CO_2/Climate Report

A Periodical Newsletter Devoted to the Review of Climate Change Research

2003-2005 Science Review
A Synthesis of New Research Developments

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1.0 INTRODUCTION

As part of an ongoing literature review and assessment process within the Atmospheric Science Assessment and Integration Division (ASAI) of Environment Canada's Science and Technology Branch, this issue of CO_2/Climate Report provides a synthesis of more than 675 key scientific papers and reports relevant to climate change that have appeared within the international peer-reviewed literature during 2003 through to 2005. As with past reviews, this synthesis is not intended to be a full assessment of the state of scientific knowledge on climate change. Rather, it is a brief summary of recent, incremental research highlights. For a more comprehensive assessment of the science of climate change, readers are referred to the Arctic Climate Impact Assessment (ACIA) prepared by the Arctic Monitoring and Assessment Programme, the Third Assessment Report (TAR) released by the Intergovernmental Panel on Climate Change (IPCC), and to other special IPCC reports published in recent years[1-5]. Another useful Canada-focused report is Climate Change Impacts and Adaptation – A Canadian Perspective[6]. Finally, earlier issues of the CO_2/Climate Report can be consulted for summaries of research papers published prior to 2003. Recent issues of these reports can be accessed on the ASAI science assessment website at www.msc.ec.gc.ca/education/scienceofclimatechange.

In the interests of brevity and utility, the 2003-5 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.

2.0 ATMOSPHERIC COMPOSITION

2.1 Carbon Dioxide

Antarctica ice core data indicate that variations in carbon dioxide (CO_2) concentrations during the past 650,000 years are highly correlated with changes in temperatures, varying between minima of ~200 parts per million (ppm) during cold glacial periods and maxima of 280 to 300 ppm during interglacials. Through most of the record, there is evidence of a slight lag in CO_2 changes relative to that of temperature of about one millennium, suggesting that CO_2 acts as a feedback mechanism. A notable exception appears to be the deglaciation that took place some 430,000 years ago, when CO_2 changes lagged temperature changes by four to five millennia. While CO_2 concentrations have been relatively stable during the Holocene, varying between 260 and 280 ppmv, there are indications that they have never reached a steady state during this time[7-10].

By comparison, atmospheric concentrations of CO_2 averaged approximately 379 ppmv in 2005. This is an increase of 6.4 ppmv (1.7%) above that for 2002, a rate unprecedented in more than 40 years of measurements. Recent increases in emissions from Siberian forest fires may be a factor. More importantly, current concentrations appear to be about 27% higher than the highest values detected in the new 650,000 year Antarctic ice records[10-12].

Prior to the industrial revolution, land use change was likely the primary human source of greenhouse gas emissions. Some suggest that land clearing and rice cultivation by expanding human settlements in Europe and Asia already began to alter the atmospheric composition of greenhouse gases as far back as 6000 BC - thus marking the onset of the 'Anthropocene era' of Earth's climate history. Progressive land use change over the subsequent millennia may have warmed the atmosphere by as much as 0.8°C. Conversely, reduction in agricultural activities during the Little Ice Age (400 years ago) may have helped temporarily reduce atmospheric concentrations of carbon dioxide and thus enhanced the global cooling taking place at the time. Estimates for recent emissions from land use change, using revised data on tropical deforestation, suggest a net annual release of 1.1 ±0.3 GtC/year. This value is significantly lower and less uncertain than past IPCC estimates of between 0.6 and 2.5 GtC/year[13-18].

However, emissions of carbon dioxide from the combustion of fossil fuels are currently the dominant source of increasing concentrations of carbon dioxide. These have increased dramatically from less than 2 billion tonnes of carbon dioxide ($GtCO_2$) - or about 0.5 billion tonnes of carbon (GtC) - in 1900 to more than 25 $GtCO_2$ in 2002. Despite the long history of human emissions of greenhouse gases, estimates indicate that emissions during the past 50 years account for about two thirds of the accumulated total[19-20].

Peat harvesting is also a modest source of CO_2. In Canada, the process of extraction, delivery and final

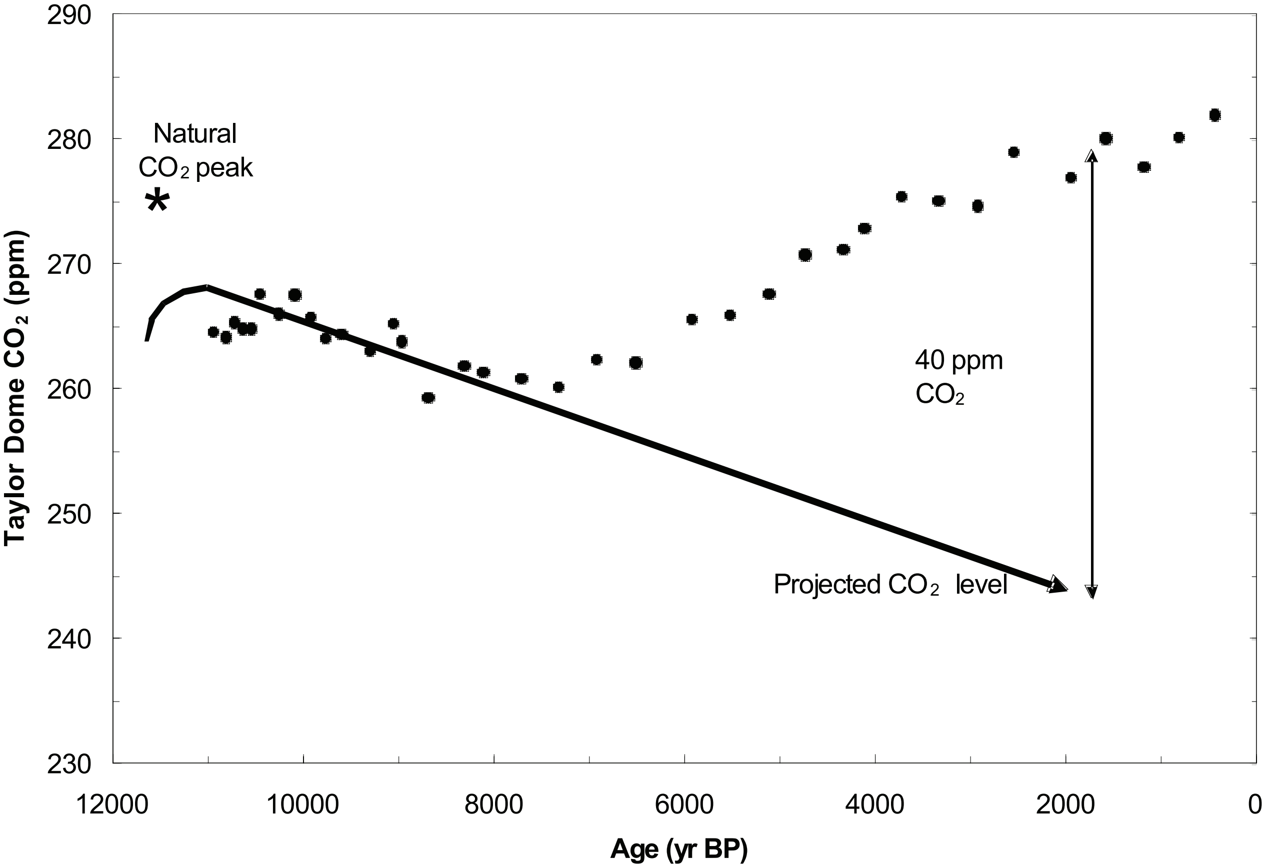


Figure 1: CO_2 concentrations reconstructed from Antarctic ice core data, compared with Holocene CO_2 trend projected toward values reached during previous inter-glaciations. The departure of the ice core CO_2 record from the projected trend about 8000 ybp may mark the onset of influences due to human land use change (Ruddiman 2003, reference #18).

decomposition at end use released about 0.9 MtC in 2000. This is less than 1% of all Canadian emissions due to human activities. However, it would take about two millennia to restore the carbon through wetland processes[21].

The global network of observing stations used to monitor global 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. Related analyses need to take into account the influence of interannual changes in atmospheric circulation caused by oscillations such as the North Atlantic Oscillation (NAO) and the Pacific-North American (PNA) pattern on the horizontal transport[22].

Satellite observations indicate that global net primary productivity (NPP) of land ecosystems has increased by 6% since 1982, adding 3.4 GtC per year to the land carbon storage. A major part of this increase has occurred in the tropics, particularly in the Amazon region. Changes in climate, including reduced cloud cover over the tropics, have been a primary factor. When model based estimates of offsetting respiration are added, the global net ecosystem productivity (NEP) between 1982 and 1998 shows very large variations from one year to the next, ranging from a significant source of 0.6 GtC/yr to a large sink of 2.1 GtC/yr. Furthermore, despite the large regional growth in NPP, the tropical regions are not, on average, a significant net sink for carbon. However, they are the primary cause for the observed inter-annual variability in global NEP. In contrast, North American regions have consistently removed an average 0.2 to 0.3 GtC/year from the atmosphere. A new carbon inventory of temperate and boreal forest carbon in the Northern Hemisphere supports this conclusion, suggesting that, during the 1990s, these forests stored about 0.9 GtC/year into standing biomass alone. This amount is about double that for the 1980s, and enough to account for about half of the estimated sink for atmospheric carbon dioxide within global land ecosystems (also known as the 'missing carbon'). Although there is debate about the true magnitude of the European ecosystem sink, some studies suggest it could be as high as 0.3 to 0.55 GtC/year[23-26].

A number of environmental factors have significant influences on the role of terrestrial ecosystems as sources and sinks of carbon dioxide. Some decrease ecological productivity or increase carbon loss through respiration and combustion, and hence reduce the magnitude of sinks or enhance sources. For example, about two-thirds of the large increase in atmospheric CO_2 concentrations observed during the intense 1997-98 El Niño event was likely due to increased wild fire caused by drought[27].

In the future, the combined effects of higher CO_2 concentrations, warmer temperatures and changing hydrological characteristics are expected to significantly change regional ecological processes and hence carbon dynamics. Such climatic effects can add to or offset concurrent effects of enhanced CO_2 fertilization. For example, higher NPP in peatlands caused by elevated CO_2 concentrations may result in significant increases in export of dissolved organic carbon from aquatic ecosystems, some of which may become converted to gaseous CO_2 and escape into the atmosphere. In the Alaskan tundra, the positive CO_2 and N fertilization effects on NPP may be more than offset by increased carbon loss from deeper soils. Furthermore, in more polluted regions, rising concentrations of tropospheric ozone may reduce plant productivity and hence offset some of the potential gains provided by CO_2 enrichment[28-32].

Experiments with coupled climate - dynamic vegetation - carbon cycle models indicate that such ecological feedbacks may gradually slow down the net terrestrial uptake of atmospheric CO_2. In fact, land ecosystems could become a net source of atmospheric CO_2 by 2100. Although oceans appear likely to remain a large sink for atmospheric carbon, if the magnitude of land sources becomes large, they could more than offset the ocean sink by 2100. Simulation results to-date suggest that the net effects on atmospheric CO_2 concentrations by that time could vary from a modest increase of 90 ppmv to as much as to 680 ppmv rise relative to that expected without considering these feedbacks. This large range in the projected intensity of ecological feedbacks adds to the uncertainties in climate response to external forcings[12,33-36].

Several recent assessments of current ocean carbon sinks, using observational data, indicate average annual sink magnitudes of approximately 1.6 GtC/year during the 1980s, increasing to about 2 GtC/year during the 1990s. Results suggest a greater uptake in tropical regions relative to higher latitudes than previously estimated in ocean model simulations. Experts suggest that, given the poor performance of such models against current data, their projections for future ocean carbon uptake should still be used with caution[37-39].

There are also concerns that increasing atmospheric CO_2 concentrations will cause a gradual rise in ocean surface acidity as it is absorbed at the ocean surface. Ocean surface pH has already decreased by 0.1 during the past century and could drop by a further 0.7 within the next three centuries. This drop in pH could significantly impact biological activity, particularly species with calcium shells or skeletons, and reduce the ability of oceans to absorb excess atmospheric CO_2. Although perhaps unrelated, ocean productivity has decreased by about 6% in recent decades[40-42].

2.2 Other Greenhouse Gases

Antarctic ice core data indicate that atmospheric methane (CH_4) concentrations have varied during the past 650,000 years between minimum values during glacial periods of ~400 parts per billion (ppb) to maximum values of about 770 ppb during interglacial climate stages. While methane concentration changes appear to follow those of temperature very closely during most of the glacial-interglacial cycles, there was an unusual lag of response during the deglaciation of 430,000 years ago, similar to that observed for CO_2. The cause of this lag is not well understood[9,43].

Some have hypothesized that human contributions to the global methane budget may have already started with the onset of rice production in Eurasia about 3 millennia ago. However, given the poor understanding of natural contributions to methane production variability, it is as yet difficult to identify the possible onset of such human contributions from ice core records[18,44].

For the past few decades, atmospheric methane concentrations have been measured at a global network of monitoring stations that span from Alert in the far north to the South Pole. Analyses of these data show that growth rates in atmospheric methane concentrations were large (between about 10 and 15 ppb per year) throughout the 1980s, but slowed down and became more variable during the 1990s. These changes in growth rates may be due to a decline and large fluctuations in emissions from natural wetlands and other biological sources during the past decade. Isotopic analysis of observed data, for example, suggest that a brief return to a large increase in concentrations between 1998 and 1999 was caused by an unusually high flux from wetlands, particularly in the tropics, and from excessive biomass burning during that year. Concentrations remained relatively constant between 1999 and 2002, than increased again by about 5 ppb in 2003. By 2004, concentrations at Canada's primary methane observing site at Alert (Nunavut) averaged about 1850 ppb. It remains uncertain whether the recent trends are indicative of a new methane budget steady state or a temporary respite in its upward trend[11,45-47].

One of the reasons for declining wetland emissions of methane may be acidification due to sulphate deposition in polluted regions of the Northern Hemisphere. Acidification can inhibit the microbial processes that produce methane from wetlands. Model studies suggest that acidification may already have reduced global methane production from wetlands by 8%, and could further reduce it by 15% by 2030. However, the combined effects of sulphate emission reductions and climate change could reverse this trend beyond 2030. In fact, climate model-wetland studies suggest that, by the time of CO_2 doubling, the latter could generate an average annual increase in hemispheric wetland production of methane of almost 80%, with largest increases in high latitude summer seasons. Such feedbacks are as yet difficult to project with confidence and are not included in global climate models at this time[48-50].

Biological processes within lakes may also contribute about 10% of natural methane emissions. Thus the creation of reservoirs for hydro-electric energy production may add significantly to global methane emissions, particularly if such reservoirs are shallow. In some Arctic regions, decaying permafrost may also increase the area of wetlands across the Arctic and thus add to the natural emissions of methane from these regions. The processes involved, however, are complex and variable. Another secondary natural source of methane may be mud volcanoes. At a global scale, these may release about 2-3% of the total methane budget, increasing to 5% during eruption periods[51-54].

While most methane is removed from the atmosphere through chemical reactions with the OH radical within the atmosphere, about 10% is removed through absorption within terrestrial soils. Such removal may be most significant in regions where soils are undisturbed and not significantly affected by nitrogen deposition[55].

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. Such an event may have been a factor in the abrupt warming that marked the onset of the Eocene some 55 million years before present (Mybp). Possible mechanisms for such sudden release of hydrate-derived methane include hydrothermal volcanic vents and the eruption of methane rich pore water from the ocean floor following disturbances such as landslides[56-57].

New Antarctic ice core data indicate that global nitrous oxide (N_2O) concentrations have also varied in close correlation with temperature changes during glacial-interglacial cycles of the past 650,000 years. Highest values of almost 280 ppb occurred during interglacial periods. Current concentrations are now about 320 ppb[11,43].

3.0 RADIATIVE FORCING

Most climate modeling studies use the effect on equilibrium temperature response at the Earth's surface of changes in net global radiative balance at the top of the atmosphere (TOA) as a 'climate sensitivity' metric for comparing the relative effects of different types of external climate forcings on the Earth's surface climate. However, this metric fails to allow for the differing altitudinal, seasonal and latitudinal effects and feedbacks of alternative forcings. Changes in TOA energy balance due to increased ozone concentrations in the upper troposphere, for example, have a significantly lower impact on surface temperatures than an equivalent change in TOA radiation from an increase in CO_2 concentrations. Likewise, models tend to underestimate the forcing effect of aerosols. Hence, some argue for an adjusted TOA forcing index or alternative methodologies that allow for these differences in climate sensitivity[58-60.]

3.1 Greenhouse Gases

Recent studies into changes in TOA radiation balance due to historical increases in tropospheric ozone suggest a net increase of +0.49 W/m^2, and a related warming of average global surface temperatures of almost 0.3°C. However, the forcing and hence warming varies significantly from region to region and with season. Some areas of Eurasia and North America, for example, are estimated to have experienced a related warming in summer of as much as 0.8°C. Future changes in ozone forcing may increase net TOA radiation by up to another 0.5 W/m^2 by 2100, further adding to greenhouse forcing from well mixed gases. This may be further amplified by positive ozone abundance feedbacks due to colder stratospheric temperatures and increased exchange flux of ozone across the tropopause[61-63].

It appears unlikely that aircraft emissions of ozone precursors such as NO_x at upper tropospheric levels will have a significant climate impact. That is because any local increase in ozone caused by these emissions is also likely to result in increased concentrations of the OH radical and hence induce concurrent decreases in methane concentrations[64].

3.2 Anthropogenic Aerosol

Results of climate model studies into the direct and indirect radiative forcing of current anthropogenic emissions of sulphate and other aerosols continue to show considerable uncertainty. Some suggest that indirect forcings of sulphate aerosols alone could have offset greenhouse gas induced warming over the past century by -0.5°C. Others suggest net direct and indirect effects of all aerosols could have offset warming by as much as -1.3°C. This uncertainty is, in part, due to inadequate allowance for reduced humidity above clouds, cloud and precipitation feedbacks, the role of high level ice clouds and the effect of black carbon (soot) aerosols. More recent studies that have attempted to include some of these factors suggest indirect aerosol forcing on the order of -1 W/m^2, which is significantly lower and much closer to that observed (between -0.6 and -1.2 W/m^2) than results from earlier studies using simpler schemes[65-71].

The role of rising concentrations of black carbon (soot) aerosols in the above radiative forcing appears to be particularly complex. For example, black carbon may often coat other aerosols that reflect sunlight, thus making the positive forcing role of soot significantly greater than implied by past assumptions of simple aerosol mixing. However, if the soot is injected into the atmosphere by aircraft traveling at high altitudes, its net effect could be negative. Some of the changes in hydrology and atmospheric dynamics caused by increased black carbon aerosol concentrations may also be offsetting. Finally, when sooty aerosols are eventually deposited on the Earth's surface through gravity, they can also significantly reduce the reflection of sunlight by high albedo surfaces such as that of snow and ice. These surface effects, enhanced by snow and ice melt feedbacks, may already have caused a positive net forcing over the Northern Hemisphere to date of 0.3 W/m^2, with some very polluted areas experiencing regional forcing of up to 1 W/m^2. Hence, while their net global effect may actually be quite small, sooty aerosols do have important regional climate impacts[72-76].

While studies may disagree on the net magnitude of total aerosol forcing, they agree that these effects are highly variable in space and time, both because of regional differences in the type and magnitude of emissions and the changing feedback processes from one season and/or one region to the next. Over the Arctic Ocean, for example, the combined direct and indirect effects of aerosols can have a modest average net warming effect (in contrast to strong cooling influences at lower latitudes). This annual mean is a result of a strong warming effect in the region in winter, offset by a net cooling effect in summer. Likewise, large local emissions of aerosols from recent biomass burning in Southeast Asia may have had a significant positive regional impact on radiative forcing, particularly over cloud-covered areas. On a global scale, these regional and seasonal differences, in turn, have large influences on atmospheric circulation (including a southward shift in the Inter-tropical Convergence Zone (ITCZ) and hence on cloud and precipitation patterns[66,77-78].

Some studies continue to imply that increasing upper tropospheric aerosol emissions from air traffic may have significantly impacted on regional cirrus cloud properties and hence net radiative balance. However, general circulation model simulations indicate that surface climate response to changes in the TOA (top of atmosphere) radiation due to jet contrails may be significantly less than that due to a similar CO_2 TOA forcing. Furthermore, the net effect on surface temperatures will be significantly mitigated by the effects of climate system inertia[79-80].

Future projections for aerosol emissions presented in the IPCC Special Report on Emission Scenarios (SRES) indicate that there will likely be little additional global masking of the effect of rising greenhouse gas concentrations during the next century. This is largely because of air pollution control measures being implemented, particularly in developed regions of the world. However, because emissions in some developing country regions are expected to continue to increase, the regional distribution of future aerosol forcing is expected to change significantly[81-82].

3.3 Land Use Change

The net global forcing caused by changing global vegetation cover due to human activities over the past few centuries remains uncertain, with estimates ranging from modestly negative to modestly positive. However, such changes have been one of the dominant historical factors in regional climate change. For example, land use change likely had a cooling influence in northern mid-latitudes. In the Amazon, it appears to have caused a significant reduction in regional precipitation, particularly during the rainy seasons. Were all global forests to be replaced by grasslands, global climates could immediately cool by 1.1°C, increasing to more than a 2°C cooling once slow vegetation and ocean system feedbacks are fully realized. Changes in both surface albedo and moisture and latent heat fluxes are important factors. Plausible changes in vegetation cover to 2100, based on SRES projections, indicate possible related localized warming due to these effects of up to 4°C. Hence, some argue that climate model simulations for both historical and future changes in climate, particularly at the regional level, should also include land use change as an anthropogenic forcing factor[83-88].

3.4 Natural Forcings

Reconstructions of solar activity during the Holocene (the current interglacial) using tree ring and ice core data indicate that periodic changes in solar irradiation have been an important factor in the variability of global climate throughout this period. The level of solar magnetic activity during the past 70 years has been comparatively high, with only 10% of the entire Holocene record showing similar activity levels. Hence, solar forcing has likely been a significant factor in warming trends of the past few centuries. Although Danish experts had in the past suggested a close relationship between solar cycle length and northern hemispheric land temperatures throughout the past half-century, recent corrections of errors in their analysis suggest otherwise. While cycle lengths have, on average, not changed significantly, temperatures have increased rapidly. New estimates of incoming solar radiation at the top of the atmosphere derived from satellite-based measurements also suggest that solar irradiance has increased over the past 23 years. While the magnitude of this increase is controversial and its long term persistence uncertain, it does suggest that it may have added to the strong positive radiative forcing of greenhouse gases during the past few decades. However, experts generally agree that solar forcing is unlikely to have been a dominant factor in climate changes of the past half-century. Furthermore, the mean loading of aerosols from volcanic eruptions in the stratosphere has been increasing during the past half-century, causing an estimated cooling effect exceeding any positive forcing from recent increases in solar irradiance. Hence the net solar-volcanic forcing during the past 50 years is estimated to be negative[88a-94].

Past analyses of surface radiation network and satellite data have indicated that the total solar radiation reaching the earth's surface decreased between 1983 and 1990. This decrease was part of a trend referred to as 'global dimming'. However, new studies using updated data show that this trend has changed in recent years. Although levels have not yet returned to 1960 levels, the net incoming surface global radiation has increased over the total 1983-2001 period by +0.16 W/m^2. This reversal in trend appears to be related more to increased atmospheric transparency related to air pollution control measures taken in many regions of the world, rather than to enhanced solar insolation at the TOA. This is also consistent with new satellite measurements of planetary albedo, which indicate a small decline in net albedo between 2000 and 2004[95-99].

3.5 Net Radiative Forcing

Model simulations driven by the historical net forcing from the combined effects of changes in GHG and aerosol concentrations, solar insolation, land use and snow albedo suggest that the Earth is currently absorbing 0.85 W/m^2 more energy than it is radiating back to space. Much of this excess energy is being stored in the ocean, as indicated by ground based and satellite measurements of rising ocean heat content over the past 10 years. Hence, because of this ocean heat sink, the full impact of the radiative energy imbalance will not be realized as changes in temperature at the Earth's surface for many decades. This lag buys time to prepare for and mitigate the full impacts. However, the longer such mitigative action is delayed, the larger the ultimate change that will occur and the greater the risk of irreversibility[73,100].

Greenhouse gas and aerosol emissions from both the Organisation for Economic Co-operation and Development (OECD) and Asian countries played dominant roles in this increase in net radiative forcing until 1980. However, OECD programs for acid rain reductions have removed much of the masking effect of sulphate aerosols since then, in contrast to that over Asia. Hence, by 2000, the OECD role dominated over that of Asia[101].

4.0 MODELS

4.1. Model Processes and Development

4.1.1 Atmospheric Processes

Accurate representation of the role of aerosols and water vapour/cloud feedbacks within the climate system continues to be a major challenge to climate system modellers. However, there is ongoing progress in resolving some of the uncertainties. For example, observational data of east-west temperature and humidity gradients across Europe in recent decades are consistent with a strong positive water vapour feedback. Likewise, both satellite observations and simple model studies indicate that absolute humidity in the upper troposphere (where the water vapour feedback is particularly important) increases by about 9 ppm per degree of warming. However, this is not enough to maintain constant relative humidity. Hence, while these results support a strong positive water vapour feedback, models that assume constant relative humidity may be overestimating its magnitude[102-103].

Inclusion of improved understanding of aerosol and hydrological processes into related climate models parameterizations has helped to 'darken' modeled clouds and bring simulated atmospheric absorption of incoming shortwave solar radiation closer to that observed. Simulation results also indicate that, in the tropics, clouds are more responsive to changes in vertical dynamics and local sea surface temperature (SST) anomalies than to average changes in SSTs. Indirect effects of aerosols on clouds, in addition to altering cloud brightness and lifetime, affect the amount of latent heat transported through the atmosphere by clouds. Furthermore, inclusion of interactive cloud schemes rather than fixed clouds significantly amplifies the climate response to external forcings, particularly over the Arctic. These and other findings are reminders of the need for continued improvement in the microphysical descriptions of aerosol and hydrological processes within climate models in order to improve climate simulations[104-108].

Although most observational data appear to be in general agreement with model simulations of atmospheric processes and response to recent warming, there also continue to be significant discrepancies that need further investigation. For example, in contrast to global trends projected by models, satellite observations indicate that, since 1985, the amount of outgoing radiation at the top of the atmosphere (TOA) has actually increased over the tropical region between 40° S and 40° N. This increase was offset by increased solar radiation reaching the surface. Both trends appear to be a response to less cloud cover at these latitudes, and may be related to a multi-decadal cycle not properly captured by models. Furthermore, satellite and radiosonde data also show a marked cooling trend in the stratosphere that cannot be fully explained by most model simulations forced by changes in well-mixed greenhouse gas, stratospheric ozone and water vapour concentrations. This may be linked to poorly resolved gravity wave physics in the models. Recent simulations with a model that addresses this deficiency show improved agreement with observations. Simulation results also indicate an enhanced meridional temperature gradient near the tropopause that induces a positive dynamical feedback loop involving a strengthened polar vortex. Should this feedback continue, continents in the Northern Hemisphere will likely continue to warm rapidly during winter. The strong polar vortex would also delay stratospheric Arctic ozone recovery. Furthermore, continued stratosphere cooling/warming troposphere would tend to alter gravity wave propagation and angular momentum transport and thus produce more intense positive phases of the Arctic/North Atlantic Oscillations[109-111].

4.1.2 Land Processes

Three decades of research into continental land surface processes have provided significant improvements in parameterizing these processes within climate models. However, despite this progress, the ability to accurately quantify the response and variability of land surfaces to climate change remains elusive. This is partly due to insufficient observational data needed to parameterize the processes involved. However, various other improvements, such as higher model resolution, adjustment of canopy conductance algorithms to the type of forest involved, and allowance for land ecosystem - ocean circulation system feedbacks are also needed[112-116].

Direct CO_2 effects and changes in climate are also important factors in determining the role of land ecosystems as a feedback within the global carbon cycle, and hence in atmospheric greenhouse gas concentrations. The former largely dominates the photosynthetic response of vegetation, and the latter the ecosystem respiration processes. Related hydrological feedbacks also become important modifiers of these impacts. It remains uncertain how these factors will affect carbon storage in land ecosystems. Hence estimates vary from a continuing large land carbon sink throughout the next century (thus offsetting the effects of human emissions of CO_2) to a mid-century transition to a source of atmospheric CO_2 that becomes large by 2100. Key factors in determining which is more likely are the adequacy of nitrogen and other nutrients supplies needed to maintain current CO_2 sink processes and the response of the Amazonian ecosystem to changes in climate. These uncertainties in land ecosystem response add to uncertainties about future atmospheric CO_2 concentrations and hence climate projections[12,36,117-121].

There are also other climate vegetation feedbacks that may be important. For example, climate change may alter isoprene emissions from surface vegetation. Since isoprene is an ozone precursor, this influences ozone concentrations and greenhouse forcing. Hence deforestation in tropical regions such as Brazil may suppress isoprene emissions and hence ozone production in these regions. However, over the boreal forests of Canada, warmer climates may enhance isoprene emissions. