driven primarily by changes in terrestrial rather than ocean processes. Only about 20% of the world's ocean surfaces currently act as significant net natural carbon sinks. One of these sink regions appears to be the Southern Ocean, where primary productivity may be much larger than previously estimated (although limited below its full potential by as yet poorly understood factors). While the remainder of the oceans are either near equilibrium or a weak source region, some coastal estuaries can have high respiration rates and hence be large sources regions. On average, the intensity of the carbon uptake in the sink regions appears to be large enough to dominate the weaker source regions and result in net global ocean uptake of carbon from the atmosphere. Consistent with this conclusion is the evidence that average concentrations of carbon in ocean surface waters are rising. However, the highest concentration of surface water carbon from anthropogenic sources is actually found in the tropical Atlantic, which is otherwise a net natural source region for atmospheric CO_2. In contrast, the Arctic Ocean appears to be only a small sink (about 1%) for anthropogenic CO_2. Much of the tropical Atlantic anthropogenic carbon is advected to the North Atlantic by surface ocean currents, where it then sinks into the deep ocean. Measurements suggest that this carbon has already penetrated to the ocean bottom in regions north of 50ºN. While there may also be transport southward into the South Atlantic, there is no evidence that the anthropogenic carbon has reached the deep ocean there. Models developed to simulate these transport mechanisms still have some difficulties in reproducing these results[83-100].

Less than two percent (about 685 GtC) of carbon in the global oceans is in the form of dissolved organic carbon (DOC). However, this carbon is an important indicator of spatial and seasonal variations in biological carbon production in ocean surface waters. For deep ocean DOC, concentration gradients can provide information on changing processes in DOC production over past millennia. During peak surface production periods (which can be influenced by such diverse factors as seasons, episodic advection of iron rich dust into a region and transport of nutrients by ocean eddies and other mechanisms), as much as 70% of the biological carbon produced can be in the form of DOC. Hence the concentrations of DOC can vary considerably in space and time. However, the role of this carbon in the total global carbon budget is not well understood[101-105].

Another form of organic carbon is black carbon, which is found in significant quantities in sedimentary organic carbon on the ocean floor (generally of much older age than other sediment carbon). This abundance suggests that it is either a significant component of DOC or that river export of carbon to oceans are currently underestimated[106].

Future Changes in the Global Carbon Cycle: The confidence in the use of coupled biogeochemical-climate models and other modelling tools to investigate changes in net primary productivity within both ocean and terrestrial systems with time continues to be limited by inadequate understanding of nutrient supply limitations, plant physiology, soil response and ecosystem dynamics. However, while results must be used with caution, study results imply that physical and biological responses of oceans to changing environments may reduce net uptake of carbon dioxide from the atmosphere in regions such as the Southern Ocean in future decades. Related simulations of terrestrial ecosystem response to recent and future changes in CO_2 and climate suggest ecosystems have and will continue to become increasingly productive with time, but that CO_2 fertilization effects will eventually begin to saturate during the coming century and be diminished by climate factors. The response is also sensitive to the rate of change and regional factors. Statistical techniques based on past relationships between carbon fluxes and environmental factors, for example, suggest that European biomes may soon switch from a long term sink to a net source as climate changes. Likewise, experiments imply spruce-fir forests in northeastern US could become source regions under warmer climates. Changes in snow cover in alpine regions may also cause large shifts in carbon and nitrogen dynamics, and related fluxes, in these regions[107-118].

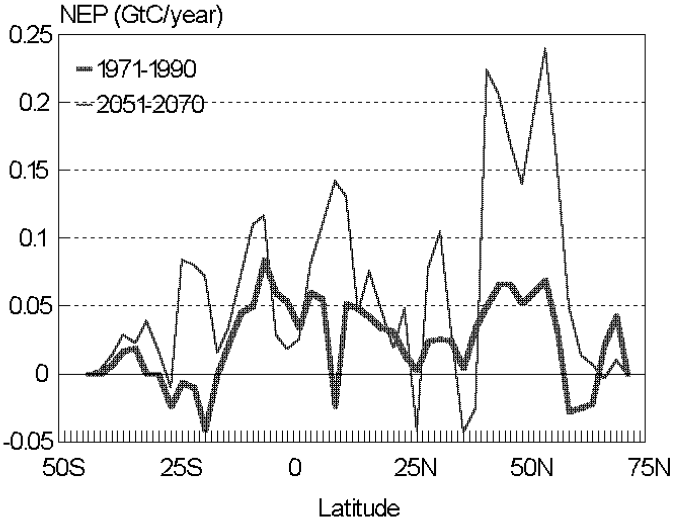

Figure 1. *Simulations of terrestrial ecosystem response to the combined effects of increased atmospheric concentrations of carbon dioxide and projected changes in climate (using the Hadley Centre coupled model outputs) suggest that some land areas (particularly in mid latitudes of the Northern Hemisphere) will experience significant increases in net ecosystem productivity by the second half of the next century relative to that of recent decades. Other areas will see a decrease in NEP. Globally, NEP begins to stabilize at about 3 GtC/year after 2050. Reference: Cao et al. 1998 (#107).*

2.2 Methane

Atmospheric concentration: High resolution ice core data indicate that methane concentrations varied within 40 ppbv of a mean value of 695 ppbv between 1000 and 1800 AD, then increased rapidly during the subsequent industrialized period. Growth rates peaked at about 17 ppbv/year in 1981, then declined. Global methane concentrations were about 1730 ppbv by 1997, and rising at approximately one-third the rate observed during the 1980s. Average methane atmospheric life-time appears to have increased over time, and is now estimated at 7.9 years. The global methane budget may be approaching a new equilibrium, with eventual stabilization of atmospheric concentrations at approximately 1800 ppbv. A five percent reduction in human emissions would be enough to achieve such a stabilization[119-122].

Sources and sinks of methane, and hence its regional atmospheric concentration, can vary substantially by latitude, season and altitude. Horizontal and vertical atmospheric transport mechanisms can also contribute to concentration variability[123-127].

Sources: Combinations of measurement techniques, including eddy correlation methods, tethered balloon data, aircraft data collection and potentially satellite systems, provide useful means of analyzing regional sources of methane. These show that, in contrast to the modest but variable sink for methane provided by drier soils, wetlands are a primary source of methane emissions. Recent estimates for current methane emissions from global wetlands suggest 92 Mt/yr from natural wetlands, compared to 53 Mt/yr from rice paddies. However, because of their inhomogeneity, emissions from unmanaged natural wetlands vary significantly between and within regions, and with time. On long time scales, they also respond to the effect of climate change on wetland conditions. During the last interglacial and the peak Holocene, for example, drier conditions resulted in significantly lower emissions in northern Eurasia compared to today, while future climate warming and precipitation changes could enhance emissions. Understanding the processes that control these emissions, both in the short and long term, is difficult because of the complexity of the microbial communities involved in methane generation and oxidation, the possible entrapment of methane within a bog matrix, and other environmental factors. Models developed to simulate these processes still oversimplify these complexities and their outputs must therefore be used with caution. They suggest, however, that most of the wetland methane emissions occur through the plants (which facilitate gas transport between soil and air), and that warmer climates may initially increase emissions. Deposition of nitrates or sulphates could help reduce emissions. Likewise, lower water levels tend to reduce emissions in the long term, although an initial increase may occur from release of trapped methane bubbles. Conversely, flooding of carbon rich peatlands for shallow hydro-electricity reservoirs or other purposes would provide a long term increase in methane emissions[128-151].

Measurements and model studies, which continue to provide improvements in estimates and understanding of the processes involved in methane emissions, also show high variability in such emissions from managed rice paddies, but continue to provide improvements in estimates and understanding of the processes involved. Emission rates are found to be sensitive to latitude, crop timing, soil temperature, wind speed and plant density, but less so to the amount of organic fertilizer applied and to yield. In China, total emissions from rice cultivation are now estimated at almost 10 $MtCH_4$/year, with about 80% released in mid and late growing seasons. Options for reducing emissions include use of biogas generator residue as an alternative to organic fertilizer, selection of appropriate rice cultivars, and water management[152-162].

In addition to cultivation of rice paddies, anthropogenic sources of methane include landfill sites and animal waste management systems in developed countries and cooking fires and biomass burning in tropical regions. Some of these are as yet poorly estimated. In Canada, recent estimates for manure slurries suggest annual national emissions of almost 1 Mt of CH_4, significantly higher than previously estimated. Other natural sources of methane include tundra lakes (which can release a high pulse of methane during spring break-up), decaying permafrost, some supersaturated ocean regions and boreal forest fires[163-170].

2.3 Nitrous Oxide

Atmospheric concentrations of nitrous oxide in 1997 reached 313 ppbv, and are increasing at a sustained average rate of approximately 0.7 ppbv/year[171].

Global emissions from all N_2O sources are estimated to be about 15 MtN/year, with about 30% related to food production activities. Emissions from agricultural activities are sensitive to soil conditions, temperature, field management techniques, timing of fertilizer applications, fertilizer type, and thaw-freeze cycles. For rice paddies, flooding methods are also a factor. The increase in agricultural emissions may have more than doubled the natural continental flux of reactive nitrogen within the terrestrial ecosystems. Further increases appear unavoidable, although higher ambient CO_2 concentrations may be a mitigating factor. The related effects on humans and ecosystems of the nitrogen flux are believed to be cumulative and important, but remain poorly understood.[157,172-183].

Measurements suggest that forest landscapes, which are a natural source of nitrous oxide, generate a large pulse of emissions when forests are cleared by burning, and continue to emit at sustained high levels for extended periods after the burn. Such forest landscape emissions can now be simulated quite well using various landscape and process models, provided detailed information on soil water and temperature is available[135,147,149,151,184].

Oceans are also a large natural source of N_2O that responds quite rapidly to climate influences. Isotopic studies suggest several processes, some previously unknown, may be involved[185-186].

2.4 Halons

Atmospheric measurements indicate that the tropospheric concentration of CFC-12 continues to increase, but at a significantly reduced growth rate of 3.6 pptv/year. That for CFC-11 is now declining at -1.3 ppt/year. Meanwhile, concentrations of CFC replacements, although still at about 100 pptv or lower, are increasing rapidly. There is also evidence that fluorinated ethers appear to be potent greenhouse gases. Meanwhile, investigations indicate that fluorites found within terrestrial landscapes are a natural source of CF_4 and SF_6, but that this source is insignificant compared to anthropogenic emissions[171,187-189].

2.5 Ozone

Data on atmospheric ozone concentrations are available from both ozonesondes and satellite systems and have been used to estimate trends and vertical profiles of concentrations and to assess related chemistry and transport mechanisms. However, statistical analyses of these data suggest that at least some of the regional trends reported in the past may be biased by poor data or analysis techniques and by other factors such as climate variability. Such biases can be reduced by using both data types, but results must still be used with caution. These results suggest a substantial increase in lower tropospheric ozone in the Northern Hemisphere during the past century, and continued increases in regions such as northeast and southern Asia[190-194].

