Environment Canada / Environnement Canada

CO_2 / CLIMATE REPORT

A PERIODICAL NEWSLETTER DEVOTED TO THE REVIEW OF CLIMATE CHANGE RESEARCH

2002 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 some 285 key scientific papers and reports relevant to climate change that have appeared within the international peer-reviewed literature in 2002. As with 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 highlights. For a more comprehensive assessment of the science of climate change, readers are referred to the *Third Assessment Report* (TAR), released by the Intergovernmental Panel on Climate Change (IPCC), and to other special IPCC reports published in recent years[1-3]. Earlier issues of the *CO_2/Climate Report* can also be consulted for summaries of research papers published prior to 2002. Recent issues of these reports can be accessed on the MSC science assessment website at www.msc.ec.gc.ca/education/scienceofclimatechange.

In the interests of brevity and utility, the 2002 literature review is based on a selection of papers representative of the broad range of new contributions towards improved understanding of the science behind the climate change issue. Because of the conciseness of the review, readers should consult the relevant papers as referenced 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.

Spring 2004 Issue

Inside....

2.0 ATMOSPHERIC COMPOSITION

2.1 Carbon Dioxide

Global atmospheric concentrations of carbon dioxide (CO_2) averaged approximately 374 parts per million by volume (ppmv) in 2002. This is an increase of 2.2 ppmv (0.6%) above that for 2001. Ice core studies from Antarctica indicate that current concentrations are unprecedented in at least the past 420, 000 years and significantly higher than the 260 to 280 ppmv level apparent during the pre-industrial period of the Holocene. Holocene concentrations also experienced a 20 ppmv increase ~8000 years ago. Vegetation model studies indicate that this increase was likely due to ocean emissions, since terrestrial ecosystems seem to have been accumulating carbon and thus removing CO_2 from the atmosphere throughout the Holocene. While a recent analysis of sediments in a high altitude lake suggests that CO_2 concentrations might also have been as high as 360 ppmv about 2000 to 4500 years ago, these results are inconsistent with all other analyses, have significant uncertainties and have not been replicated in any other studies[4-6].

While emissions of carbon dioxide from the combustion of fossil fuels are the dominant source of increasing concentrations of carbon dioxide in recent decades, land use/land use changes are a second major contributor. Land use change emissions vary significantly, depend on soil characteristics, climate, the nature of the change and other factors. For example, conversion of forests or grasslands to cultivated lands can cause very large losses. Likewise, experimentation with Quebec wetlands indicate that peat harvesting can also change these ecosystems from sinks to significant sources of CO_2. However, recent satellite-based studies indicate that previous estimates of emissions from deforestation activities may have been too high. If so, land sinks required to balance the global carbon budget may be smaller than previously thought. Such terrestrial sinks can be achieved through the conversion of forests to grasslands, or croplands to forests or grasslands. Changes in US land use practices, such as increased conservation tillage, reduced summer fallow and conversions to grasslands, have already been helping to sequester some 21 million tonnes of carbon (MtC) per year during the past few decades[7-11].

The global network of observing stations used to monitor trends in atmospheric carbon dioxide concentrations also provides useful data on the regional and temporal distribution of natural CO_2 fluxes into and out of the atmosphere. A recent collaborative study, using 16 different atmospheric transport models to analyze these data, concluded that the Northern Hemisphere was a significant natural carbon sink (net removal of carbon dioxide from the atmosphere) during the mid-1990s. This carbon uptake appears to have been quite evenly distributed between continents. Within North America, temperate forests appear to have been a large sink of about 0.8 billion tonnes of carbon (GtC) per year, but the boreal regions (mostly in Canada) seem to have been a small source. Other studies indicate that the global oceans are also a net natural sink for carbon, averaging about 1.8 GtC/year during the early 1990s. More of this ocean uptake appears to occur in low latitudes, and less in mid to high latitudes, than previously estimated. This adds support for a large mid-latitude Northern Hemispheric land sink for carbon. However, at least some of the quasi-decadal variability in atmospheric CO_2 concentrations could also be due to changes in atmospheric circulation regimes. Variability in circulation should therefore also be considered in efforts to reconstruct the distribution of sources and sinks[12-14].

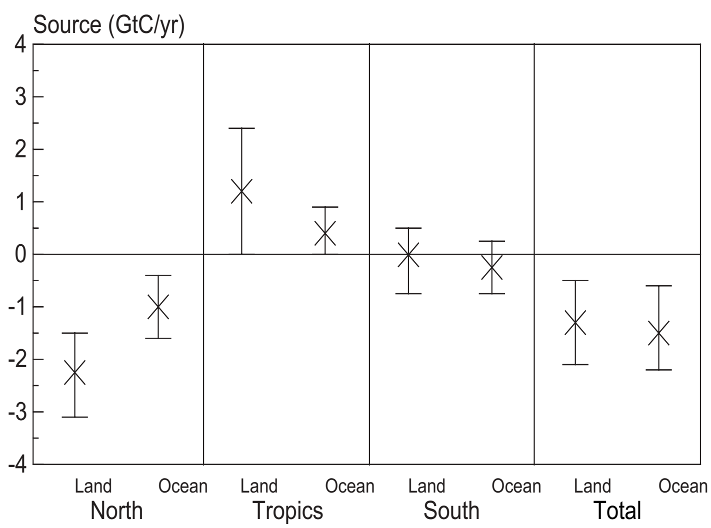

Figure 1. Inversion modelling results of Carbon sources and sinks, mean flux (x) and uncertainty range. Regional aggregation: northern land (boreal North America, temperate North America, Europe, temperate Asia, boreal Asia), tropical land (tropical America, northern Africa, tropical Asia), southern land (South America, southern Africa, Australia), northern ocean (North Pacific, Northern Ocean, North Atlantic), tropical ocean (tropical west Pacific, tropical east Pacific, tropical Atlantic, tropical Indian), southern ocean (Southern Ocean, South Atlantic, South Indian). Adapted from Gurney et al. Ref. #13.

A number of environmental factors have significant influences on the role of terrestrial ecosystems as sources and sinks of carbon dioxide. Some of these factors decrease ecological productivity and hence reduce the magnitude of sinks or enhance sources. For example, industrial SO_2 emissions have had a large impact on the productivity of forest ecosystems in Quebec downwind of a copper smelter. Likewise, in New England hardwood forests, the harmful effects of increasing concentrations of surface ozone appear to have largely offset any past growth enhancement in such forests from CO_2 and N fertilization. In Canada's southern boreal forests, multiple stressors involving insect infestations and damage due to unusually frequent freeze-thaw cycles appear to have contributed to a significant dieback in aspen during the 1990s. There are also indications that forest fire behaviour in the Canadian boreal forest is significantly influenced by variations in surface moisture conditions caused by ENSO-like fluctuations in atmospheric circulation patterns, thus contributing to multi-year variability in regional carbon fluxes[15-18].

Various studies continue to demonstrate that, in general, increased atmospheric CO_2 concentrations and enhanced nitrogen supply to ecosystems tend to enhance biological growth. For example, a closed canopy stand of sweet gum trees exposed to a three-year period of free air enhanced CO_2 concentrations experienced a net increase of 21% in net primary productivity (NPP). However, there was also evidence of an accelerated rate of carbon cycling. Likewise, grasslands exposed for an extended period of time to both enhanced CO_2 concentrations and N fertilization initially experienced a significant increase in net ecosystem carbon uptake. However, complex non-linear feedbacks cause the respiration of old carbon within the ecosystem to gradually increase until the net response eventually becomes negligible. CO_2 fertilization effects can also have other complex indirect effects that further complicate the understanding of the net influence. For example, data collected in the western Amazon indicate that a strong enhancement in the growth of woody parasitic plants like the liana in recent years is likely due to CO_2 fertilization effects. However, this enhanced growth in parasitic species appears to be increasing the risk of tree mortality, thus negatively affecting both ecosystem biodiversity and the net carbon sink capacity of Amazon ecosystems[19-21].

Another important influence on ecosystem behaviour is that of long term climate change. Several studies indicate that warmer temperatures and changing hydrological characteristics will significantly change carbon decomposition rates in peatlands, thus affecting the export of dissolved organic carbon from wetlands. Such climatic effects can add to or offset concurrent effects of enhanced CO_2 fertilization. For example, projected changes in temperature, precipitation and atmospheric CO_2 concentrations over the next century will likely result in little effect on net CO_2 exchange rates for coastal tundra ecosystems in the vicinity of Barrow, Alaska (currently a modest sink). However, methane emissions would increase significantly. Should warming become higher than projected, the region would likely become a significant source of CO_2 and methane emissions would increase even more[22-24].

Many studies have suggested warmer temperatures will significantly enhance soil respiration rates and hence carbon loss. However, studies in New England hardwood forests indicate that soils in such mid-latitude regions may experience a shortened duration of enhanced soil carbon losses when exposed to warmer climates because of the limited size of accessible carbon pool in these soils. Furthermore, increased mineral nitrogen supply caused by the warmer temperatures would help enhance growth and hence carbon uptake. This suggests that the magnitude of carbon losses from such soils may have been overestimated in related model studies, and that modellers need to properly include these complex, non-linear feedbacks and constraints in their simulations. On the other hand, recent studies in the southwest USA also suggest that invasion of woody species in grasslands may not always result in enhanced carbon uptake as often assumed. At wet sites, for example, an increase in woody species appears to decrease soil carbon content, more than offsetting gains in above ground carbon. Such results still need further investigation[25-27].

Estimates of the year to year variability in the ocean carbon sink based on observational data are significantly higher than those projected by carbon budget models. The interactive effects of storms and ocean oscillations such as NAO and ENSO, both not included in model studies, may be an important factor in this variability[28-31].

2.2 Other Greenhouse Gases

Although global atmospheric methane concentrations have been increasing throughout the 1980s and 1990s, the rate of growth began to slow and to fluctuate more from year to year in the latter part of that period. Concentrations actually declined slightly in 2000 and remained virtually unchanged at about 1790 ppmv between 2001 and 2002. Experts caution that, while these recent trends suggest that global methane fluxes may be undergoing significant changes, they may not be a good basis on which to project future trends[4, 32].

Measurements over mud volcanoes in Italy indicate that these could be another significant natural source of atmospheric methane not usually considered in related studies. Meanwhile, data collected from two hydroelectric reservoirs in boreal regions of northern Finland indicate that such reservoirs may also remain significant sources of methane and CO_2 for decades after flooding[33-34].

Natural gas hydrates represent a vast reservoir of methane that, if released through climate feedbacks, could cause a very rapid increase in atmospheric concentrations. While considered very unlikely within the next century, such processes appear to have occurred in the past and may be more likely then previously hypothesized. For example, new high resolution isotopic data from ocean sediments suggest a gradual ocean warming may have triggered an abrupt release of some 1200 GtC of methane from frozen hydrates below the ocean floor some 55 million years ago, causing sea surface temperatures to rise by 8°C within a few thousand years. Other recent studies indicate that the current base for stable hydrate reservoirs under the ocean floor may be quite rough and therefore more exposed to decay under a warming ocean than previously thought. Related experiments suggest that a significant fraction of any sudden release of methane from hydrates at the ocean floor would survive the transit to the ocean surface and be released into the atmosphere[35-39].

Global N_2O concentrations have increased by an average of 0.2%/year since 1981, and appear to be about 10% above pre-industrial concentrations as evident in ice core data for the past 1000 years. These estimates are lower than that reported in the last IPCC assessment[40].

Chemistry-transport model studies indicate that declining concentrations of the OH radical (a major element in both methane and ozone chemistry) over marine environments have largely offset rising concentrations in industrialized regions, resulting in global concentrations that have remained remarkably constant over the past century[41].

3.0 RADIATIVE FORCING

3.1 Greenhouse Gases

Future changes in atmospheric concentrations of methane and halocarbons are expected to have a relatively small impact on global radiative forcing relative to that of CO_2. However, tropospheric ozone concentrations could add more than 1 W/m^2 to the net forcing over the next century[42].

3.2 Anthropogenic Aerosol Emissions

Analyses of historical records indicate that direct and indirect global radiative forcing from increasing atmospheric concentrations of sulphates may have increased from near zero and -0.17 W/m^2 in 1850 to –0.4 W/m^2 and -1.0 W/m^2, respectively, in 1990. Other recent studies using satellite data in conjunction with coupled climate model simulations suggest similar indirect sulphate aerosol forcing values of between - 0.85 and -1.4 W/m^2. These aerosol effects are highly sensitive to regional conditions, being particularly strong and often underestimated in high moisture and low albedo areas, but much lower in the presence of cloud. Hence models with high spatial and temporal resolutions are needed to properly simulate aerosol influences on regional radiation budgets. The sensitivity of the indirect aerosol forcing to increasing concentrations has decreased as the concentrations have increased, and the geographical pattern of significant forcing has gradually shifted with time. For example, concentrations in the industrialized world have now stabilized or begun to decrease, while those in southeast Asia and adjacent regions are still increasing[43-45].

Black carbon aerosols are also a significant factor in recent changes in climate, both in terms of temperature and circulation. Recent estimates suggest a net global top-of-the atmosphere forcing to date from black carbon of as much as +0.51 to +0.8 W/m^2. Recent climate events in southeast Asia can also be best reproduced when both black and sulphate aerosol effects are considered in model simulations[46-48].

Satellite observations indicate that higher aerosol concentrations may also be increasing the presence of ice crystals in towering clouds, thus enhancing moisture flux into the stratosphere[49].

Analysis of climate data during the three day period of aircraft free skies immediately following the September 11, 2001 US terrorist attack suggest that aircraft contrails cool daytime maximum temperatures by reducing incoming solar radiation and increase night-time minimum temperatures. These processes alone may have contributed an estimated 1.1°C to the reduction in diurnal temperature range over the US during the past few decades[50].

3.3 Land Use Change

Recent studies suggest that the net direct and indirect climatic effects of all historical changes in land use could be as important in explaining observed global warming over the past two decades as the net forcing from increasing concentrations of greenhouse gases and aerosols. Furthermore, land use change may also have been a factor in recent changes in global circulation, and hence in temperature and precipitation extremes over regional land areas. This further complicates the ability to attribute recent warming to specific causes, and is an important reminder that this factor needs to be included in future climate model projections[51-52].

3.4 Natural Forcings

Solar-climate studies indicate that variations in the solar radiation reaching the Earth have affected climate on time scales from decades to billions of years, but that such climate response always appears to be amplified relative to that expected from the actual magnitude of the solar forcing. Analyses of recent sun spot-climate relationships suggest that this amplification may be more than a factor of two. This would be consistent with about one-third of global warming during the past century being attributable to solar forcing. However, over the past two decades, that forcing has been negative and hence has offset rather than contributed to recent warming. Better understanding of these feedbacks would help improve the modelling of the climate response to other radiative forcings as well[53-54].

A decrease in total solar irradiance by 1.4% and a Pinatubo-type volcanic eruption every six years would be required to offset the anthropogenic forcings projected by the SRES scenarios for the next two decades. Such natural forcings are plausible on a decadal time scale, but would be extremely unlikely to be sustainable over a century time period. This is consistent with evidence from ancient writings about historical sky conditions that suggest atmospheric loading of volcanic aerosols, averaged over long time periods, have remained relatively constant since 300 BC[55-56].

3.5 Net Radiative Forcing

Estimates are now available for the magnitude of many of the different types of human and natural forcings that have affected the global climate system over the past century. One recent study into the aggregate effects of all anthropogenic and natural changes in aerosols alone suggests a net negative global forcing of -0.23 W/m^2. However, most of the contributing forcings have large uncertainties, and others caution that their combined effects cannot be simply added[57].

From a probability perspective, experts estimate that there is a 75 to 97% likelihood that the net radiative effect of all human and natural forcings of the past century has been positive, with a median net forcing estimate of between 0.94 and 1.39 W/m^2. There remains a finite possibility of 3 to 25% that a very strong net direct and indirect aerosol effect has more than offset that due to rising greenhouse gas concentrations, thus inducing a net global cooling effect. Should this be the case, all warming of the past century would need to be due to natural climate variability rather than climate forcing. However, others note that effects from different types of aerosol forcings may be largely offsetting, and estimate that net forcing from historical changes in all anthropogenic aerosols may only be in the order of -0.39 to –0.78 W/m^2 [47, 58].

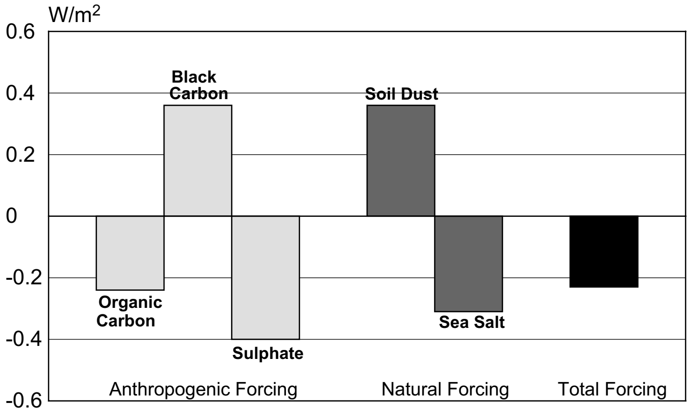

Figure 2. Annual global mean aerosol direct radiative forcing in W/m^2. Adapted from Takemura et al., ref. #57.

4.0 MODELS

4.1. Model Processes and Development

4.1.1 Atmospheric Processes

Recent model experiments simulate a strong water vapour feedback effect to radiative forcing that is relatively insensitive to the vertical resolution or cloud scheme used. These results are contrary to arguments proffered by some skeptics. Simulations of the climate response to the 1991 Mount Pinatubo eruption also suggests a 60% enhancement of the initial aerosol forcing through water vapour feedback, consistent with that projected by most model studies for an enhanced greenhouse effect. However, others caution that aerosol and greenhouse forcings are different in nature and therefore not directly comparable[59-61].

Several experts have noted that high level cloud feedback effects due to climate change may be strongly negative over the Pacific Ocean, rather than positive. However, evidence from new satellite data suggests that these arguments are based on underestimations of both the reflection of incoming solar energy and the enhanced outgoing radiation caused by anvil clouds[62-63].

Satellite data also indicates trends in incoming and outgoing components of radiative fluxes over tropical/subtropical regions (40°S to 40°N) since 1985 that are inconsistent with those expected due to an enhanced greenhouse effect. Rather, these trends appear to be related to a 24 year natural cycle in cloud cover in the region. Such long-term variability in critical elements of the climate system adds to the challenge of attributing recent trends to external forcings[64-65].

Studies indicate that physical, chemical and dynamical processes in the lower stratosphere also provide important feedbacks to climate change. Because of planetary wave activity, these feedbacks differ significantly between the Northern and Southern Hemispheres, particularly in polar regions. Failure to adequately consider these differences appear to have resulted in overestimated risks of the formation of Arctic ozone holes in the coming decades[66].

The frequency of spring-time episodes of ozone depletion in the lower troposphere of the Canadian high Arctic has increased significantly since 1966. This may be attributable to enhanced bromine release from open leads in the Arctic sea ice, and hence linked indirectly to climate change[67].

4.1.2 Land Processes

Land surface parameterization schemes used in coupled climate models still vary considerably in complexity and performance. Comparative tests of a range of these schemes over a cold Russian landscape indicated that more complex schemes generally performed better. Schemes without surface resistance to evapotranspiration performed particularly poorly. The inclusion of two way feedbacks within the schemes did not appear to improve agreement between them. The Canadian scheme, CLASS, has been enhanced to include ecosystem carbon and nitrogen flux processes, thus allowing it to respond interactively to transient changes in atmospheric CO_2 concentrations and in climate. Validation tests over boreal sites show this upgraded version of CLASS can explain 86% of carbon fluxes at an aspen site, but only 54% at a black spruce site. The poorer performance for the latter may reflect spatial variability in vegetation and soils at the site and the role of ground fluxes, neither of which are adequately addressed in the model. Experts argue that future land classification schemes should build on those that perform well now, and that modellers need to pay much more attention to the complexity of carbon flux feedbacks such as those related to spatial variability, soil respiration and nutrient cycling. Likewise, the indirect effect of vegetation response to warmer climates on surface albedo, which is particularly important in mid to high latitudes, need to be incorporated into the models[27, 68-70].

While many studies have indicated that higher CO_2 concentrations will reduce evapotranspiration loss per unit leaf area, increases in leaf area index may more than counterbalance this reduction. Hence, higher CO_2 concentrations may have little effect on global evapotranspiration[71].

4.1.3 Ocean Processes

Sea ice models that include the influence of brine rejection during freezing on ocean processes show improved simulation of thermohaline processes in the waters below. Likewise, inclusion of multi-layer thermodynamic schemes increases sensitivity of ice volume to changes in radiative forcing while adding ice dynamics reduces overall climate system sensitivity[72].

4.1.4 Model Development

The close correlation between the evolution of climate modelling and computing technologies over the past 40 years is indicative of the importance of computing power in complex modelling. However, pressure for answers to policy-relevant questions has also been an important factor. The latter has resulted in unprecedented tension between timely delivery of modelling results and the credibility of such results. This tension has been partly addressed by the use of a range of models, from very complex, advanced high resolution systems to simple schemes. The advanced systems are required to simulate the detailed complexities of atmospheric and ocean processes within the climate system, but are very expensive to operate and are in many respects unsuitable for effectively addressing regional details of climate simulations or model uncertainties. As demonstrated by recent tests with the Canadian and the Hadley Centre RCMs, regional climate models can be used to efficiently downscale outputs from global models by enhancing the regional detail included in the simulations. Earth System Models of Intermediate Complexity (EMIC) have now also emerged as a complementary tool to help explore long-term variability and uncertainty issues. These models sacrifice resolution and complexity for the ability to fully integrate a range of climate system components that are important to such long term response. More advanced EMICs now include coupled climate models at their core[73-77].

Experts agree that the diversity in coupled climate models caused by differences in parameterization schemes helps to improve understanding of climate processes. However, differences between some American models caused by diversity in computer programming and data handling techniques are not helpful, and should be reduced by standardization amongst models[78].

Recent inter-comparisons of performance of a large number of coupled climate models show encouraging results, although significant discrepancies persist. Most models continue to have difficulty with proper simulation of ENSO behaviour and related climate teleconnections, and do poorly in capturing winter cyclone behaviour in certain geographical regions such as the to lee of mountains. They also substantially underestimate cyclone and anticyclone frequencies over North America, particularly for more intense events. In general, there is good agreement between model simulations of inter-annual climate variability with observations, but considerable differences between models. There is a persistent overestimation of temperature variability in low latitudes. In the Arctic, coupled climate models generally do better at simulating cloud than do atmospheric GCMs, although not for many other aspects of regional climates outputs. This appears to be largely due to the added uncertainties linked to sea ice feedbacks, which are not included in the AGCMs. However, researchers caution that observational records are also far from perfect. Hence discrepancies between observed and simulated climates may occur due to errors in data, rather than poor model performance[79-83].

Simulations with both HadCM2 and HadCM3 models show regional trends and century scale climate variability similar to those observed, but over-predict Northern Hemisphere cold season precipitation. Control runs display some modest regional biases in temperature and generally much lower decadal scale variability than observed. The lack of flux adjustments in HadCM3 made little differences in results. Meanwhile, Canadian Middle Atmosphere Model simulations show good agreement with observed data for that region of the atmosphere[64, 84-86].

4.2 Model Simulations and Projections

In general, coupled climate models show a climate sensitivity to radiative forcing ranging between 1.7 and 4.2°C for CO_2 doubling, and an average global transient response of 1.3 to 2.3°C at the time of CO_2 doubling. For most models, inter-annual temperature variability also decreases in winter for the Northern Hemisphere extratropics and over high latitudes of the Southern Ocean, and increases in summer in low latitude land areas and in northern mid-latitudes. In general, models project an increase in precipitation, with a greater fraction of the precipitation over land areas occurring as heavy or extreme events. Most, but not all models generally project an increase in precipitation variability where mean values increase. Several simulations indicate that, by the time of CO_2 doubling, the Saharan desert will have shifted northwards by about 0.55° Lat and will have become significantly hotter and drier. Future climate patterns may also have a more pronounced El Niño like pattern. This occurs because of complex interactions between differing rates of warming of eastern and western regions of the tropical Pacific Ocean and related changes in cloud conditions, precipitation and atmospheric and oceanic circulation. Various models also suggest an enhanced positive Arctic Oscillation under warmer climates[81, 87-92].

The combined effects of natural and human forcings to date appear to have already committed the earth to another 0.5°C warming over the next 50 years. GISS studies project that additional forcing under a typical SRES scenario may add another 1.5°C or so to that by 2050. This added effect could be reduced by 50% if atmospheric concentrations of greenhouse gases were to be successfully stabilized over the next few decades. In comparison, UK model studies suggest a 90% probability that warming over the next 30 years under SRES type emission scenarios will be between 0.3°C and 1.3°C, increasing to 1.2 to 6.9°C by 2100. Arctic sea ice may disappear completely in late summer by 2100. Another Monte-Carlo type study using a simple model to undertake 25, 000 plausible future simulations estimated a 40% risk of exceeding 5.8°C warming by 2100 (the upper limit of the range of plausible global warming estimated by IPCC TAR) but only a 5% chance that it will be lower than 1.4°C (the lower limit of the IPCC range). However, others caution that such probability projections, while very useful for policy makers, may not fully capture all uncertainties[93-97].

An abrupt collapse of the global thermohaline circulation system today (in the absence of global forcing) would cool the Northern Hemisphere by about 1-2°C, cause soils to become drier and reduce Net Primary Productivity (NPP) relative to current climate. Much of the Southern Hemisphere would also cool slightly. However, some geographical regions could warm by as much as 8°C[98].

5.0 TRENDS

5.1 Past 400, 000 years

5.1.1 Glacial-interglacial cycles

Paleo studies indicate that changes in the Earth's orbit may be a key triggering mechanism for glacial-interglacial cycles. However, responsive changes in atmospheric greenhouse gas concentrations and altered surface albedos are important positive feedback mechanisms that significantly amplify the initial orbital forcing. Ice core analyses indicate that the response of this greenhouse gas feedback has been virtually coincident with changes in Antarctic climates, at least during the past four glacial-interglacial cycles. In the Northern Hemisphere, ice sheet inertia appears to have delayed climate response to orbital forcing by several millennia relative to Antarctica. Hence the processes involved in such millennial scale changes in climate are very complex, and can differ between Hemispheres. The processes involved may differ from one cycle to the next, suggesting that past events may not be good analogs for the current interglacial. Past interglacials may also have been significantly longer than the 10,000 years previously thought. Some argue that the current interglacial could, in fact, last another 50,000 years. Human factors may further dampen or even prevent the next re-glaciation, thus ushering in the 'Anthropocene' stage of Earth's climate[99-103].

5.1.2 Abrupt Climate Anomalies

Abrupt global climate anomalies during the past glacial were likely linked to large changes in the Atlantic thermohaline circulation system (THC) via atmospheric and ocean feedbacks. The changes in the THC may in turn have been triggered by relatively small alterations in land hydrological processes associated with ice sheets, particularly during periods of intermediate ice volume. Some of the abrupt anomalies occurred with regularity. Dansgaard-Oeschger events, for example, reappeared with a frequency of almost every 1500 years. These events were generally more rapid but of shorter duration during periods of high ice volume, and slower and longer during low ice volume periods. In the intermediate stage, one event may have helped trigger the next. During the Holocene climate, when land ice volume has been low, the climate has remained remarkably stable. There also appear to be linkages between abrupt climate anomalies and tropical Pacific behaviour. While most studies suggest that large changes in the THC are likely triggered by solar or other external forcing, it is also plausible that they can occur spontaneously[104-109].

5.2 Current Interglacial

5.2.1 Holocene

Although global climates appear to have been quite stable since the climate optimum of some 8000 years ago, the West Antarctic ice sheet may not yet be in equilibrium with the current interglacial climate. Hence at least part of the negative ice sheet balance in this region, and related increases in sea levels, may be due to natural millennial scale processes[110-111].

Sediment records from southern Ecuador indicate that ENSO behaviour has varied significantly over the past 12,000 years. Internal ENSO dynamics appear to generate an internal long term 2000 year oscillation in the frequency of El Niño events. However, external solar forcing may have been a factor in a general reduction in frequency over the past 1200 years[112].

5.2.2 Past Millennium

Various land, ocean and cryospheric proxy data sources can provide useful indicators of past climates. However, reconstructing climates from these data can be complex and should be undertaken with care. The use of Sr/Ca ratios in coral may, for example, be a useful indicator of temperature in some regions. However, in the cold water corals off Massachusetts these ratios appear to also be heavily influenced by the effect of algal symbionts.

Borehole data are useful in detecting long term trends in climate. A recent Canadian borehole study, for example, indicates that much of Canada experienced a lengthy period of cool temperatures during most of the past millennium, with extensive surface warming beginning in the 18th and 19th centuries. The onset of this recent warming occurred later, but was greater in magnitude in western Canada than that in the east. However, in the case of borehole data, the climate signal is a response to changes in surface energy balance rather than in temperature, and is therefore not directly comparable to temperature-based proxies. Borehole data also have greater difficulty in capturing decadal scale climate fluctuations. Hence, care must be taken to validate all reconstructions against observational records. Furthermore, since each type of proxy data has its own unique advantages and limitations, there is great value in using a composite of multiple proxies in climate reconstructions[113-117].

Tree ring proxy records suggest that the west coast of New Zealand experienced two short periods (~50 years) of regional warming during the 12th and 13th centuries similar in magnitude to that of the past few decades. Another study using a more comprehensive tree ring data analysis for 14 different locations across Northern Hemispheric mid-latitudes implies that the past millennium may, on average, have been cooler and more variable over land areas than indicated in previous studies. It also suggests that the Medieval Warm Period was a large-scale phenomenon within mid-latitude land areas that rivaled average temperatures of the 20th century. However, this analysis did not include the anomalous warming of the past few decades, nor addressed climates of the tropics, high latitudes or ocean regions. Other studies indicate that, when these are considered, the 1990s were the warmest decade and the 20th century the warmest century of the past 1200 years[118-120].

In some regions, tree rings data can also be used to reconstruct past humidity. In southern Manitoba, for example, such data indicate that large scale droughts exceeding any observed during the past century have occurred in previous centuries, and that the humidity of the past 200 years have been relatively stable relative to earlier variability[121].

5.3 Past Century

5.3.1 Climate Reconstruction Methodologies

Experts note an urgent need for a comprehensive global observation system designed for climate change and related studies to replace the existing eclectic mix of data collected for other purposes. Increasing the spatial density of observation networks can also help to better understand and relate the spatial patterns of climate variations to large scale climate fluctuations. They further caution that, because existing data are often contaminated and include significant gaps, care must be taken in addressing these deficiencies before they can be trusted for accurate trend analyses. In Canada, for example, recent work to better homogenize daily temperature records resulted in significant adjustments to mean annual maximum and minimum temperature values. There are also indications that data from automated climate stations have varying temperature and precipitation biases relative to those from nearby manned stations. For Canadian stations, these biases average about +0.2°C for temperature and can be as large as –13% for moderate to heavy precipitation observations. Hence, an overlap in observational records is essential if long-term climate stations that have become automated are to be used for trend analysis[122-125].

5.3.2 Temperature

Analysis of surface radiative temperatures derived from satellite data indicate that average global temperatures at the ground surface have increased by 0.43°C/decade since 1982, and that the daily temperature range (DTR) has decreased by 0.16°C/decade. These results are in close agreement with those for surface air temperature based on climate station data, but are significantly higher than those obtained for the lower atmosphere based on past studies of satellite-based microwave data. This difference in temperature trends is not apparent in mean trends for longer records and may therefore be linked to changes in lower atmospheric lapse rates, which decreased prior to 1979, then increased again since. There is still uncertainty as to what causes these inter-decadal lapse rate changes. The observed decrease in DTR is likely due to a global scale increase in cloud cover and related land surface processes. Investigators note that, although the changes in cloud cover may be a response to past anthropogenic forcings, models significantly underestimate the magnitude of this response. However, other researchers maintain that the recent temperature trends may be at least partially caused by factors other than greenhouse gas forcing, and that the climate system sensitivity to such forcing may therefore have been overestimated[126-129].

The spatial and temporal patterns of observed trends in regional climates are varied and complex. For example, the Antarctic Peninsula has warmed rapidly in recent decades, while other parts of Antarctica have cooled. In contrast, average Arctic air temperatures changed very little between 1950 and 1990, then warmed significantly during the past decade. Since Arctic winds also appear to have weakened, wind chill temperatures have warmed even more than real temperatures, particularly in the western Arctic. Contrary to expectations, one study suggests a lack of evidence in the Arctic data for polar amplification of global temperature changes. However, experts warn that, given the data sparseness in these complex polar regions, such conclusions need to be accepted with caution. Elsewhere, recent reports indicate that temperatures across BC have warmed by between 0.5 and 1.7°C over the past century (with greatest warming in the spring season) while those over the northeastern US have cooled in recent decades. Model studies suggest the latter may be related to enhanced advection of moisture into the region from a warmer tropical Pacific Ocean, contributing to enhanced cloud cover[130-137].

Trends in ground temperature profiles also indicate that the Earth’s continental lithosphere is heating up. The estimated additional 9.1×10^{21} joules of heat stored there during the past 50 years is comparable to that of both the atmosphere and the cryosphere, and an order of magnitude less than that for oceans. This indicates that all parts of the global climate system are warming[138].

5.3.3 Hydrological

The behaviour of the global hydrological cycle is complex and regionally variable. The combined effects of increased cloud cover and a decrease in the diurnal temperature range, for example, may have actually decreased surface evaporation in many locations, despite rising mean global temperatures. Increasing differences between surface temperatures of the Indian and western tropical Pacific Ocean regions and those for the eastern tropical Pacific may also have contributed to enhanced drought conditions over the mid-latitude land areas of the Northern Hemisphere in recent years. Meanwhile, the combined effects of severe droughts and river management have substantially increased the salinity of water in the mouth of the Mississippi River, reducing delta plant productivity and hence increasing the risk of erosion[139-141].

Within Canada, average precipitation over southern BC has increased by 2-4%/decade over the past century. Rivers and streams in the region have experienced earlier spring run-off and a consequent increase in early spring flow levels, but decreased flow during most of the rest of the year. Annual stream flows have generally increased substantially in the Yukon and the northern BC mountains but decreased in the Prairies. The western Hudson Bay drainage basin also shows enhanced streamflow in the northern sector but decreased discharges from rivers further south in central Manitoba. The Great Lakes Basin region has experienced an increase in autumn precipitation in recent decades, likely due to increased advection of warm tropical air masses into the region. Precipitation has also increased over the past three decades in eastern Canada. However, during the same period, ground water recharge in the east appears to have declined. Meanwhile, in the Northwest Territories and Nunavut, streams are experiencing earlier spring freshets, but show no evidence of a trend in streamflow volume[130, 142-146].

Paleo records for several Manitoba sites show evidence of some extremely dry years between 1670 and 1775. This is a reminder that 20th century hydrological data may not give an accurate reference basis for establishing natural risks of drought under current climate conditions[121].

5.3.4 Cryosphere

The Antarctic ice sheets appear not yet to have come into equilibrium with the Holocene climate. This complicates the ability to predict its future response to climate change. The processes for changes in ice sheet mass balance are also complex. For example, recent radar interferometry data of Antarctic ice sheet outlet glaciers indicate that positive feedbacks within glacier recession processes and changes in ocean temperatures can both contribute to an enhanced rate of melt of the underside of such glaciers. These factors may be much more important than surface ice shelf melt in determining glacier dynamics and decay. Ice shelves along the Antarctic Peninsula also appear to be degrading rapidly. Some of these changes may be unprecedented since the onset of the current interglacial some 10, 000 years ago. In Greenland, ice sheet studies indicate that percolation of melt water into the ice can lubricate flow and contribute to sudden surging. Some experts argue that such decay mechanisms could cause ice sheets and glaciers to respond to climate change much more quickly than previously thought possible. Others, however, caution that some of the apparent trends may simply reflect better observations based on satellite data as opposed to past visual reports[110, 147-150].

The processes noted above appear to be causing a slow net decline of ice volume in both the West Antarctica and Greenland ice sheets, currently adding about 0.16 mm/year and 0.13 mm/year to sea level rise, respectively. However, there is still significant uncertainty about the net balance of the East Antarctic ice sheet. Some suggest it may be very slowly accumulating ice, while other studies imply that its current inequilibrium with past long term climate change may still be resulting in a contribution of ~0.25 mm/year to global sea level rise[151-152].

A recent review of trends in several hundred glaciers around the world over the past 50 years concludes that there is no strong evidence for a net increase in the rate of glacier melting at the global scale. However, there are numerous studies that indicate significant regional changes in recent decades. Alaskan glaciers, for example, have declined in ice volume over the past 50 years, adding an estimated average 1.4 mm/decade to sea levels. This decline has accelerated since the mid-1990s, but was not included in IPCC TAR sea level rise inventories. Several glaciers in southern BC have also retreated more than 1 km since 1895. Likewise, model studies of glacier behaviour in Europe suggest that recent retreats are so significant that they have only a 4% percent chance of occurring naturally within the past 2000 years. In the Himalayas, there is evidence that some glaciers are retreating at the rate of 30-40 m/year, and that related runoff is increasing the instability of down stream lakes. There is related evidence of an increase in the frequency of sudden catastrophic floods from abrupt lake discharges over the past 30 years. Meanwhile, ice core data from glaciers on Mount Kilimanjaro, in tropical Kenya, indicate that their extent has decreased by ~80% over the past century and that they are likely to completely disappear within the next two decades. This loss would have serious implications for local communities that rely on melt waters for daily water resources[130, 153-159].

Passive microwave studies suggest that Arctic multi-year sea ice has been decreasing by almost 9%/decade since 1978. This estimate is slightly higher than that used in the IPCC TAR. Total Arctic ice extent is decreasing at a more moderate rate of 6.4%/decade. If this trend continues, Arctic Ocean ice cover in late summer will disappear by 2100. However, the observed changes may be at least partly due to natural variability. Barrow, Alaska also shows evidence of earlier snow melt, which in turn reduces mean albedo and increases regional radiative heating. In the BC interior, the ice free period of many of the BC lakes and rivers have increased by 2-6 days/decade[130, 160-163].

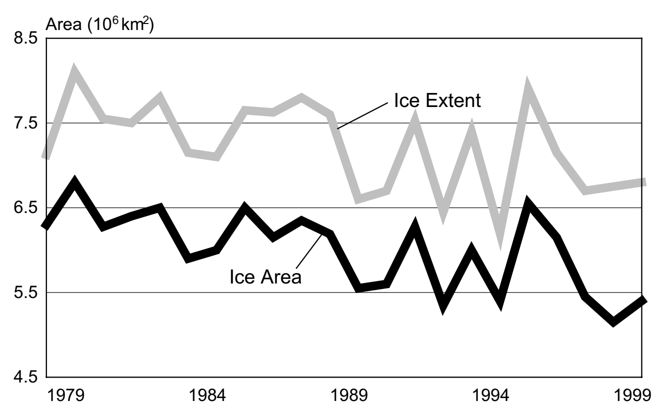

Figure 3: Trends in Arctic ice cover, 1979-2000. The top line is the annual minimum ice extent and the bottom line is minimum ice area. From Comiso, ref. #160.

Meanwhile, in northern Russia, warming climates are contributing to a rapid degradation of permafrost, with significant impacts on many communities. There is as yet no clear evidence of a similar rapid degradation of permafrost across northern Canada. Experts note the need for better international monitoring and risk assessment and the development of adaptation strategies[164-165].

5.3.5 Circulation and Variability

Observations indicate that the long term variability of large scale atmospheric circulation patterns such as the Arctic/North Atlantic Oscillations (AO/NAO) and perhaps the El Niño Southern Oscillation are important factors in the decadal scale variability of the Arctic climate. The effect of changes in these circulation patterns on the export of freshwater and sea ice into the North Atlantic may be a key linkage. However, recent warming of Arctic land areas appears to be unprecedented in at least the past 300 years. Furthermore, the recent changes in atmospheric circulation could themselves be consequences of global change. Thus it remains difficult to know how much of the recent changes in Arctic climate is due to simple natural variability verses a consequence of global climate change. There are indications that the Arctic circulation and related anomalous halocline structures may now be beginning to return to pre-1990 conditions, although it has not fully recovered[166-169].

Ice core studies on Mount Logan (Yukon) indicate a long-term regional warming and increase in precipitation consistent with a gradual intensification of both the Pacific North America pattern and the Pacific Decadal Oscillation over the past 300 years. On shorter time scales, the amplitude of the Aleutian Low in the North Pacific has almost doubled over the past 50 years, mainly due to winter deepening. This has changed the seasonality of the North Pacific climate and may have had important impacts on local ecosystems. Further south, a multi-decadal Pacific Ocean oscillation on time scales of ~50 years seems to be an important contributing factor in recent changes in upper Pacific Ocean circulation systems, both north and south of the equator. These changes, highlighted by a significant shift in behaviour ~1976-77, have resulted in decreased tropical ocean upwelling, reduced CO_2 outgassing, and an El Niño like circulation system that may have contributed to the intense El Niño events of the past few decades. The above changes in circulation may not be entirely natural, since model studies indicate that greenhouse gas forcing may also contribute to such changes. Hence, as for the Arctic, attribution of observed changes in the Pacific region to regional natural variability or radiative forcings remains difficult. If the current pattern is due to a natural oscillation, a return to the more rapid circulation pattern could be imminent. This would once again enhance the rate of CO_2 outgassing and accelerate its increase in the atmosphere, and have significant impacts on regional climates and ecosystems[170-173].

A regional change in the Antarctic Oscillation (AAO) towards a positive bias may explain many of the complexities of recent changes in various climate parameters in that region. A recent assessment suggests that as much as 90% of the cooling in interior Antarctica and half of the warming on the Peninsula may be due to this AAO bias. Changes in the stratosphere due to ozone depletion may have contributed to the positive AAO bias. Hence changes in Antarctic climate may be as much influenced by ozone depletion as by an enhanced greenhouse effect[174-175].

Paleo reconstructions of the Southwestern Asian monsoon behaviour over the past 1000 years show that the region's monsoon wind strength has also increased over the past four centuries. While it remains uncertain whether this trend was linked through teleconnections to a warming of global climates, it is consistent with projections for increased intensity of the southwest monsoon under future warming. Changes in monsoonal behaviour can have large impacts on regional societies, causing severe droughts when decreasing and severe flooding when there is too much rain[176-177].

In the North Atlantic, extreme wave heights have increased in the northeast sector in winter over the past four decades. Significant increases have also occurred off the Canadian coasts in summer and fall, but other areas and seasons have experienced decreases. These changes appear to reflect a northward displacement of dominant storm tracks due to the influence of the NAO[178-179].

5.3.6 Extremes

Analyses of trends in a variety of indicators of global extremes in temperature, precipitation and other climate variables show large multi-decadal variability that make trend analysis difficult. There is no good evidence to-date to indicate that such extremes are becoming more variable. However, there is significant evidence of trends in some extremes. For example, warm summer nights have become more frequent over the past few decades, particularly in mid-latitude and sub-tropic regions. This has contributed to a reduction in the number of frost days and in the intra-annual extreme temperature range. There has also been an increase in some regions in the extreme amount of precipitation derived from wet spells, in the number of heavy rainfall events, and/or in the frequency of drought. Most of the major river basins of the world have experienced a significant shift towards a higher frequency of extreme floods, with three-quarters of extreme events occurring since 1953. Such trends appear to be very unusual, with an estimated 1.3% probability of being entirely due to natural variability. However, they are consistent with expected responses to warmer climates. These results, however, may not apply to more modest flood events and cannot be extrapolated to smaller river basins, where most floods occur[180-183].

The frequency of spring-time low ozone concentration events in the lower 2 km of the atmosphere in the Canadian high Arctic has been increasing at 6%/decade since 1966. These appear to be linked to increased concentrations of bromine compounds arising from more open leads in the Arctic ice pack, and hence appear to be linked to climate change[67].

5.3.7 Ecological

In many respects, biological response to climate change may be easier to detect than the weak climate signal that caused the response. Hence experts note that monitoring of biological species may be a useful climate change indicator. Three separate comprehensive assessments of past research into such ecological shifts show that about 80% of changes in behaviour of some 1500 to 1700 biological species reported were consistent with that expected due to regional changes in climate. On average, these species shifted poleward by 6 km/decade and advanced their onset of spring activity by 2 to 5 days/decade. If ecological responses to future changes in climate differ significantly amongst species, this could seriously disrupt their interdependence within ecosystems and effectively tear such communities apart. These results appear now to be sufficiently convincing to allow both the biologists and economists involved to agree with high confidence that climate change is already affecting global ecosystems[184-188].

There has been a pronounced shift in the abundance of various crustacean species in the eastern North Atlantic since 1960, with warm water species becoming more abundant and cold water ones less so. A similar shift is apparent in biota on adjacent land areas, and appears to be linked to warmer ocean temperatures and NAO behaviour. In southern BC, growing degree days have increased by 5-16%, while warmer temperatures in the Fraser River have contributed to increased mortality of migrating salmon stocks. Rising ocean temperatures offshore have also altered salmon distribution and migration patterns and affected bird populations. Finally, past studies indicate that polar bear populations in the Beaufort Sea are sensitive to sea ice conditions and declined during the 1980s because of severe ice conditions. However, there is as yet little data to indicate how they have responded to recent reductions in sea ice[130, 189-190].

The influence of variations in weather circulation patterns can also affect regional moisture fluxes and hence risk of wildfire. Since 1959, for example, weather patterns variations were a major factor in the occurrence of high area burn years across Canada, particularly in the western and central regions[18].

5.3.8 Socio-Economic

Recent case studies provide reminders that extreme weather events and changes in climate can have significant impacts on regional, national and global economies. For example, warming climates in southern BC have already decreased space heating requirements by 5% over the past century, while cooling requirements have increased by 24%. In the Prairies, the 2001 drought (the third most severe in the past century) cost the Canadian economy an estimated $4-5 billion. On a larger scale, global economic losses due to natural disasters in 2002 reached a record total estimated at US$55 billion, an increase of $20 billion over the previous year. Floods and windstorms caused most of the damage, with the extensive flooding in Europe being particularly costly. Such natural disasters have helped create 25 million environmental refugees[130, 191-193].

5.3.9 Detection/Attribution

Some experts argue that the recent trends in a broad range of climate indicators such as temperature and precipitation, weather related disasters, retreating glaciers, snow cover and sea ice, thinning ice sheets, decaying Arctic permafrost, and ecological disruptions all add up to a global climate system already undergoing large and disruptive changes. However, because of the large natural variability inherent in climate and the multiple forcing factors that may be involved in these trends, attributing such change to specific causes remains a challenge. Model sensitivity studies suggest that the anthropogenic signal in these changes is likely to be most easily detected in sea surface temperatures, subsurface temperatures and salinity data in the global oceans. Regionally, the Arctic, Atlantic, North Pacific and the southern oceans offer best locations for early detection. Hence sustained monitoring in these regions should be a high priority[194-195].

A survey of detection/attribution experts indicates a general agreement that characterization of natural variability continues to be the largest cause of uncertainty in such analyses, and that such variability is generally underestimated in climate models. However, they also agree that there is a relatively high level of confidence in the ability to detect changes in global mean temperatures and in the vertical pattern of these temperatures. Furthermore, there is general consensus that greenhouse gas forcing and ozone depletion have both been important forcing factors in recent decades. This adds to the difficulty of attributing the changes in vertical temperature patterns to specific human causes. This uncertainty should diminish as the stratospheric ozone depletion role diminishes with time. Finally, contrary to arguments by critics, there is no evidence of systematic biases in attribution studies to date. In general, these studies show that the confidence in the human role in climate change over the past century is stronger than that for natural forcings[196-197].

Recent studies have added to the evidence of the human role in past changes in climate. While differing in temporal and spatial detail and in the types of models and methodologies used, all indicate that combined natural and human forcings to date explain the global surface temperature trends of the past century quite well. Similar results are achieved in analyses of the observed rise in heat storage in the upper oceans. Although positive natural radiative forcings appear to have dominated these climate trends in the first half of the century, the shift to negative natural forcings during the past 50 years results in a near zero net natural influence over the century. On the other hand, human forcings were relatively neutral during the first half of the past century but became strong in the second half. Hence these dominated over the century. That due to greenhouse gas increases was enough to warm the world by 0.9°C over the century, but was offset by cooling effects of 0.4°C from other human factors, primarily in the Northern Hemisphere. As a result, the human role over the past 50 years is easier to detect in the Southern Hemisphere, where these offsetting influences did not mask the role of greenhouse gases. The use of ensembles of simulations from multiple models also enhances the detectability of the human role, including the ability to separate signals for greenhouse gas and aerosol forcing[94, 198-202].

On a regional scale, attribution studies indicate that the rapid decline in Arctic sea ice conditions observed since 1970 is consistent with climate forcings of the past century but too large to be entirely explained on the basis of internal variability of natural forcings. On the other hand, other studies indicate that the significant increase in the fresh water flux into the deep North Atlantic Ocean over the past four decades (largely from higher latitudes and consistent with a slowdown of the thermohaline circulation system) may be linked to changes in NAO rather than warmer climates. In the tropical and subtropical regions of the world, radiative fluxes at the top of the atmosphere show a net increase in outgoing top of the atmosphere infrared flux over the past few decades. This increase in outgoing radiation is almost entirely offset by a decrease in reflection of incoming solar radiation, which is particularly pronounced over the US. This has resulted in minimal net radiative changes in these latitudes. The observed trend in outgoing longwave radiation in this region is opposite to that expected from an enhanced greenhouse effect, and may reflect the effects of natural long-term variability and of the Pinatubo volcanic eruption on regional cloud cover. If so, this should soon undergo a reversal[65, 93, 203-205].

6.0 Impacts

6.1 Methodology

In general, climate change scenarios based on ensembles of model experiments simulate observed climates with greater accuracy than do individual model simulations. Such improved performance also enhances the credibility of ensemble simulations for future climates. Downscaling techniques can also often improve on the poor performance of GCMs at the regional scale, particularly in reproducing extreme high and low temperature events. However, results still tend to underestimate the severity of these extremes. Adding white noise to the model output data could help address this bias[206-207].

Given the limited skill in model simulations, particularly at the regional level, methods need to be developed to better quantify related uncertainties. These uncertainties may be far greater than often assumed. Various approaches offer potential, including Bayesian statistics, disintegrated uncertainty analysis and systematic uncertainty analysis[208].

6.2 Hydrological resources and events

Recent ensemble simulations with the GFDL coupled climate model project that a 2.3°C global warming by 2050 will be accompanied by a 5.2% intensification of the global hydrological cycle. However, the simulations show large differences in precipitation change at the regional level, varying from increases of 20% or more for northern high latitudes and some tropical regions to a decrease in other regions. In the mid to high latitudes of the Northern Hemisphere, soil moisture is projected to increase in winter but decrease in summer. Some regions at lower latitudes become drier all year. For British Columbia, warmer climates will generally produce a wetter environment, with peak flows earlier in the year. However changes in seasonal flows will vary from basin to basin, depending on the relative contribution of rain, groundwater and snow/glacier melt to runoff[130, 209-210].

6.3 Agriculture

Warmer growing seasons are likely to benefit the growth potential of many crops in northern latitudes such as that of Canada and the northern US. For example, in the northern US states, the combined effects of warmer climates and enhanced CO_2 concentrations could increase average wheat yield in 2050 by 60-100% relative to today. Some regions further south would likely experience reduced yields. However, impacts are very sensitive to precipitation projections of the climate scenario, with dry scenarios increasing the risk of significant decreases in yield and wet scenarios reducing such risks. Early planting and other simple adaptation techniques would help reduce, but not eliminate negative effects. Other studies indicate that lack of cool days in the fall (which prepare plants for winter cold), together with reduced snow cover and increased risk of freezing rain, could also contribute to increased damage to over-wintering forage crops[211-213].

The impact of climate change on animal production will vary from region to region and will depend substantially on adaptation strategies implemented to address these impacts[214].

6.4 Natural Ecosystems

In general, warmer temperatures will cause plant species to migrate pole-ward. Recent studies indicate that such migration could result in 32% of plant species across Europe disappearing from their present locations by 2050. Direct CO_2 fertilization effects will also enhance the growth response of many species. However, other factors are also important determinants of species response to climate change and enhanced CO_2 and may result in a complex geographical pattern of response. In the polar taiga-tundra region, for example, local tree-line stability and other factors are important influences that modify the effects of warmer temperatures. In many parts of the world, the combined effects of climate change (particularly sea level rise) and other human factors will put severe pressure on the future viability of many coastal salt marsh ecosystems. Such risks are particularly high in the tropics. Meanwhile, studies of various ecosystems exposed to enhanced CO_2 show that the CO_2 fertilization response varies with time and with other environmental stresses. Free air carbon dioxide enrichment experiments with natural aspen ecosystems, for example, show that concurrent exposure to enhanced ozone concentrations largely negates the growth benefit of CO_2 enrichment. Furthermore, the combined CO_2 and ozone exposure causes a dramatic increase relative to control experiments in both rust infection on leaves and in the population of aphids. Since ozone pollution currently affects almost 30% of the world's temperate and sub-polar forests, increasing to an estimated 60% by 2100, this suggests that the CO_2 fertilization effect inherent in most global carbon budget models may be overestimated, and hence that the projected rise in CO_2 concentrations may be underestimated. Adding to this concern is evidence from grassland plot experiments that show minimal response of NPP to elevated CO_2 for the first two years of various treatment combinations, but a decline relative to non-CO_2 treatments in the third year[215-220].

Climate change will also affect the survival and productivity of insects and diseases in complex ways, adding to the environmental stresses on ecosystems noted above. For diseases, pathogen development and survival rates, disease transmission and host susceptibility will all be impacted, with the greatest impact possibly arising from a relatively small number of emergent pathogens that infect new hosts. In the forests of Ontario, warmer winters and longer summers will likely increase the duration, extent and frequency of spruce budworm outbreaks. Aspen stands in the southern Canadian boreal forest are also expected to experience increased damage from the combination of increased insect and fungal stresses and more frequent freeze-thaw cycles. Such damages will in turn affect forest health and likely cause a rise in the number of post-damage forest fires[15, 221-223].

Hibernating species such as the Canadian brown bat are expected to undergo a pronounced northward expansion in range as milder winters improve their hibernation survival rate. Some butterflies may undergo regional extinctions because of changes in precipitation, affecting their role in ecosystem biodiversity and services. In polar regions, the complex interaction of harvesting patterns and changes in regional temperatures and ice conditions could cause rapid shifts in populations of cold climate species like penguins and petrel. In Canadian Prairie lakes, changes in minimum winter temperatures may significantly alter the assemblage of species present, and hence lake biology. However, detailed projections of how various insect and animal species will respond are limited by the lack of understanding of the complex interactions of the multiple stresses of climate change and other factors[224-227].

In the ocean environment, the distribution and abundance of various aquatic species are likely to change significantly as oceans warm and circulation patterns change. For example, as temperatures in tropical regions surpass tolerance thresholds, the distributions of inter-tidal mussel species are expected to shift poleward. Interactions of low tides with maximum period of insolation could also lead to extinction of some mussel populations in certain northern locations. Likewise, paleo evidence from Alaskan lakes show a strong relationship between the spawning of sockeye salmon in these lakes and climate related shifts in the circulation regimes in the northeast Pacific[228-229].

6.5 Cryosphere and Sea Level

The projected changes in Arctic climates are expected to dramatically reduce sea ice cover and significantly degrade permafrost. Reduced ice cover will, in general, make Arctic shipping much easier, but could be a major threat for some of the important Arctic species that rely on ice for their habitat and present challenges for the people in the region who rely on these species. Reduced sea ice in the margins of the Arctic Ocean will also expose coastlines to accelerated erosion caused by an intensification of the ocean wave regimes. The low lying coastlines of the delta regions of the great Arctic rivers are particularly vulnerable. Meanwhile, the thickness of the permafrost active layer could increase by 30-40% in most permafrost regions of the Northern Hemisphere by 2100, with greatest changes in northernmost locations. This would cause significant ground settlement in most affected regions, and catastrophic slope movement in some locations. Since permafrost underlies some 25% of the Earth's land mass, many communities and other infrastructure would be significantly disrupted, particularly in ice rich regions. While much of the melting ground ice may evaporate, it will also have pronounced effects on the permeability of soils, the melting of surface ice and the seasonality of streamflows. These changes, in turn, will affect ecosystems. There is also a risk that permafrost degradation could cause the release of large amounts of methane gas from natural gas hydrates, perhaps explosively (also see section 2.2). While risks of such emissions within the next century are assumed to be small, there is little research to support this conclusion. A multi-national drilling program in the Mackenzie Delta has recently been initiated to better understand this concern. However, experts argue that a comprehensive international permafrost monitoring system is needed to provide better understanding of all consequences of permafrost degradation[161, 165, 230-233].

Because of the complexities of glacial mass balance processes, projections for the response of Antarctic ice sheets to warmer climates continue to vary considerably. A recent RCM study projected that a 2°C regional warming and reduced sea ice cover could increase local precipitation by 30%, resulting in snow accumulation on Antarctic ice sheets that significantly exceeds any offset from increased melting. Without considering the effects of ice dynamics, this could reduce global sea levels by 0.7 mm/year per degree of warming. However, other studies indicate that ice dynamics must also be considered. For example, a panel of experts has recently agreed that there is a 5% risk of a collapse of the West Antarctic Ice Sheet within 200 years (which would cause sea levels to rise by 1 m/century) and a 30% chance that rapid decay of the ice sheet would add 20 cm/decade to sea levels. Others studying the Amery Ice shelf in Antarctica have also noted that warmer temperatures combined with changes in ocean circulation could increase the rate of ice melt at the bottom of the shelf. Ice shelf break-up would in turn reduce restrictions in glacier flow and negatively affect the net mass balance of the Antarctic ice sheet[234-236].

The effect of sea level rise on coastal erosion will be complicated by other factors as well. For example, both reduced river flow in the Mississippi River due to projected increased drought and increased storminess may aggravate the direct effects of sea level rise coastal erosion in the Mississippi delta region[141].

6.6 Extremes

Model simulations continue to show that warmer climates will likely enhance heavy precipitation probability in most regions of the world, including in some of those areas that experience a decrease in average precipitation. Length of wet and dry spells both increase, suggesting serious water resource challenges for agriculture. In the mid-latitudes of the Northern Hemisphere, the longer dry spells are caused by a reduced number of rain days and drier summers. Over central and northern Europe, one in forty year winter precipitation extremes may increase to one in eight years by the time of a transient CO_2 doubling. A similar increase occurs for summer monsoonal rainfall extremes over much of southern Asia. However, such events become less frequent over the Mediterranean and northern Africa. These changes in precipitation extremes, together with changes in timing of snow melt, will have significant impacts on river flows and flood risks. In one study, six of 14 large river basins assessed are projected to experience a higher probability of floods, while two show a decrease. Recent assessments of related risks for Bangladesh, where flooding already affects 20% of the land area each year, also indicate a likely increase under warmer scenarios. In this region, poor farmers and consumers are expected to bear most of the related costs. Another study projects that, for a quadrupled CO_2 climate, some extra-tropical river basins, particularly in Russia, could see current 1 in 100 year flood events increase in frequency to once every 2 to 3 years. For Canadian rivers, the return period of such extreme floods could become once every 4 years for the Fraser River, once every 8 for the St. Lawrence and once every 11 years for the Nelson. However, most high latitude rivers will have lower severe spring flood risks because of less snow melt. For similar

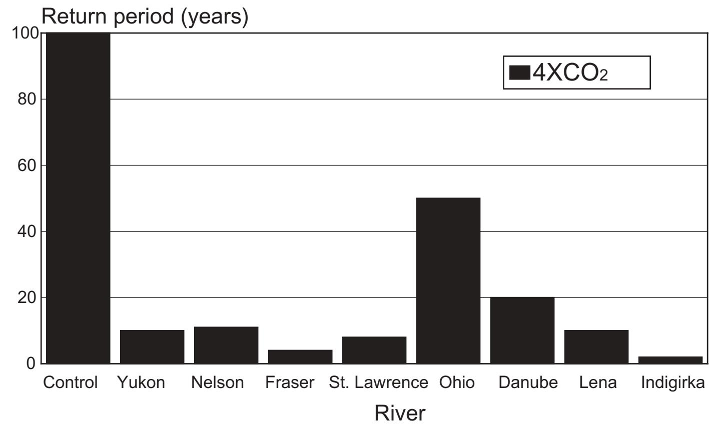

Figure 4: Return periods for the current 100 year flood for selected North American and Russian River basins under a 4X CO_2 scenario. The control bar is the current 100-year flood event. From Milly et al., ref. #181.

reasons, rivers in interior BC will likely experience decreased risks of extreme floods, in contrast to higher risks for coastal rivers. In some high-latitude rivers, changing behaviour of river ice may also play an important role. These varied factors and responses suggest the need for differentiated adaptation strategies from one river basin to the next[181, 237-241].

Projected increases in heavy precipitation events in the US could increase weather related damages to that country's agriculture crops by up to $3 billion per year by 2030. Such extreme event related losses have not been included in most agricultural impacts studies[242].

6.7 Socio-economic

The impacts of climate change are likely to increase the global number of environmental refugees from current estimates of 25 million to an estimated 150 million by 2050. Refugees will also be much more vulnerable to disease and sickness. Hence it is urgent that governments consider measures to relocate environmental as well as political refugees. Polar countries are also potentially vulnerable to the socio-economic and political consequences of an ice-free Arctic as they are generally ill-prepared to deal with these. Issues include sovereignty, fisheries management, transportation, pollution risks, and illegal operations such as smuggling[193, 243].

7.0 Policy

7.1 Science-Policy Debate

Effective communication between scientists and policy makers about the science of climate change and the related risks of danger remains a major challenge. Such communications involve not only science but also ethical issues related to future generations and to the totality of ecosystems. Within this context, questions about what can be considered dangerous human interference with the climate system (as identified in the ultimate objective of the UNFCCC) must also be included in the discussion. Recent studies suggest that a temperature rise of up to 2-3°C might be tolerable to many natural and managed ecosystems provided the rise does not occur too rapidly. However, other studies argue that even a 1°C warming will lead to large scale eradication of coral reefs. Any further delay in aggressive mitigative actions would likely preclude achieving this lower target.

Some argue that traditional knowledge of indigenous peoples could help this debate by providing local expertise and insights to complement results from conventional science. This would also help build better relationships between these communities and scientists conducting research. This is particularly relevant to northern communities. Others note that the science-policy communication challenge will likely remain until there is effective leadership to ensure that all parties collaborate towards common goals. However, there are encouraging signals that, despite the current lack of such leadership, many are awaking to their responsibilities. One factor may be the evidence that the effects of climate change on the distribution of species is already becoming increasingly apparent to the general public, and that politicians are well advised to take note[244-248].

The above communication challenge is further complicated by well publicized views of contrarians who continue to argue that the risks of climate change are overstated and that the related advice of the international science community through the IPCC is biased. While some of these skeptics frequently misinterpret the results of the science involved because of their limited knowledge of the complexities of that science, others base their arguments on the significant uncertainties still inherent in the science. They note, for instance, that IPCC assessments have largely overlooked or inadequately considered some of the human activities directly affecting the climate system, such as altered albedo due to land use change, and that the complexities of the climate system may preclude long range predictions. A declaration by American state climatologists, for example, notes that skills in predicting climates are not significant beyond that of one season, and that climate research should be focused on understanding vulnerabilities and learning to adapt to climate change and variability, rather than on climate modelling. However, there are counter arguments from experts noting that the estimates for future warming identified through the IPCC assessment process have increased, not decreased, in magnitude in recent years as knowledge improved. Further, the latest IPCC advice to policy makers may still have significantly underestimated risks of climate change because of new evidence that CO_2 fertilization effects (and hence terrestrial carbon sinks) may have been overestimated, and because of the inadequate consideration of carbon cycle-vegetation feedbacks and other environmental stresses within the climate system. Furthermore, some suggest that IPCC's failure to undertake its related analysis of policy implications within a context of alternative policies allows various advocacy groups to provide policy makers with their own value laden assessments of risks. Therefore, while the IPCC must continue its vital role in providing policy relevant science advice to the FCCC process, it should also stimulate targeted research to further reduce uncertainties and be prepared, through careful assessments, to speak to complex and contentious climate change policy issues head on[21, 249-257].

Integrated Assessment Models have helped to improve communications between scientists and policy makers when confronted with complex decision making. These tools are often used through participative assessments of alternative future scenarios that integrate future climate projections with expected changes in socio-economic variables. This both encourages social learning and helps explore alternative courses of actions that maintain future climate conditions within a tolerable range. However, most of these models do not deal well with the significant uncertainties inherent within them. Alternative model structures using pluralistic uncertainty management that systematically identifies and interprets uncertainties are now under development and may help address this weakness[258-260].

Another element in the communication challenge is the continuing debate about the appropriateness of the IPCC SRES emission scenarios as a basis for business as usual projections of future climate change. Some suggest that projections for future emissions are too pessimistic and fail to include important local air pollution factors such as black carbon. Others, however, caution that the various climate forcings differ significantly in regional impacts and that trading off effects of local air pollution with those due to long-lived greenhouse gases is over-simplistic. Adding probability estimates to various emission scenarios could help resolve this debate, and should perhaps be considered in future scenario development work[261-264].

Some researchers also contend that the international community's use of GWP values with a 100 year integration period as a basis for comparing the effectiveness in climate change risk management of reductions in one greenhouse gas versus another undervalues the effectiveness of those measures related to shorter lived gases like methane. Others, on the other hand, note that longer or shorter integration periods also pose problems. In general, experts agree that the concept is valuable because of its simplicity and transparency but that policy makers should be aware of its limitations and inaccuracies[265-267].

7.2 Mitigation

One of the oft-heard arguments against the Kyoto Protocol is that, by itself, it will have little impact on the future risks of climate change because it does not commit developing countries to take any mitigative action. Others note that, contrary to current Kyoto regulations, an equitable strategy for reducing risks of climate change must consider the long term context, and hence should focus on long term development needs of poor countries rather than just emission reductions. Alternatively, allocations

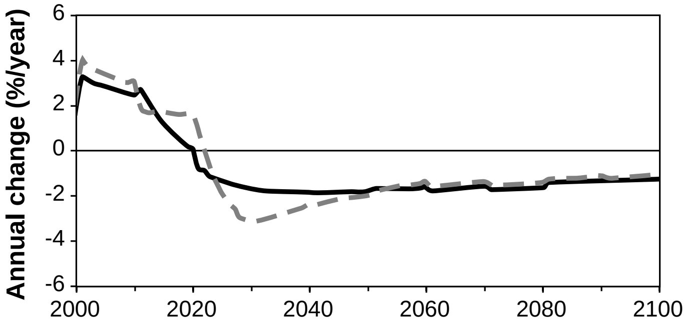

Figure 5: Annual change in CO_2 emissions, 2000-2100, leading to stabilization of atmospheric CO_2 at 450 ppm by 2100 for a scenario consistent with the Kyoto Protocol (solid line) and a scenario with a 10-year delay of implementation of the Kyoto Protocol (dashed line). Adapted from O'Neill & Oppenheimer, ref. #246.

for responsibility of individual countries to mitigative action should perhaps be based on their cumulative contribution to changes in global temperature over time, not on current emissions only. This approach is similar to the proposal recently submitted to the Conference of the Parties (CoP) of the UNFCCC by Brazil. However, there are indications that uncertainties associated with this approach (e.g., contributions related to land use change, as well as those due to non- CO_2 greenhouse gases) may be too significant to be politically acceptable. Significant spillover of Annex I country measures under the Kyoto Protocol into the energy policies of non-Annex I countries is also likely. Thus the Protocol may be far more effective in meeting the target of stabilizing greenhouse gas concentrations than many assume[268-270].

Proposed methods for mitigating the risks of climate change through emission reductions are varied and numerous. Some studies suggest that aggressive promotion of energy efficiency, fuel switching and renewable energies over the coming decades could result in stabilized CO_2 concentrations and major concurrent improvements in local air quality by 2050. If current large estimates for offsetting CO_2 sinks are sustainable for that time period, this could constrain future warming to an additional 0.75°C above current levels. In the near term, reduction of emissions of methane and black carbon and cost-effective improvements in energy efficiency may be most effective in addressing both climate change and air pollution concerns, and could buy time to introduce CO_2 emission reductions more gradually and hence at lower economic costs. However, large CO_2 emission reductions through technology change would eventually be required. Although fuel switching to hydro electric power generation, is an option, such measures also need to consider emissions from flooded reservoirs, which can be significant for shallow reservoirs. Another technological option for reducing CO_2 emissions is to capture it from emitting smokestacks and store it in liquefied form in deep saline aquifers, where it eventually dissolves within the brine solution. While there are as yet economic constraints and environmental risks associated with this potentially large carbon sink, proponents argue that these can be managed effectively through appropriate regulation and monitoring[261, 271-273].

Another controversial approach to reducing the rate of growth in atmospheric CO_2 concentrations and hence the risks of climate change is the sequestration of carbon through biological sinks. Such sinks within agricultural and managed forest landscapes have already been agreed to by the Conference of the Parties to the FCCC as legitimate offsets to greenhouse gas emission commitments under the Kyoto Protocol. However, some argue that carbon sinks claimed as offsets could effectively reduce Annex I country commitment for real greenhouse gas emission reductions from 5% below 1990 emission levels to only about 1% below, would be difficult to verify, and may not represent real incremental removal of carbon dioxide from the atmosphere. Furthermore, measures taken to achieve these sinks could result in major loss of biodiversity and primary forests. They note that efforts to reduce deforestation and harvesting of primary forests would have been a more effective, economical and environmentally friendly approach[274].

The challenge of verifying sinks is underscored by evidence of the complexity of the carbon flux response to various types of land use change measures. Integrated monitoring systems involving local land use change records, forestry inventory plots and remote sensing may be one solution. However, inhomogeniety of response is also a problem. Research indicates that, in general, forest and grassland conversion to croplands provides a significant net loss of soil carbon to the atmosphere, but forest conversion to pasturelands can result in a significant sink. Likewise, conversion of croplands to pasture or more effective management of grasslands can provide significant sinks. A shift from conventional to minimum tillage practices can both generate significant soil sinks and improve soil quality and reduce fossil fuel combustion by farm machinery. Between 1982 and 1997, changes in agricultural land management practices across the US may have already contributed to a sink of about 21 MtC/year. Further measures could add another short term sink of about 0.4 MtC/ha/year. Lengthened forest harvest rotation period and reduced harvesting intensity could also significantly enhance sinks, as could enhanced urban forest management. Although not considered under the Kyoto Protocol and often overlooked in carbon budget studies, urban forests currently sequester about 23 MtC/year across the US alone. On the other hand, increased invasion of woody species into US grasslands may actually reduce net ecosystem carbon uptake in those ecosystems. However, measures to reduce carbon loss from agricultural soils could also result in reduced transport of soil nutrients to oceans (through wind erosion) and wetlands (through water erosion), resulting in reduced biological productivity and a long term reduction in sinks in these natural eco-systems. Such complex feedbacks need to be considered in global carbon cycle studies as well as in assessing the effectiveness of carbon sinks as offsets to CO_2 emissions [8-9, 11, 25-26, 275-281].

7.3 Adaptation

Learning how to adapt to climate change requires an understanding of the who, what and why of vulnerability. This requires knowledge of culture, social structure and conditions, history and other demographic factors as well as of the physical change in climates. Adaptation research needs to be approached in two main ways. The first relates to how adaptation might reduce impacts of climate change and hence raise the level at which climate change becomes dangerous. It focuses on the physical and biological science of climate change impacts and adaptation. The second approach relates to what adaptation policies are needed, and how these should be developed, implemented and funded. It focuses on socio-economic determinants of vulnerability in a development context. In order to address both concerns, national frameworks for adaptation research must be flexible and must be designed to address various challenges, including data limitations and appropriate quality assurance of analyses. Furthermore, in order to ensure cost effective and integrated strategies, adaptation to climate change needs to be considered as an inherent element of national development, particularly for poor countries. However, these challenges vary substantially from region to region[282-284].

Case studies of how various communities have adapted to risks of climate variability in the past provide valuable lessons from adaptation to climate change. Among other things, they emphasize the importance of demographic factors, which vary from case to case, and suggest that human ingenuity may be a key element in spontaneous adaptation. This is illustrated in a case study of a small community in the southwest US, where changes over time from an agrarian/industrial economic base to a community focused on tourism and retirement living increased tolerance to climate variability. Likewise, analyses of trends in weather related mortality between 1964 and 1994 in six US cities show little change in rates for three southern stations but a decline in the three north-eastern cities. The latter appears to be due to adaptation to weather stresses through better health care, air-conditioning and other socio-economic factors. Assessment of flood vulnerability in two southern Ontario communities indicates that recent infrastructure development has been kept away from established flood plains through local regulations. However, improvements to pre-regulation homes within these floodplains, new development at their margins, and discontinuation of government flood programs suggest there continues to be significant vulnerability to increased risks under warmer climates[285-287].

Meanwhile, adaptation strategies to cope with the combined effects of sea level rise and human factors on the viability of many coastal salt marshes around the world (particularly in the tropics) will necessitate important value assessments and management decisions with respect to both social and ecological perspectives[215].

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Abbreviations for references: *BAMS = Bulletin of the American Meteorological Society*; *CC = Climatic Change*; *GBC = Global Biogeochemical Cycles*; *GCB = Global Change Biology*; *GRL = Geophysical Research Letters*; *JGR = Journal of Geophysical Research*; *PNAS = Proceedings of the National Academy of Sciences*

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