Sources of the precursors that have caused these changes in lower tropospheric ozone concentrations are varied, and may occur at locations far removed from where the ozone chemistry takes place. For example, emission plumes of ozone precursors from biomass burning in Africa have been observed to transport across the Atlantic to affect ozone chemistry over the south Atlantic in the following season. Similar transport mechanisms have been observed in the western United States.

Such regional transport and peak events can now be successfully modelled with 3D chemical transport models, although they tend as yet to overestimate rates of global increases. They also disagree on the net effect of ozone increases on the abundance of OH (which appears to have increased during the past two decades), and hence methane lifetimes[195-202].

In the upper troposphere, aircraft emissions of the ozone precursor NOx (which are expected to increase in future decades), the upward transport of polluted air by thunderstorms and frontal systems, and winter intrusions of stratospheric air masses may all be important contributors to rising ozone concentrations. Conversely, tropospheric weather systems may also contribute to small areas of low ozone concentrations, or ozone mini-holes over mid-latitude zones of the Northern Hemisphere, particularly during late winter[203-212].

In the lower stratosphere, ozone concentrations at mid to low latitudes are expected to slowly recover as chlorine concentrations in the stratosphere decline. However, increased stratospheric cooling is expected to keep stratospheric ozone concentrations during polar spring seasons at low levels over the next few decades[213].

2.6 Aerosols

Stratosphere. Following the 1991 Pinatubo eruption, concentrations of sulphate aerosols in the stratosphere peaked over high Northern Hemisphere latitudes in spring 1992, with subsequent decay rate half-life of 9.4 months. These aerosols had an important influence on the regional formation of polar stratospheric clouds. Tephra layers within polar ice cores suggest other large volcanoes, including Krakatau in 1883 and a large Peruvian eruption ~1600 AD, have had similar or greater effects on climate in the past. Analysis of the slow long term trend towards higher stratospheric aerosol loading also implicate human sources, such as carbon sulfide transmitted from the troposphere and direct aircraft emissions[214-217].

Troposphere. In the mid troposphere, sulphate aerosol concentrations over North America appear to be closely linked to transport from surface sources, rather than in situ production, and can be twice as high over polluted continental areas as over areas upstream of major source regions. In some regions, nitrate aerosols can also be important. Regional differences appear to be less apparent in the upper troposphere. Here, however, aerosols from aircraft emissions may be becoming more important. Model simulations of these tropospheric aerosol production and transport mechanisms appear to capture the sulphate concentrations and distribution reasonably well but underestimate the effective cloud nuclei radii response over North America by about 10-20%. Concentrations of black carbon are also highest over and downwind of industrial regions, and appear to be linked to both sulphate and cloud condensation nuclei concentrations. The black carbon:sulphate ratio varies from 0.01 to 0.06[218-223].

An important natural source of sulphate aerosols in marine environments is the production of ocean dimethylsulphide (DMS) and its precursors. Production is sensitive to the biological activity present, is generally lower in regions with high nitrates and in polar areas, and is higher in convergence zones. Models developed to simulate the relationships between atmospheric and ocean DMS concentrations can now successfully reproduce the temporal and spatial variability involved, but significantly overestimate atmospheric concentrations in some regions. DMS concentrations are lowest in polar regions and highest in the subtropical convergence zone, with the efficiency of conversion to sulphates (on average about 30-50%) increasing with temperature[224-227].

Other sources of tropospheric aerosols include organic aerosols from forest landscapes, aerosols from tropical biomass burning, and the long distance transport of mineral aerosols, all of which can have both direct and indirect effects on climate[228-230].

3.0 Radiative Forcing

3.1 Anthropogenic Forcings

Greenhouse Gases: While Svente Arrhenius already discussed the role of carbon dioxide in the climate system more than a century ago, much of the understanding of the absorptive properties of well mixed greenhouse gases is more recent. New methods of calculating spectral line mixing within the absorption bands of the key gases (carbon dioxide, methane and nitrous oxide) as well as improvements in radiative transfer models have helped to provide a more accurate estimate of the net direct effect of changes in their concentrations since pre-industrial times on atmospheric radiative forcing. Revised estimates of this increased forcing of 2.25 W/m^2 represent an approximate 2% increase in the natural greenhouse, or a direct warming commitment of 1 to 1.5˚C, with the greatest forcing in the tropics. Although methane is a potent greenhouse gas (with GWP values over a 100 year integration still estimated at 21) and contributes about 22% to this enhanced forcing, its role is expected to decline with time. This enhanced direct forcing by well mixed greenhouse gases is further modified by a variety of regional and transient processes and feedbacks involving aerosols, water vapour and clouds, but which are as yet inadequately understood[120,231-235.]

New calculations with an atmospheric chemistry model that includes processes involving non-methane gases suggest that reductions in atmospheric OH levels due to increasing methane concentrations may be more than double that previously estimated. This in turn affects atmospheric chemistry involving other greenhouse gases[236].

Meanwhile, new estimates of radiative forcing induced by increased concentrations of tropospheric ozone suggest an additional effect of 0.29 to 0.35 W/m^2, with the greatest increase (up to 0.6 W/m^2 in summer) occurring in the Northern Hemisphere. This added influence may be large enough to offset the direct masking effects of increased Northern Hemisphere sulphate concentrations, and could increase further to 0.48 W/m^2. The effect of increased methane concentrations on atmospheric concentrations of OH could be a key, underestimated factor in this increase[197,237-239].

Model simulations indicate that seasonal changes in Antarctic ozone in the stratosphere can also influence global circulation patterns and regional climates, and may have done so in recent decades[240].

Aerosols: Various studies over different continents show reduced solar irradiance due to an increase in columnar aerosol optical depth. In some regions, such as South America and Western Canada, much of this is related to atmospheric smoke from fires, causing net regional cooling in the range of -25 to -34 W/m^2. In more industrial regions, nitrates, sulphates and other particles of organic origin are important factors. Over the south-eastern US, such changes may have contributed to a regional summer cooling effect of up to -4 W/m^2, although incremental effects of added concentrations in regions already heavily polluted may be much smaller. Over the oceans, emission plumes also increase local cloud albedo by generating smaller cloud droplets. However, in the Arctic, increased aerosols appear to have helped heat the lower troposphere, thus deepening the Arctic inversion layer[241-249].

Much improved data banks describing the optical properties for various aerosols (as well as clouds) are now available to modellers, and have helped to improve the agreement between models on estimated climate impacts of sulphate aerosol forcing. However, significant differences over high albedo surfaces and at low sun angles still arise. Simulations are also sensitive to seasonal variations, equilibrium states of aerosols, aerosol shapes and hygroscopic properties, and the presence of clouds. While coarse resolution GCMs fail to capture the small scale processes that can be important in including aerosol effects in climate simulations, more detailed regional climate models now can simulate some of these. For example, one such study using detailed aerosol-cloud schemes suggests a reduced solar forcing due to aerosols over convective cloud regions in the tropics of -0.3 to -1.1 W/m^2 [250-257].

Estimates for the radiative forcing effects of aerosol effects on a global scale remain highly uncertain, with recent estimates for direct forcing due to sulphate aerosols alone of between -0.32 and -0.81 W/m^2, and that for black carbon of between +0.16 and +0.4 W/m^2. This implies that black carbon may be more important than previously estimated. Greatest aerosol forcing occurs over polluted regions of North America, Europe and eastern China, and during Northern Hemisphere winter. The presence of clouds within aerosol layers can significantly enhance the forcing. For indirect aerosol effects, the range of uncertainty due to different model structures combined with options for input parameters is even larger, extending from -0.1 to -5.1 W/m^2. Hence there is still considerable uncertainty as to the extent that these effects may have masked the positive forcing of increased greenhouse gas concentrations[258-266].

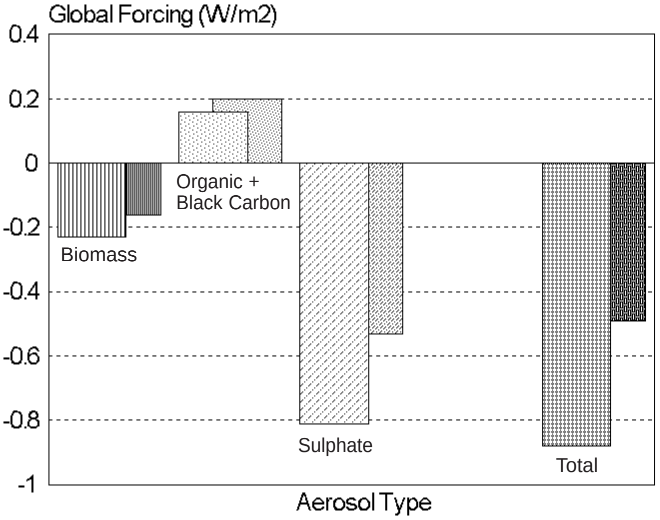

Figure 2. *Low and high estimates for global mean radiative forcing induced by current anthropogenic emissions of aerosols. Estimates were developed using an atmospheric GCM coupled to an atmospheric chemistry model. Reference: Penner et al. 1998 (#264).*

3.2 Natural Forcings

Volcanic Aerosols: Climate responses to major volcanic eruptions appear to typically commence several months after eruption, last for about two years, and significantly cool regional climates. During the first year following the Mt Pinatubo eruption, direct surface irradiance decreased by 30-40% and net radiative forcing by more than -6 W/m^2 in some regions. Comparison of GCM simulations against the observed response to the Pinatubo eruptions shows best performance when relatively weak atmosphere-ocean coupling response was used[267-270.]

Tropospheric Aerosols: Dust clouds over the tropical Atlantic Ocean may warm the regional lower troposphere by about 0.2˚C/day. However, observations suggest that, during large dust events, average net surface solar flux usually decreases more than offsetting increases in infrared flux, hence causing cooling at the surface and in underlying waters. These effects are sensitive to underlying surface albedo, aerosol size distribution and a variety of other factors. Net effects at the top of the atmosphere may be small. Inclusion of this forcing factor would improve regional performance of models[271-275].

Recent studies into the increased production of DMS over warmer oceans suggest this feedback could increase local concentrations of cloud condensation nuclei by 2-4% and cause a minor local negative forcing of less than -0.3 W/m^2. An additional tropospheric feedback involving enhanced convective activities associated with warmer oceans could theoretically add to this feedback. However, this possible feedback has not as yet been tested against observations[276-279].

Solar Forcing: A recent review by experts into the effects of solar variability on climate suggests that about 50% of changes in global temperatures during the past century, and one-third of that during the past 30 years, may be solar induced. Tree rings from around the world point to climatic effects of a 200 year variation in the length of the sun spot cycle, with the current solar warming influence diminishing over the next few decades and eventually leading to a cooling forcing, possibly by 2030. However, other factors such as solar particle eruptions, geomagnetic storms and stochastic resonance of solar forcings within a non-linear climate system may also be involved in the climate system response. Improved understanding of the complex solar properties and forcing mechanisms, as well as possible related feedbacks are required to properly include solar forcing effects in climate models[280-288].

4.0 CLIMATE MODELLING

4.1 Climate Model Processes

Atmospheric Processes: While, in general, model calculations of the clear sky greenhouse (GH) effect show good agreement with observations, significant differences still occur at high latitudes because of model error in surface temperature projections, and over some ocean areas and dry regions because of satellite data analysis problems. Sensitivity of the GH effect to changes in humidity is an order of magnitude greater in the upper than lower troposphere. Likewise, changes in high clouds have a greater effect than those for low clouds. The positive greenhouse effect/humidity feedback in the upper troposphere is evident in both the tropics and extratropics, and is particularly strong in moist upper troposphere regions over the North Pacific and North Atlantic storm tracks. However, humidity at this level is also highly dependent on concurrent dynamic and thermodynamic response, including enhanced upward motion by convective clouds. Inadequate observational data make it difficult to estimate the intensity of this feedback (although there is no evidence to suggest it could be negative)[289-297].

Horizontal moisture advection between hemispheres (which appears to be decoupled from vertical latent heat fluxes and out of phase with changes in surface SSTs in the tropics) can also be an important factor in modifying regional long wave radiation budgets. Over the west Pacific tropical warm pool, variations in SST and outgoing long-wave radiation reinforce each other through positive feedbacks that enhance convection. The latent heating induced by deep convection also affects gravity wave drag. This drag is, in turn, important in simulating the large scale structure of the middle atmosphere, and can be approximated by using cloud top height as a proxy. However, once SSTs rise above 30˚C, outgoing radiation also increases and suppresses deep convection through externally forced subsidence (a negative feed back)[298-301].

Model calculations for the role of water vapour in clear sky absorption of solar radiation, although perhaps underestimated, compare reasonably well with measurements and, hence, are not the main reason for discrepancies between observed and modelled estimates of atmospheric absorption of solar radiation. Although observational errors can also be a factor in these discrepancies, other factors affecting atmospheric transparency, such as inadequate inclusion of the role of aerosols, multiple scattering, cloud inhomogeneities, surface wind influences on albedo, and effects of incidence angles, are implicated. Improvements in these calculations are particularly important for properly simulating the hydrological cycle and hence atmospheric circulation. Relationships between variations in sea levels and fluctuations in the hydrological cycle can, in turn, be used to test such simulations[293,302-314].

Although many climate models also underestimate both the reflection and absorption of solar radiation by clouds, some recent models now show increased absorption. Cloud inhomogeneities do not appear to have a significant influence on the net absorption. These model underestimates are particularly significant in the presence of cyclonic and low clouds at mid-latitudes. In contrast, over the highly variable Pacific Ocean warm pool, the observed cloud absorption (only about 9% of incoming solar radiation) is similar to that simulated in many models. When simulating reflection of incoming shortwave radiation in this region, both the effects of lower level stratiform clouds and local spots of highly reflective cirrus tops of convective clouds (which are sensitive to the concentration, shape and size of the ice crystals within them) need to be considered. The net effect of cloud radiative forcing can be simulated reasonably well with simple models if the relative roles of clouds, surface albedo and atmospheric transmission are properly separated and other factors such as particle growth rates, terminal velocities and scattering and diffraction properties are included[293,315-326].

The presence of nearly invisible cirrus clouds at or just below the tropopause may also have important implications for radiation processes. Factors include the effects of increases in local temperatures caused by these clouds and an increase in lower stratosphere water vapour concentrations. For example, such clouds (often found in the wake of high flying aircraft, which can cover up to 5% of the sky in heavily traveled corridors) can absorb as much as 50% of local upwelling IR radiation. Aircraft contrails (which contain sulphates and nitrogen oxides that can contribute to the production of cloud ice crystals) can also have a significant albedo effect. However, at least some of this effect may be offset by related reductions in the amount of naturally occurring cirrus clouds[327-332].

Over cold and mountainous regions, the enhancement of downward IR fluxes from cloud decks depends on cloud type, the presence and size of ice crystals and the background emissivity of the cloud free atmosphere, and is least when the atmosphere is very humid. In Antarctica, model simulations of these fluxes are also affected by uncertainties about regional summer temperature and humidity profiles. In the Arctic, the net annually averaged small positive radiative forcing of regional clouds has a pronounced seasonal cycle (strongly positive in winter and spring, strongly negative in summer) that is not as yet well captured by reanalysis models[321,333-336.]

Studies into possible cloud-climate feedbacks during the last glacial maximum (LGM) suggest that circulation as well as radiative processes are important factors, particularly at low latitudes. They imply that future cloud response to the radiative effects of enhanced CO_2 concentrations will be complex, non-linear, and model dependent. Circulation processes are, in turn, influenced by top heights, multi-layering and distance between layers of clouds. While some modellers may apply ad hoc adjustments to correct for related model biases, such adjustments can have important impacts on modelled stratospheric circulation[337-339].

ENSO, as well as solar variability, may have an influence on global mean cloud optical thickness, although such changes in thickness appear to vary out of phase with changes in total global cloudiness. Hence net effect of such variations on global cloud reflectivity may be small. Recent strong ENSO events, in turn, appear to be coherent with and linked to NAO variations. For storm tracks, the growth and decay behaviour of upstream blocking anticyclone pressure systems appear to be important in changing cloud properties[340-342].

Observations of local cloud types over oceans can be useful in estimating the regional characteristics of local marine boundary layer processes, which are important in simulating fluxes between the atmosphere and oceans. Likewise, observed changes in surface climate conditions can help identify destabilized steady states and dramatic change in climate behaviour induced by small changes in snow cover and other albedo feedbacks[343-344].

Land processes. Non-linear feedbacks between the atmosphere and terrestrial surfaces affect the redistribution of energy at the atmosphere-land interface and, on long time scales, can have major global implications. Hence failure to include these feedbacks in a properly coupled manner could cause serious errors in climate model simulations of climate and in related climate change studies. Most of the variables involved can be described in surface-vegetation-atmosphere schemes based on grid-by-grid remote sensing data inputs. Likewise, snow models using such data inputs can provide improved approximations of the seasonal and interannual variability of the effects of snow cover on albedo (including vegetation cover effects), water storage and transmission rates and heat fluxes. However, these models do less well for snow cover density and characteristics. Measurements of air-land fluxes needed to better understand these feedbacks are still imprecise, both because of surface variability and irregularities in turbulent transport in the atmospheric boundary layer[345-358].

A number of advanced and new land surface schemes that have now included more realistic treatment of atmosphere-surface processes and feedbacks generally show improved performance in simulating surface heat and moisture fluxes. Their ability to simulate current vegetation distribution patterns when forced by observed climate conditions is also greatly improved, particularly when using high spatial resolutions. Although coupling such schemes to GCMs can significantly improve the GCM land-air interface representations, the coupling process becomes progressively challenging as the complexities of the land surface schemes increase. Furthermore, important discrepancies between coupled ecosystem-climate model simulations and observed conditions still persist. Hence, further related research is emerging as an important new research discipline and a priority in properly addressing climate-ecosystem feedbacks. Areas of focus for such research include the development of algorithms to help scale up from plant and canopy level processes to the landscape levels, inclusion of the soil thermal conductivity, ecosystem root distributions and soil biophysics governing soil respiration in the land schemes, and better representation of terrain based hydrology and snow cover effects, particularly in the Arctic[359-385].

Various intercomparisons of advanced land surface parameterization schemes suggest most have improved ability in simulating net radiation, surface temperatures, east-west precipitation gradients, average latent heat fluxes, the seasonality of evapotranspiration and other variables when compared with simpler schemes. These schemes also generally perform better if first calibrated for effective scaling up of data from small catchment basins to larger ones, and to model grid boxes, and show an asymmetry in response of latent heat fluxes to temperature change (with greater sensitivity to cooling than warming). However, major differences between schemes with respect to sensible heat and ground heat fluxes, spatial characteristics of latent heat fluxes, soil moisture water storage change, summer precipitation and other features still remain. These differences could be important in coupled ecosystem-climate simulations, possibly adding to uncertainties of model results[386-391].

Land use change, such as cultivation, irrigation and deforestation, can also impact on the processes included in the land surface schemes, since such changes can significantly alter surface albedo, affect evapotranspiration and latent heat fluxes, and increase regional water loss to the atmosphere. These changes can, in turn, affect diurnal temperature cycles, wind speeds, cloudiness and convective precipitation[392-395].

Ocean Processes. Systematic observations in the tropical Pacific indicate that regional heat storage and budgets over decadal time scales are influenced by a variety of interactive and variable factors, including surface heat flux, vertical heat transport, horizontal mixing and meridional advection. Studies with a primitive equation isopycnal ocean model suggest that variations in such heat storage is dominated by mass balance controlled adiabatic processes in the eastern tropical Pacific, and by temperature controlled diabatic processes in the west. Changes in the eastern Pacific, in turn, have a large influence on low-latitude tropospheric temperatures. Large variations in regional ocean heat storage, like that of the 1982/83 ENSO event, can create major oceanic Rossby waves that take more than a decade to reach mid-latitudes of both hemisphere and the Asian coast, where they cause a delayed influence on regional ocean currents and climates. Negative feedbacks within the ocean-atmosphere system in tropical-subtropical zones ensure that such anomalies switch from warm to cold phases and back again in an oscillatory fashion. Simulations with coupled climate models suggest that these decadal scale fluctuations not only encompass the entire Pacific, but are linked to variability on a global scale[396-406].

Models suggest that climate variability may be linked to a variety of ocean processes, including deep convection, ocean gyres, ocean bottom transport mechanisms, and tropical and extra tropical processes. Surface wind stress, temperature and salinity are important factors in these oscillations, which occur on time scales anywhere from a few years to more than a century. The importance of such feedbacks can vary by region, and influence a variety of ocean surface fluxes. Over the North Atlantic, for example, when some of the atmosphere-ocean interactions were included in model simulations, the inter-annual variability of winter climates was enhanced, with temperature anomalies becoming more persistent and often reappearing a year later due to ocean-atmosphere feedbacks. In the Labrador Sea region of the North Atlantic, various dynamical and thermodynamical processes (now being studied with the help of new regional data sets) appear to be important in the spread of cold, less saline waters across the Atlantic, where they interact and influence other currents and large scale ocean circulation systems as much as a decade later. There is now also observational evidence that interactions between wind, evaporation, horizontal advection and SSTs in the tropical/extra tropical North Atlantic contribute to decadal scale oscillations in circulation and upper ocean ventilation in the region, including a hypothesized Pan-Atlantic Decadal Oscillation (PADO). These oscillations are similar to model simulations of multi-decadal scale thermohaline-atmosphere feedbacks in the North Atlantic. Both the observational data and model results indicate that these changes may be linked to NAO fluctuations. Studies into past ocean climates indicate that, on even longer time scales of centuries and millennia, global scale processes such as interactions of changes in solar radiative forcing with ENSO behaviour and other non-linear internal processes may link up with regional processes to generate abrupt changes in ocean climates. Better understanding of these processes is a pre-requisite to improved assessments of such variability, and the ability to predict how such variability may change or surprise us in the future[407-422].

Sea ice behaviour and transport is influenced as much or more by atmospheric circulation and winds as other factors such as ocean currents, surface albedo and temperatures. In the Arctic, the sea ice behaviour appears to be affected by a decadal scale internal sea ice-ocean-atmosphere feedback loop, possibly linked to the NAO. Much of the Arctic sea ice is eventually transported into the North Atlantic, where it causes a large but variable flux of fresh water and negative latent heat flux into this region. This in turn affects regional temperatures, vertical mixing, the thermohaline circulation system, and even regional sea levels. Similarly, in the marginally stable Southern Ocean, changes in surface temperature and salinity induced by the formation, transport and melting of sea ice can affect convection processes and deep water formation rates. Hence atmosphere-ocean-ice feedbacks constitute an important aspect of the climate system, and need to be included in coupled climate models. Despite poor observational data and lack of inclusion of some processes that may be important, recent advancements in ice-ocean models have significantly enhanced the ability to realistically simulate these feedbacks and hence understand polar and sub-polar ocean and ice behaviour[423-438].

In the Southern Ocean, total in situ deep water formation (some of which is vented in the Indian Ocean decades later) may be comparable to the influx from the North Atlantic Deep Water into the region. This would be more than three times larger than the Weddell Sea deep water flux, often assumed to be the primary source of deep water formation in the Southern Ocean. Most ocean models also tend to underestimate deep ocean temperature and salinity in the Southern Ocean, although inclusion of brine release during sea ice formation and improved shelf topography can reduce these biases[439-441].

Uncertainty about the rate of heat penetration into the deep ocean is a key source of model simulation uncertainty. Coarse resolution ocean model experiments indicate that vertical ocean diffusivity plays a dominant role, particularly through deep ocean carbon and heat uptake. However, many ocean processes take place at scales significantly smaller than such models can properly simulate. High resolution mesoscale ocean models which reproduce such ocean processes very well are now available to investigate their role in much greater detail. These models can generate spontaneous, decadal scale internal ocean variability and baroclinic instabilities that result in a more chaotic ocean behaviour that coarse resolution models fail to simulate. They can also partition heat loss from the ocean mixed layer between surface fluxes and transport mechanisms more accurately, and provide new insights into ocean current structure. However, resolving currents in narrow straits remains a challenge. Furthermore, such higher resolution may not result in better model performance if the model fails to include the diversity of air-sea interaction regimes that exist across the global ocean or deal with the thermal radiation and upwelling processes involved in the decay of transient ocean anomalies[442-451].

4.2 Model Evaluation

A key test for the ability of a model to properly simulate the climate systems is its performance in simulating current climate regimes. Efforts to evaluate a large number of atmospheric GCMs under the WCRP AMIP program indicate that current atmospheric GCMs perform significantly better than earlier versions, and can be useful in data recovery for data sparse areas as well as for simulations of climate responses to changes in radiative forcings. However, they continue to show significant deficiencies in the details of the simulations. Most, for example, have a cold bias linked to snow-ice albedo problems, fail to simulate the coldest and warmest conditions, are deficient in coupling between stratospheric and tropospheric processes, and under-predict interannual variability of various atmospheric parameters. There are also problems in some regions in accurately simulating the seasonality of precipitation, particularly snowfall, and in simulating atmospheric features related to extreme weather events, such as storm tracks and blocking frequencies . There are concerns that some of the discrepancies between model output and observed data may be due to poor data quality[452-462].

Evaluation of coupled ocean-atmosphere GCMs must not only address model performance in simulating current climate conditions but also the extent of drift in the simulated climate with time. For the latter, effective parameterization of the complex feedbacks between atmospheric convection, cloud and boundary layer processes, SSTs and large scale ocean-atmosphere dynamics appear to be particularly important. While some models correct such drift through flux adjustments, others are now able to control drift quite well without such adjustments. Most coupled models now show broad agreement between simulated climate and observations. Some also show much better simulation of storms and seasonality of precipitation. However, factors such as inadequate representation of sea ice-atmosphere radiative fluxes and resolution continue to cause problems. For example, most models continue to have difficulties in accurately simulating polar climates, while some also show significant biases in tropical climate regimes. Computing time also continues to be a major constraint in transient simulations, although intermittent coupling has been used with some success to address this constraint[463-486].

Alternative methods for testing complex model performance include the use of simple climate models, evaluation against paleo climates and, for transient experiments, comparison of simulations using climate forcings of the past century with observed changes. Simple climate models, for example, have been used to evaluate GCM deficiencies associated with failure to include the effect of middle atmospheric chemistry on atmospheric dynamics and occurrence of stratospheric clouds[487-488]. For paleo studies, recent model simulations perform well for simulations of the Last Glacial Maximum, although less well for the glacial-interglacial transition period and for interstadials such as the Younger Dryas event. They also suggest the need for multiple forcing (solar, greenhouse gases and albedo feedbacks) to achieve agreement with paleo climate reconstructions of glacial-interglacial changes, and indicate that ocean processes and air stability may be key factors in these changes. Some recent simulations indicate that tropical ocean temperatures may have been about 2˚C colder during the Last Glacial Maximum than estimated from CLIMAP program reconstructions[489-498]. Finally, comparisons of simulations with several coupled models forced with radiative changes of the past century with observations indicate good agreement on long term global and zonal trends. However, there are significant discrepancies at the regional scale. In some regions, this may also be due to inadequate observations[499-501].

4.3 Model Results

Global temperature and precipitation. Equilibrium model projections and other related studies continue to show a wide range of potential warming for doubled CO_2 climate scenarios, extending from as low as 0.4˚C to above 5˚C. Inclusion of aerosol effects reduces the net effect due to greenhouse gases by about 20%. Several recent coupled model experiments suggest a transient response at the time of CO_2 doubling of between 1.5 to 3.5˚C. However, researchers caution that the climate system responds in a non-linear fashion and that climate models as yet do not properly include some of the biogeochemical, biogeographical, ocean and other long term feedbacks that may be important. This need for caution is further emphasized by the lack of evidence from model projections for abrupt shifts in climate as it responds to changes in radiative forcings, even though paleo studies suggest these have frequently occurred in the past. Hence model results should still be used as indications of climate sensitivity to radiative forcing, rather than as predictions[502-508].

Ocean Ice Cover and Circulation. Model results generally agree that, as the global climate warms, sea ice extent will decrease substantially in both polar regions and the thermohaline circulation (THC) will weaken in the North Atlantic due to increased fresh water influx and enhanced warming equatorward. However, the projected changes in the

THC system may take decades to exceed its natural variability and may make the system more stable. However, these changes are not likely to affect ENSO behaviour. The consequences for changes in the response of the Southern Ocean are less certain. In this region, a reduction in regional deep convection due to increased fresh water influx could result in a delayed intensification of ocean turnover, with important implications for Northern Hemisphere ocean temperatures as well[435,501,509-512].

Regional Characteristics, Variability and Extremes. The response of the tropical oceans to a positive radiative forcing involves both a fast surface response within years and a slower decadal-scale response of the ocean thermocline. While east-west tropical temperature gradients initially increase, the final response is more complex and depends on the effects of the forcing on latitudinal differential heating. Under various climate scenarios for high atmospheric CO_2 concentrations, latitudinal temperature gradients in low latitude regions appear likely to intensify, increasing mid-latitude precipitation, while gradients at high latitudes are likely to weaken. Hence, temperature and precipitation changes at the regional scale can vary considerably, and are difficult to predict with confidence or to detect against background climate noise and natural variability (particularly in polar regions). While temperature gradient changes may not have a large influence on the average intensity of the Asian monsoons, they are expected to affect its seasonality and regional characteristics. Several recent coupled model experiments also suggest a tendency towards an increase in temperature extremes (which are very sensitive to local soil moisture and albedo response), enhanced atmospheric moisture content (and hence latent heat transport at most latitudes), an increase in precipitation extremes, and displaced storm tracks in some regions. Extreme winds are likely to decline in mid-latitudes, except in areas of ice retreat. There is further evidence that, in mid latitudes, both PNA oscillations and storm intensity may be enhanced, while the total number of storms could decrease. While most GCMs are as yet unable to properly project the effects of climate change on tropical storm intensity and frequency, there is both theoretical and some model evidence that these could both increase. However, their range is unlikely to expand[483,513-525].

Regional Climate Models (RCMs). RCMs can provide much greater spatial detail important to regional climate response to radiative forcing than can GCMs, and results from various RCM experiments over Europe and the USA have provided more realistic projections at the regional level. However, RCMs continue to be constrained by the quality of boundary inputs provided by global models to which they are linked. They are also sensitive to the domain size used in their experiments, and are often subject to problems with hydrological and radiative budgets. Hence their results, like those from GCMs, should still be used with caution[526-537].

5.0 Climate Trends

5.1 Paleo Climates

Glacial/Interglacial Climates. Models, ice core data, sediment records and other paleo data sources are useful resources for studying climate regimes and processes of past glacial and interglacial climates, although they must be used with caution. Analyses suggest that, in addition to the possible triggering of 100 kiloyear (ky) glacial-interglacial cycles by a similar cycle in the earth's orbital eccentricity, other factors such as frequency variations in the 41 ky cycle in orbital obliquity, greenhouse gas feedbacks (e.g., sudden methane release from seabed hydrates) and changes in planetary shape during deglaciation may also be important causal or feedback factors[46, 538-550].

There is new evidence that the interglacial of some 400,000 years ago was longer and perhaps warmer than subsequent interglacials, and was accompanied by sea levels some 20 m higher than today. This is equivalent to a complete melt of both of the Greenland and West Antarctic ice sheets, and implies that such a response could happen again in a warmer world. The last interglacial some 135 ky ago appears to have had average global annual temperatures similar to today, although with warmer summer climates. During that event, strong local sea ice feedbacks to regional changes in solar insolation also seem to have resulted in a change in the Antarctic climate well before that of the Northern Hemisphere[551-554].

Recent climate model simulations for the LGM some 25 ky ago appear to be sensitive to initial conditions used in the simulations, but provide evidence for cooler tropical oceans than implied by past paleoclimate studies. Weaker pole to equator temperature gradients and the presence of large ice sheets also caused significant changes in global atmospheric circulation, with the jetstream over North America much further south and altered storm tracks over Antarctica. The Southern Ocean was ice covered during winter up to latitude 60˚S, and sea levels were some 120 to 140 m lower than today. Greenland cooled more than Antarctica, and more in winter than in summer, while most continents were also at least 5˚C colder and drier. C4 plants appear to have been a more dominant species in many regional ecosystems. Global dust transport was more intense at the time, with as much as 50 times the iron deposition over East Antarctica and presumably over regions of the Southern Ocean. Response of ocean circulation and biological productivity appears to have varied considerably from region to region[551,555-571].

During the subsequent deglaciation, beginning about 15 ky ago, monsoons strengthened and caused subtropical deserts to shrink, but total vegetated area remained somewhat constant as effects of ice sheet retreat were offset by those due to rising sea levels. The deglaciation process was accompanied by a warming in Antarctica of about 15˚C, a Greenland warming of as much as 25˚C, an abrupt climate transition in New Zealand, and rapid ice retreat and warm summer seas in the North Sea. It may have also caused increased climate variability, including the Younger Dryas event. Although European land climates followed similar patterns, vegetation response was delayed by several centuries and interrupted by the Older and Younger Dryas events[44,572-581].

Paleo records also show that the longer term fluctuations between glacial and interglacial conditions were also regularly interrupted by millennial scale interstadial cooling events. These typically show amplitudes of 3˚C or more during periods of glaciation and a more modest 1˚C during interglacials. During the last glaciation period, for example, abrupt climate anomalies such as the Dansgaard-Oeschger cycles and Heinrich events appear to have caused interconnected changes of regional climates from pole to pole, with climates in Greenland cooling by 5-8˚C over a few decades to centuries. These events were usually accompanied by fluctuations in CO_2 concentrations of up to 20 ppmv, and appeared in Antarctica about one to two millennia earlier than in Greenland. This suggests that the events are influenced by an inter-hemispheric see-saw process or a primary tropical forcing mechanism. The Heinrich events, which occurred about every 5-10 ky, appear to have been triggered by sudden discharges of icebergs, primarily the Laurentian ice sheet, with possible contributions from the European ice sheets as well[565,582-596].

Abrupt cooling events during the last deglaciation process, such as the Older and Younger Dryas events, have been studied in much greater detail than earlier events. The onset of the Younger Dryas, which appears to have been at least hemispheric and perhaps global in scale, resulted in cooling in polar regions and eastern North America by about 12-15˚C over 200 years, and a rapid warming of 5-10˚C within a few decades near the end of the event[597-600].

The Last 10,000 Years (Holocene). During the early Holocene (until about 6 ky ago), diverse regions such as Mexico, British Columbia and Sweden were drier than today, while other regions (e.g. central Colorado and central Africa) experienced wetter summer conditions and more abundant ecosystems. By the mid-Holocene (between 6 and 4 kybp), this pattern of response had altered. Related changes in vegetation appear to have been an important feedback process, amplifying the changes in solar insolation through surface albedo change and indirectly influencing ocean climates (particularly in boreal zones). Colorado, for example, became drier again, while the tropical dry region from the Sahara to the Gobi deserts became wetter and more vegetated. Peatlands and wetlands also expanded throughout Canada in response to changing Arctic frontal positions and the emergence of land out of the sea. While global average temperatures were likely within 1˚C of today's during the peak Holocene, some land regions were significantly warmer. Increased ocean evaporation under the warmer climates also enhanced the poleward transport of moisture[572,601-616].

Temperatures in the Northern Hemisphere has declined slowly since the mid-Holocene, although some regions of the Southern Hemisphere show little evidence of a similar decline. The lack of a more dramatic change in either temperature or sea levels in response to declining NH summer solar insolation is consistent with a non-linear climate system that changes in an abrupt manner. A variety of indicators from various regions also suggests that the late Holocene climate fluctuated on time scales varying from centuries to millennia. Changes in regional moisture associated with these fluctuations caused pronounced changes in regional vegetation patterns[617-627].

Last Millennium. High resolution ice cores, glacier mass balance data, tree rings, and measurement of sediment grain size in stream beds are among the tools that have become useful in reconstructing climates of the past millennium. New research results from these sources suggest that climates 1000 years ago were about 1˚C milder over Greenland than today, while northeast China was wetter, and hence more benign. Both regions also show significant variability in precipitation in subsequent centuries, with the Greenland snow accumulation rates providing evidence of a century scale variability, perhaps linked to solar or NAO variability. During the Little Ice Age, Greenland was about 0.5˚C colder than today, and upwind forest fire activity was at a minimum. However, the circulation patterns over the region changed to current patterns about 200 years ago. In northern Siberia, tree rings indicate that the 20th century is now the warmest of at least the past 500 years. In North America, central regions experienced periodic droughts during the past millennium that were far more severe than any encountered during the past century. Likewise, the most severe floods in the North American south-west appear to have occurred some 400 years ago, although other regions of the country have experienced unusually wet conditions in recent years as well. These past extremes could happen again due entirely to natural variability[572,628-640].

5.2 Climate Trends Of The Past Century

Data Collection and Analysis Techniques: Statistical studies indicate that direct analyses of global sea surface temperature data sets appear to be reliable for the abundant data period since 1951, but less so for earlier data sparse periods. Analysis of land station data also needs to carefully address a number of factors that can bias trends, including the presence of zero values, urbanization effects, change in regional albedo, and non-normal distribution of the data. Alternative methods for addressing these concerns include development of corrected reference stations and comparison with data generated by coupled climate models. Urbanization effects, which can be quite large but variable from day to day, are subject to a combination of factors that can differ from one region to another, and hence require multiple comparisons with rural sites to accurately estimate and remove. Satellite platforms also appear to provide useful information about surface climate variability, although these data sources have systematic biases and noise that can be quite large[641-651.]

Various proxy indicators of past surface temperatures have proven to be useful in providing complementary information to direct surface temperature measurements. One source of information is anecdotal records. Borehole data have also proven to be a useful means of reconstructing long-term surface temperature trends over land areas, although site selections need to be chosen carefully to avoid the effects of human perturbations of local land surfaces. Vegetation growth indicators, such as alpine tree limits and tree ring data, have become important tools as proxies for past summer temperatures and for precipitation, although there are indications that tree ring density has become less sensitive to temperature fluctuations during the last half century (perhaps leading to overestimates of recent global warming if not accounted for). Trends in properties of polar lakes can also help understand local climate change. Within oceans, acoustic sound waves have been successfully used to precisely measure seasonal changes in average temperatures of sea water along the sound wave path. Coral records can also provide good local temperature histories provided sites are redundantly sampled to reduce observational error[652-664].

The accuracy of temperature estimates within the troposphere and stratosphere based on the satellite-based MSU system continues to be actively debated. Experts directly involved with the analyses argue that the microwave data can be merged quite accurately by using the more stable units on NOAA 6, 10 and 12 satellites and correcting for discontinuities and drift, although they acknowledge that accuracy over the oceans remains a concern. Others suggest that the record is too short for credible trend analysis, that corrections for stratospheric signals when estimating lower tropospheric temperatures enhance the noise from surface temperatures and soil moisture, that methods for data analysis need to be improved, and that there remain spurious jumps in the data. Likewise, while radiosonde data can provide useful complementary information on atmospheric temperatures, more work needs to be done to take careful account of systematic changes in reporting practices, instrumentation and number of stations[665-670].

Satellite systems can also be used to estimate and possibly monitor trends in other climate variables, including cloud optical depths, top-of-the -atmosphere radiances or wind field data. However, there are still problems in reconciling such data with surface based measurements[671-673].

Methods for measuring surface trends of other climate variables, such as moisture budgets, snow accumulations and cloud cover, also need to consider local influences (including urbanization effects) to ensure accurate estimates of regional trends. Where good correlations exist, such methods can be used as proxies for long term changes in indicies such as the NAO[674-678].

Temperature Trends: Analysis of global land and ocean surface data show that, despite the cooling influences of ozone depletion, nine of the ten warmest years of the instrumental record occurred between 1987 and 1997, with the last year about 0.1˚C warmer than any previous year. The winter and spring of 1997 were particularly warm. However, some regions have been consistently cooler than normal, and satellite MSU data suggest the lower troposphere is still near the 30 year norm. Recent corrections of the MSU data for the effects of satellite drift now suggest a slight warming of the lower troposphere since measurements began in 1979, although the magnitude of the trend remains controversial. Trends in radiosonde temperature as well as tropospheric thickness data also suggest minimal tropospheric warming for the same time period. These results contradict earlier reports that the troposphere has been cooling, but also suggest either an increasing bias in surface or satellite data with time or a decoupling of surface and tropospheric atmosphere for a period of at least two decades. Radiosonde data records do show a significant warming between 1960 and 1979, prior to the start of the satellite record[665,679-691].

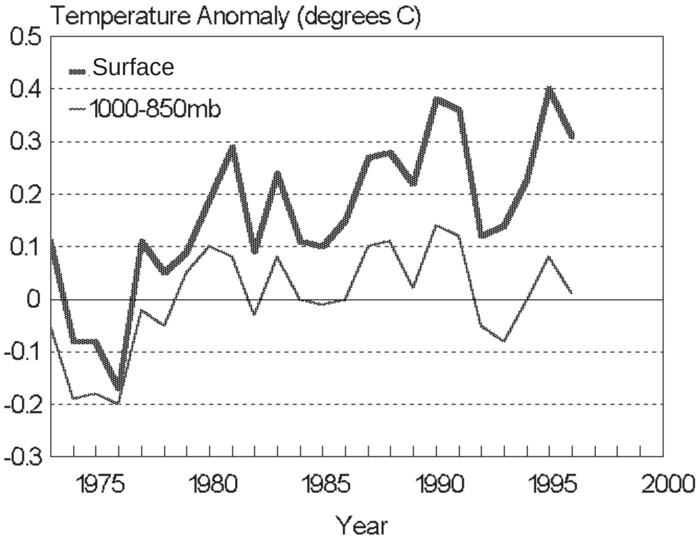

Figure 3. *Comparison of trend in global average surface temperature with that for the lower troposphere as reconstructed from NCEP reanalysis data for 1973-1996. The NCEP data shows very little warming since 1979 (the period covered by the satellite MSU data) but a significant warming trend when the preceding 6 years are added. Reference: Pielke et al. 1998 (#685).*

In the upper atmosphere, temperature data collected at the mesopause (87 km altitude) show a mid-winter cooling of 9˚C between 1990 and 1996. Within the stratosphere, temperatures have also cooled over the past three decades, primarily through two abrupt steps ~1981 and 1991[688,692-694].

Studies continue to report that most regions, including Europe, the Mediterranean, the Bahamas, Antarctica, the Southern Ocean and Northern China, have experienced significant warming over the past century. The extent of warming varies by season, with most experiencing greatest increases in minimum temperatures and in winter and/or spring. Many regions also show decreasing daily temperature range, frequently associated with an increase in low level cloudiness and hence a decline in sunshine duration. In contrast, some regions such as south-east China and Newfoundland, have experienced colder climates in recent years, perhaps due to factors such as reduced solar insolation due to pollution and long term ocean oscillations such as the NAO[695-705].

Proxy data sources support the results from instrumental records. Various recent borehole studies show a broad scale 20th century warming in North America, Europe, South Africa and Australia of about 0.5˚C, and current temperatures as much as a degree warmer than 500 years ago. Tree rings and other proxies also suggest current regional temperatures in New Zealand are the warmest in at least the past 5 centuries, and that the climate in the central Canadian Rockies are the warmest in at least the past 1000 years. Likewise, coral records in the southwest Pacific indicate a regional warming of ocean waters by 0.3˚C over the last 300 years. A compilation of 17 independent proxy records from dispersed locations in both hemispheres now show that, globally, the 20th century is the warmest of the past millennium. These records show good evidence of a global scale Little Ice Age, but not a global Medieval Warm Period[654,655,706-712].

Attribution of Temperature Trends: Coupled model simulations of long term natural variability suggest that the recent trends in rising SST values in the tropical/subtropical oceans have less than a 1% probability of occurring due to internal climate variability alone. However, when forced with a combination of estimated greenhouse gas, aerosol, volcanic and solar influences of the past century, simulated temperatures are very similar to that observed and three standard deviations above the modelled noise level. Strongest signals are associated with greenhouse gas and volcanic forcings. Similar model-based analyses using fingerprint and pattern correlation techniques also suggest the combined anthropogenic forcings of greenhouse gas plus aerosol effects may already be detectable at multi-decadal and large spatial scales, but that detection at decadal and smaller spatial scales may not be possible within the near future. Finally, plausible explanations for the lag between hemispheres in changing temperatures appear to be associated with combined solar and anthropogenic forcing, with an associated climate sensitivity of between 1.5 and 4.5˚C for a CO_2 doubling. However, large scale and long-term oscillations in the natural ocean climate are also important in temperature fluctuations on times scales of decades and longer, and may have contributed to recent interdecadal behaviour. These natural fluctuations need to be better understood to properly predict and detect future climate change[626, 713-733].

While some past studies have suggested that temperature trends over the past few centuries can also be well correlated with solar variability, new results indicate that attribution of recent trends to solar forcing alone would require climate sensitivities that may exceed physical plausibility. In fact, analyses of long term records using both observed and proxy data, some extending back 600 years, suggest solar forcing was a dominant factor until the 17th century, that volcanic events played a key role in the 18th and 19th centuries, and that greenhouse gas forcing appear to be important in the 20th. Similar results are achieved using Bayesian statistical analysis, which indicate that the solar signal in the past 100 years of climate data is barely detectable, while there is a robust relationship between temperature trends and greenhouse gas concentrations. Coral records in the southwest Pacific also show a trend towards lower δ13C values (indicative of human perturbation of the carbon cycle) coincident with rising temperatures[711,732,735-745].

As indicated, attribution of changes in regional scale climates to global forcings is not as yet realistic. However, some local climates in industrialized areas show recent cooling that appears to be clearly linked to very large regional increases in concentrations of aerosols. Likewise, some regional changes, like those in Antarctica and the Norwegian Arctic, can be at least partially explained by changes in atmospheric circulation[746-748].

In the stratosphere, cooling and changes in circulation within the stratosphere during the last few decades appears to be caused primarily by ozone depletion, although linkages to variations in the NAO could also be a factor. There is evidence that the thermosphere is shrinking, consistent with expected cooling from enhanced greenhouse gas concentrations. However, there is no clear indication of similar trends in the ionosphere[694,749-751].

Precipitation/Hydrology: The percent of global land area experiencing very dry or very wet conditions, although highly variable, appears to have increased since the late 1970s. Although this change is coincident with recent changes in behaviour of ENSO, it is also qualitatively consistent with model projections for response to enhanced greenhouse gas and aerosol forcing. At the regional scale, numerous studies show changes in rainfall and drought patterns, indicative of larger scale changes in atmospheric circulation. Some of these trends appear to be long term and generally consistent with expected responses due to warmer climates. In other regions, such as in the Saharan arid regions, continental USA and Australia, they can be linked to complex relationships with larger scale interdecadal oscillations. In South America, many of the abrupt changes in precipitation and in related river flows can be linked to SST changes. In some areas (e.g., the central Sahel), these changes are associated primarily with variations in number of rain days, rather than rain intensity, while in others (e.g., USA and Nigeria), the trends are caused by changes in rainfall intensity[699,752-771].

In the UK, average river flows during the past decade have been low and unusual, but not unprecedented. In the US Sacramento Basin, there has been a decrease in spring runoff with time, consistent with more precipitation falling as rain. However, in SE South America, flows appear to be increasing[772-774].

Humidity and mid-day dewpoints have increased over most of the USA since 1961, particularly in spring and summer. Some of these trends can be explained by more frequent occurrences of warm, moist air masses. On a global scale, stratospheric humidity also appears to have increased significantly between 1992 and 1996, with important implications for ozone chemistry. In contrast, satellite data indicate that average precipitable water within the tropical troposphere has decreased by an average 3% since 1979, with greatest decreases over oceanic subtropical high pressure and desert land areas. However, the level at which these changes have occurred, and hence the effect on radiative forcing, cannot be determined from these data. In some regions of the tropical oceans, changes in both stratocumulus and deep convective clouds, and hence in associated radiation budgets, appear to be closely linked to variations in SSTs. However, analysts caution that cloud data in many ocean regions are strongly biased by changes in observing practices and other measurement problems[775-781].

Large Scale circulation: Since 1963, a change in the Arctic Oscillation has caused the Arctic polar vortex to decrease in size and shift eastward. This is consistent with regional changes in surface temperature and pressure patterns, including surface warming over Eurasia and a cooler lower stratospheric polar vortex. Over the USA, summer and winter air mass exchange frequency has decreased since 1948, as has the winter frequency of moist tropical air masses in the North American southeast. There is also evidence of increased air mass exchange between the troposphere and stratosphere, perhaps due to an increase in tropospheric vertical diffusion caused by higher greenhouse gas concentrations[782-785].

In the Pacific Ocean, abrupt increases in ^{14}C in corals growing along the Galapagos Islands provide further indications of a sudden, systematic change in tropical Pacific Ocean circulation around 1976. Tree ring chronologies also suggest a trend in ENSO behaviour over centuries towards greater variability in winter and more frequent cold events. In the northeast Pacific, SSTs have increased and salinity decreased over the past 60 years, resulting in increased column stability, reduced mixing and regional nutrient supply to surface waters, and hence an altered fish environment. North Pacific subarctic and subtropical gyres also appear to have strengthened during the 1970s, cooling the thermocline and reducing Bering Strait ice concentrations. These changes in turn may be linked to a regional ocean climate oscillation on both decadal and much longer time scales. Enhanced east-west summer temperature gradients in the western Pacific have contributed to altered monsoon behaviour and increased extreme summer temperatures in eastern Asia over the past 40 years[733,786-794].

Analysis of tropical Atlantic SSTs suggest that north-south SST gradients induced by changes within the south Atlantic may be linked to a decadal scale oscillation that influences North Atlantic variability. Oscillations in the North Atlantic may in turn be a factor in triggering decadal scale oscillations in Arctic sea ice cover and sea level pressures. Over the western Mediterranean, temperature and salinity have increased, consistent with reduced freshwater input due to long term regional changes in atmospheric circulation[430,795-799].

Extreme Weather: Regional temperature extremes, which can be assessed using both minimum/maximum temperature records and degree day thresholds, often occur in clusters and appear to be linked to changes in large scale circulation features. For example, recent record breaking temperature extremes in the British Isles, together with similar unusual extremes in precipitation, were accompanied by a shift in seasonal rainfall patterns. In China, northern regions have experienced fewer temperature extremes in recent decades[517,767,800-802].

There does not appear to be a significant long term trend during the past century in tropical cyclone activity in either the North Atlantic or North Pacific, or in the frequency of hurricanes reaching the US Gulf coast. However, there is evidence of significant multi-decadal and inter-annual variability, with lowest North Atlantic hurricane activity in mid-century, and during El Niño years. Similarly, hurricanes off Australia appear to be less frequent during El Niño events. However, other regions can have opposite responses, suggesting possible global mechanisms that link cyclone behaviour in different regions. Both changes in vertical wind shear in the troposphere and in sea surface temperatures appear to be possible factors[518,803-808].

Extreme waves and winds in the Northeast Atlantic and in the seas off northwestern Europe experienced a decline in intensity from 1900 to 1970, but have returned to earlier intensities in recent decades. There may be linkages to NAO. These changes affect extreme tides in the region[809-815].

Assessment of American weather-related disasters suggest that increased losses for modest events appear to be primarily attributable to demographic factors, but those due to the big events (>$100 million) appear to be partly attributable to shifts in weather. Trends towards increasing ratios of heavy to light precipitation may be one factor, although events are often associated with a combination of weather factors. Likewise, a decline in deaths due to lightning strikes may be due both to declining rural populations and long term variability in thunderstorm frequency[816-822].

Snow and Sea Ice: Southern Ocean sea ice cover varies considerably with time, largely in response to ENSO type oscillations. While there is no clear evidence of net change in Southern Ocean sea ice characteristics from satellite data of the past few decades, proxy records and model studies suggest a net decrease in extent, concentration and thickness over the century. In the Arctic, sea ice has thinned dramatically in recent decades, largely due to warmer upper ocean water temperatures and an increase in inflow of saltier Atlantic waters. This has, in turn, led to a significant decrease in upper ocean salinity. Meanwhile, across much of northern Canada and Russia, winter snow accumulation has increased since the mid 1930s. However, the later decades of the 20th Century have been characterized by extensive decreases in winter and spring snow depth and snow cover over large regions of southern and western Canada[501,702,823-829].

Land Ice/Sea Level Rise: Satellite instruments, including altimeters and gravity measuring systems, can provide very accurate measurements of seasonal and interannual changes in sea levels. These indicate that only about 50% of short term fluctuations in sea levels can be attributed to changes in ocean heat fluxes and hence thermal expansion. Hence other factors must also be important[829-830].

In general, small temperate and polar glaciers around the world, including climatically sensitive glaciers in Alaska, the European Alps, Antarctica and central Asia, show varied response to changes in climate over the past several centuries, often associated with inter-decadal and longer term changes in atmospheric circulation. Most have experienced pronounced and accelerated retreats during the 20th century, primarily induced by enhanced summer season ablation, and many of these are expected to disappear within the next century. Because of their small size, these collectively have contributed less than 0.1 mm/year to global sea level rise during the past 30 years. Larger glaciers appear to be less responsive at this time[618,624,831-838].

There is evidence of increased net accumulation of snow at higher elevations of the interior East Antarctic ice sheet over the past decade, equivalent to a reduction in sea levels of about 0.4 mm/year. However, at lower altitudes, elevations of ice mass appear to be decreasing. Smaller shelves along the Antarctic Peninsula and elsewhere also appear to be retreating. The northern Larsen ice shelf, which presently appears to be in a stable pattern, could also change to rapid retreat if ice front configurations were to undergo substantial change. In contrast, the Ross Ice Shelf appears to be thickening and advancing, suggesting a stable ice front at that location. In general, the net mass balance change of the ice sheet over the past century has been small . In West Antarctica, several years of radar altimetry data show a retreat of the grounding line of one key glacier which, together with recent paleo evidence of a complete collapse of the West Antarctic Ice Sheet in the distant past (perhaps during the prolonged interglacial some 400 ky ago), suggest that the stability of this ice sheet may be less than oft assumed and in need of further careful study. Meanwhile, in western Greenland, satellite data indicate that ice sheet margins have retreated in recent years in some regions and increased in others. Summer melt, ice cover in adjacent waters, and iceberg calving rates appear to be important factors[839-853].

Other Trends: A variety of ecological variables can provide useful proxy indicators of regional changes in climate, although their interpretation can be complex. Satellite monitoring of ecological productivity through the NDVI index, for example, can provide indications of trends in degree days, annual precipitation and/or moisture characteristics for many regions. Shifts in tree lines, populations of fish, birds, insects and animals are also often associated with changes in regional climates, including snow cover and sea ice. In alpine regions, changes in high altitude plants and insects may provide early indicators of a climate shift, while diverse cold water larvae species may provide a good climate proxy in Antarctic waters. A Canadian coordinated network of ecological stations, known as EMAN, will be important in following these trends within Canada[854-859].

Some ecological trends noted recently include a recent decline in black guillemot poulations in Alaska (due to a decrease in local cod food supply) and a dramatic drop in gemfish populations off New Zealand (due to more frequent southwest winds and related changes in ocean temperatures). In the Pacific, there has been a dramatic but complex change in biotic distribution over the past several decades, including major declines in some species. The treeline in Canada currently shows infilling and a shift north, while in eastern Spain, forest loss due to wildfire has increased dramatically. Surface albedo has declined in Israel (due to irigation) and the former Soviet Union (due to reduced snow cover)[857,860-865].

6.0 Impacts and Adaptation

6.1 CO_2 and Nitrogen Fertilization

In general, ecological response to the direct effect of enhanced CO_2 concentrations results in positve gains in plant yields, but the response depends on complex, non-linear interactions between elevated CO_2 and the processes that affect the acquisition and retention of nitrogen and other nutrients within ecosystems. These can result in long term responses that are quite different from those in the near term. Systems with high nutrient fluxes are in general more responsive than those with low fluxes. For some species (such as soybean seedlings), the photosynthesis:respiration ratio increases under elevated CO_2 even if temperatures rise. On the other hand, for rice crops higher temperatures can largely offset yield gains from direct CO_2 effects. Higher CO_2 can also mitigate, although not completely avoid, the adverse effects of crop exposure to surface ozone. Various grassland communities grown under enhanced CO_2 concentrations, for example, generally show significant enhancement in biological productivity during initial exposure, but varied response in subsequent months and years. A net change in species composition usually results. Some grass species also show significant improvement in performance of subsequent generations grown from their seed. Responses can also be affected by soil acidity, resulting in poorer response of certain grasses on acidic soils, and may have important indirect effects on ecosystem organisms and on decomposition. Scots pine seedlings and young birch trees grown under elevated CO_2 also show complex responses that include both enhanced biomass/root productivity and greater respiration and soil CO_2 efflux rates. In rice paddies, the stimulation of root growth under higher CO_2 conditions also enhanced methane emissions. Better understanding of these complex processes and consequences will require comprehensive studies with a hierarchy of models and observations at scales from molecular to ecosystems[866-883].

Assessments of response of multiple plant species within a high CO_2 environment created by naturally vented CO_2 suggest little change in leaf structure due to such long term exposure, but a significantly lower stomatal conductance relative to adjacent control sites. On a larger scale, despite the significant increase in atmospheric CO_2 concentrations over the past century, there is little evidence of a major increase in carbon uptake in the tropics. Likewise, vegetation model projections for ecosystem response to combined effects of elevated CO_2, higher temperatures and increased precipitation over northeastern China suggest an increase in NPP for some of the regional ecosystems but an overall slight net decline due to significant declines in NPP for other regional ecosystems. Hence, while some species may individually respond strongly to CO_2 fertilization, there may be limits on total ecosystem response, perhaps due to accelerated carbon turnover[884-886].

Recent studies continue to show that reduction of nitrogen in tissues of plants grown under elevated CO_2 results in higher C:N ratios and appears to provide poorer food quality relative to controls. Related impacts on foraging insects and animals appear to vary with species, and may be compounded by the effects of concurrent climate change. Furthermore, plant species less desirable for consumption may have a competitive advantage, thus affecting species composition and biodiversity. Within ground litter, however, the C:N ratio appears to change very little because of a C:N balance readjustment that appears to occur during leaf senescence. Within soils, there is evidence that microbial response to enhanced CO_2 within natural, undisturbed ecosystems are constrained by soil nutrient limitations[887-894].

6.2 Methods for Improved Impact Analysis

Models used to assess the impacts of climate change on agricultural ecosystems, hydrological processes and lake ice phenology, for example, generally show improved performances with data inputs at resolutions higher than those available from current GCM outputs. While a number of techniques are available to downscale GCM model outputs to higher resolutions, each has its limitations. Statistical methods such as weather generators or correlations of local climate conditions with synoptic weather behaviour, for example, can simulate regional conditions quite well and are computationally efficient, but may have problems with estimating extremes and long-term variability. By comparison, regional climate models such as the Canadian RCM can produce simulations of climate components (e.g., the regional hydrological cycle) with comparable skill, but continues to be constrained by errors in the boundary conditions provided by the GCM within which it is nested[895-910].

Effectively addressing the challenges of climate change requires the collaboration of scientists, policy makers and the public. Integrated regional impact assessments, properly undertaken, can help achieve such collaboration. However, the analytical tools used to help in such assessments must be chosen carefully, since studies suggest that projected impacts of climate change are sensitive to the analysis technique used[911-912].

6.3 Forest Ecosystems

Because of the relatively narrow climate niches of their diverse biota, tropical forest ecosystems (including flora flourishing within their canopies) are particularly vulnerable to changes in climate and may thus be valuable early indicators of climate change. Adaptation strategies for reducing the impacts on these forests include reduction of additional stresses of direct human influence and reduced forest fragmentation[913-922].

For North American mid-latitude forests, about 40% of tree species will likely experience a significant expansion of their range or density, while another 40% will be in decline in response to a major shift northward of their climate optima under 2x CO_2 climate conditions. However, local climate conditions and management practices will be important in modifying such response. Concurrent impacts of pest outbreaks such as the spruce budworm may be significant in some regions, but are also modified by complex interactions with host conditions and predator response. Warmer climates may also have major implications for forest soil water balance within the boreal forest during the growing season (although less so in other seasons), and lead to more extreme and longer fire seasons. In central Ontario, this could cause shrinkage of the boreal forest, an increased dominance of Great Lakes forest types, and related impacts on wildlife, such as a decline in moose and caribou and an increase in white-tailed deer. Such changes would be in addition to any generated by natural processes. However, studies using transient scenarios suggest that transitional changes may be significantly different from those projected from equilibrium climate change scenarios, since changes in temperature and precipitation may not occur concurrently[911,923-930].

Such changes in natural ecosystems have important implications for the interaction of soil biota and properties, as well as for biodiversity and the development of related biodiversity conservation strategies. For example, warmer soils appear to decrease concentrations of leachate and total inorganic nitrogen in soils, although increased nitrogen uptake by vegetation masks these changes. These relationships are, however, not well understood and need to be studied in order to better assess long term vegetation response to climate change[931-938].

6.4 Polar/Alpine Ecosystems

Species populations of temperature sensitive insects and host plants within Arctic and alpine ecosystems can respond rapidly to climate change, and may be important indicators of such change. Predicted responses include a northward movement of the treeline. However, other indirect factors, such as changes in soil moisture, decreased water tables and increased nutrient supply may have a greater effect on arctic species composition or biomass than changes in temperature alone. For example, immediate phenological shifts are expected as a result of earlier snowmelt. Hence climate change can be expected to significantly change the diversity of subarctic-alpine ecosystems[14, 939-945].

6.5 Aquatic Ecosystems

Changes in the delicate balance between precipitation and evaporation will have major implications for water table levels and hence, the conditions of wetlands. This in turn affects the role of wetlands in sequestering carbon, controlling floods and as wildlife habitat. Shoreline wetland areas appear to require careful attention given their susceptibility to changing water levels and their significance for recreation. In the Great Lakes, for example, climatic changes will likely push fluctuating water levels beyond that with which some wetlands can cope. Studies in sedge fen ecosystems under warmer climates without significant changes in precipitation suggest increased summer water deficits and increased carbon loss, but decreased methane emissions. Reduced water export through wetlands may also result in short term increases in local lake acidity, in larger fluctuations of instream DOC and in reduced dissolved organic matter loads to lakes. The impact of climate change on aquatic biota may depend on their species diversity, genetic diversity and other factors, and more exotic species invasions are expected. However, many questions still remain about the nature of such responses[946-955].

6.6 Water Resources

Changes in regional hydrology will not only be affected by changes in temperature and precipitation, but also by local land surface regimes and human factors such as soil degradation and land surface change. Impacts on hydrology will not be distributed evenly. Projected regional changes include such diverse consequences as decreased runoff, groundwater recharge and water quality in southern Britain, increased river flows in northern Britain, increased flood frequency during winter for surface flow dominated streams in Belgium, and higher water temperatures in streams and lakes throughout North America. A study using transposition of climates from other regions similar to that which might occur in the Great Lakes Basin under warmer climates also suggested much larger interannual variability in precipitation than observed in existing basin climate, but only a small net change in basin water supplies[956-961].

Ice formation on American lakes under 2xCO_2 climates may be delayed by up to 40 days and ice melt could be up to 67 days earlier. Maximum ice thickness could decrease by as much as 0.44 metres. These changes would reduce fish winter kill in most shallow lakes, but may endanger snowmobiles and ice fishermen[961, 962].

6.7 Agriculture

Crop yield models such as CERES and YIELD still exhibit many weaknesses in projecting impacts of future climate change on agricultural yield, perhaps due to indirect climate impacts and other factors that are not included in the models (e.g., climate-insect interactions). Variables such as night-time temperatures appear to be particularly important. Hence, results of studies using different methodologies still show significant differences and need to be used with caution and not in isolation of each other. A general review of such studies suggests that, in developed countries, the overall impact will be small and likely positive. However, there could be large percentage changes in production at the regional and local level, particularly in poor, low-latitude countries. In addition, warming beyond that projected for 2XCO2 could have more dramatic negative effects at the global scale. Use of appropriate adaptation strategies can help to reduce these effects[963-973].

Some regional impacts of climate change on agriculture include:

- significant changes in local growing seasons and overall productivity in Africa due to the combined effects of soil degradation and climate change[957];
- enhanced summer soil moisture deficits and increased daily maximum temperatures in diverse regions such as Turkey, India and the Canadian Prairies, thus affecting crop yields. Increased evaporation would exceed any changes in precipitation[967,974-975];
- Projected increase for some crop yields, such as corn and sorghum, in Quebec, but decreases in others such as wheat and soybean[976].

6.8 Flora and Fauna

Studies into ecosystem response to climate change must consider not only the direct response of individual species, but also the changes in interaction between them. Traditional knowledge of aboriginal peoples may assist in advancing such knowledge. There is good evidence, both from observations of year-to-year response of breeding habits to changes in climate and from trends towards earlier breeding during the recent warm decades in Europe that amphibian and bird populations are very sensitive to changes in climate. Likewise, recent evidence for stressed polar bear populations in the Canadian sub-Arctic indicate that these and other Arctic species are particularly sensitive to changes in ice cover. Migrant pests are also expected to respond quickly to increased CO_2 concentrations and altered climates, and may be able to colonize newly available crops and habitats. Changes in extreme weather events such as hurricanes can also have an impact on ecosystem populations. However, the nature of the response is complicated by abiotic and biotic barriers and therefore difficult to predict.[977-983].

6.9 Extreme Weather/Circulation

The response of atmospheric circulation and extreme weather events to climate change is as yet poorly understood and needs much more research. Paleo records and comprehensive model studies may be particularly useful in such research. Based on Rossby wave concepts of climate variability, future climate change may well manifest itself predominantly as a change in the natural modes of climate system variability. Warmer climates will also, on average, increase evaporation and atmospheric moisture content, which may in turn both exacerbate drought events and favour more intense rain/snow events (and hence local flooding). In the North Atlantic, a study using the ECHAM model output suggest extra-tropical storm tracks over the region will likely be displaced northward, but shows no evidence of a significant increase in average intensity (in contrast with some other studies). Storm surges along regions of west Europe are also projected to increase in height by 10-40 cm, although this appears to be within the normal range of expected variability in most regions of the North Sea[984-990].

Several recent studies using climate model data outputs together with hurricane models suggest a small to modest increase in tropical cyclone intensity and frequency, but provide no evidence of expansion of cyclone zones. Some regions could experience dramatic changes in cyclone frequency, and in the Atlantic increases will be greater during La Nina events. This is supported by evidence that high intensity tropical cyclones appear to occur over the warmest waters and last several days longer than lower intensity events elsewhere. However, in the Pacific ocean, storm intensities are generally well below their potential based solely on SST calculations, suggesting that other environmental influences could be even more important than SSTs in determining maximum storm intensity. Since many of these factors are not as yet included in related hurricane models, projections need to be used with caution[518,991-997].

Warmer climates will cool the stratosphere, reduced the frequency of sudden stratospheric warming, and thus intensify and increase the stability of the polar vortexes. These effects are expected to cause the Antarctic ozone hole to become larger and last longer in the near future, increase the likelihood of Arctic ozone holes, and slow down the recovery of the ozone layer on a global scale. The net effect on ozone column concentrations at mid-latitudes is still uncertain, with some models suggesting an increase in concentrations and others a decrease[998-1003].

6.10 Land Ice/Sea Level Rise

The response of ice sheet dynamics to climate change is dependent on underlying geology and other local factors as well as changes in temperature and precipitation. Possible future response for the West Antarctic Ice Sheet (WAIS) could range from minimal dynamical response and slow growth to a complete collapse within the next few centuries, although both extremes seem very unlikely. More accurate predictions will require better understanding of the dynamics involved. For the larger eastern Antarctic ice sheet, changes in regional ocean temperatures and circulation patterns could increase basal melting rates of its coastal ice shelves and thus at least partially offset predictions of increased accumulations in central regions. Some studies suggest that the melting process could dominate in the long term, resulting in the contribution to sea level rise of approximately two meters over the next 1000-2000 years. However, the processes involved are also poorly understood. Meanwhile, predictions of Greenland ice sheet melt based on coupled climate model predictions of regional temperature and precipitation changes suggest a net contribution of 7.6 cm to sea level rise from this source by 2100[839,840,1004-1011].

Most temperate and alpine glaciers are expected to recede, and many to disappear by 2100 in response to continued warming, although the response will vary considerably between glaciers and with the local nature of the change in climate. One estimate, based on a coupled climate model simulation of climate change, suggests a 13 cm contribution to sea level rise from this source by 2100[618,834,1008,1012-1014].

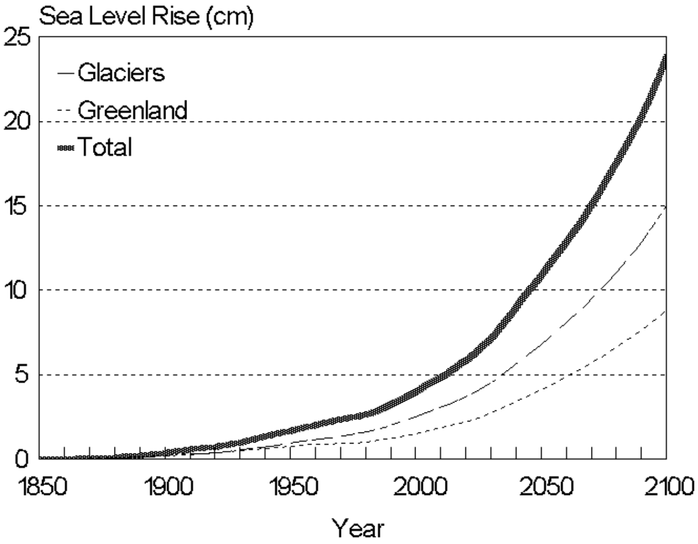

Figure 4. *Projected contribution of temperate glaciers and the Greenland ice sheet to global sea level rise, based on climate change scenarios with both greenhouse gas and aerosol forcing. Reference: Gregory and Oerlemans 1998 (#1008).*

The impacts of the above changes, together with that due to thermal expansion of sea water, on coastal tide levels, will be further modified by other factors, including changes in sea level pressure and tectonic action of land masses. About 3% of Canada's coastline is highly vulnerable to such changes, while 30% has moderate sensitivity and the remainder is relatively insensitive. With projected changes for future sea level rise, many regions now emerging out of the ocean through tectonic lift (e.g., Hudson Bay region) may once again become submerged. Other countries will be much more vulnerable. In many areas, retreat and accommodation to such change may be preferable to developing defensive barriers. Both economic and ecological consequences of possible sea level rise remain highly uncertain[1015-1017].

6.11 Economic and Health Impacts

The human cost of climate change is very difficult to estimate, both because of uncertainties in climate change projections and poor understanding of human response processes. For example, the US economic costs due to projected sea level rise alone vary from $0.2 billion to more than $4.6 billion, and net costs for all impacts could vary from 0.35 to 2.16% of GDP. Hence, estimates for costs are as yet very unreliable, and must often be provided in qualitative terms. Some regions, such as Russia, may in general benefit from warmer climates in terms of public well being because of the current difficulty in dealing with cold climates in the region today. Wealthier regions like that of western Europe, where cold extremes are of less concern, may benefit much less. In Egypt, impacts on the agricultural economy, when integrated across the sector, may be minor, and of greater benefit to consumers than producers. For Canada, largest negative impacts, even after appropriate adaptation measures are implemented, will be associated with natural ecosystems, water resources and weather extremes, and the economic sectors most affected or dependent on these. Hence most critical social and economic impacts will vary significantly by region. Studies suggest that response should focus on risk assessment and risk reduction, including the development of appropriate adaptation and opportunity programs[955,1018-1024].

Health effects may also be more serious in some regions that others, since climate is only one of a number of factors that affect health. Projected spread of tick borne diseases into Europe, for example, can be mitigated by increased innoculations because of the presence of excellent health care. In developing regions of the world, other concurrent stresses on health and a much less adequate health care system causes a much greater vulnerability to factors related to climate change, particularly subsistance populations[1025-1028].

7.0 Policy

Skeptics of global warming concerns continue to argue that scientists involved with the IPCC are biased and have inadequately considered arguments for the role of solar forcing in recent global trends. There are also those who suggest that a doubling of carbon dioxide in the atmosphere is neither likely nor harmful, that the earth has natural feedbacks that maintain a remarkably stable planetary temperature, or that the best option, in the face of high uncertainty, is to wait and see. However, others maintain that the IPCC process has evolved in a manner that seeks to tread the tightrope of being both scientifically sound and politically acceptable, and that its conclusions are sufficiently robust to already justify actions to reduce the risks of climate change[284,1029-1043].

The general public awareness of the risks of climate change in most countries is flawed at best, and not conducive to voluntary acceptance of life style changes that may be needed to reduce these risks. While effective interaction between scientists and media can help improve awareness, such interaction requires skill and caution, and can often cause further distortion of information[1044-1045].

While the Kyoto agreement provides an important first step towards reducing the risks of climate change, emissions from non-Annex I countries will continue to grow and CO_2 concentrations will likely exceed 380 ppmv by 2010 and 500 ppmv by 2050. Furthermore, each decade in delayed mitigative action will increase required subsequent rates of emission reduction by 1.5% per decade. Some argue that, given the inertia of the climate system, this argues for early action and a concerted international effort involving all countries to reduce global greenhouse gas emissions. While reducing carbon intensities of energy use may provide best options for such reductions in developed countries, population growth and improved energy efficiency are particularly important factors in developing regions. Hence optimal mitigation policies will vary by country and region, and could use joint efforts in order to engage developing countries. Mitigation policies must also address possible conflicts with competing policies dealing with other environmental or social concerns, such as ozone depletion. They also need to be based on sound, state-of-the-art science, and can draw on past lessons associated with other environmental policy developments[1046-1054].

One option for future reduction in industrial CO_2 emissions is capture from smoke stacks or as a by-product of hydrogen extraction processes, and disposal in either terrestrial reservoirs or the deep ocean. However, related costs are as yet prohibitive, and consequences of disposal are poorly understood. Biotechnical solutions have also been proposed as means for reducing greenhouse gas emissions or removing carbon dioxide from the atmosphere. Improved farm management, for example, may be an important means of reducing sectoral emissions of greenhouse gases while improving productivity. Soil conservation programs and stimulation of sedimentation rates in rice paddies could also sequester enough carbon to significantly offset the agriculture sector's greenhouse gas emissions. Likewise, forest management strategies could substantially reduce that sector's emissions of carbon dioxide or enhance carbon sinks. Conversely, failure to deal with warmer and possibly drier climates could result in a significant increase in wildfire and related emissions of carbon dioxide into the atmosphere. However, the complex relationships between carbon, nitrogen and other nutrient cycles within forests and agricultural systems must be better understood to properly assess the consequences of such strategies[1055-1069].

Adaptation to climate change needs to be an integral component of national and international strategies to reduce the risks of climate change, and is a powerful complement to mitigation options. It must be multi-focused and multi-stakeholder, relying on close collaboration between physical and social scientists to properly assess the environmental and social consequences of climate change. It will depend on technological advances, appropriate institutional arrangements, availability of financing and good information exchange, and must consider a broad range of influencing factors. The development of appropriate inverse modelling techniques to assess vulnerabilities and tolerance thresholds, and conceptual models that inter-link ecological and social processes can both help in the design of such strategies. Meanwhile, bi-lateral organizations such as the US-Canada International Joint Commission for the Great Lakes can help foster the needed cooperation. Measures to better cope with current climate and weather behaviour (including extremes) would also provide a good initial precautionary approach for reducing the uncertain risks associated with future change[1070-1083].

Acknowledgements

This review was prepared by Henry Hengeveld and Patti Edwards, science advisors on climate change with the Meteorological Service of Canada (MSC), Environment Canada. The authors wish to thank various individuals who provided useful input and comments, including Pam Kertland (Natural Resources Canada), Ross Brown, Rob Cross and Kaz Higuchi (all with the MSC).

Bibliography

Note: *Atm. Env*. = Atmospheric Environment;
BAMS = Bulletin of the American Meteorological Society;
CC = Climatic Change; *CD* = Climate Dynamics;
CR = Climate Research; *GBC* = Global Biogeochemical Cycles; *GCB* = Global Change Biology;
GPC = Global and Planetary Change; *GRL* = Geophysical Research Letters; *JGR* = Journal of Geophysical Research;

1.0 Introduction

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2.0 Changes in Atmospheric Composition

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6.0 Impacts

6.1 CO2 and Nitrogen Fertilization

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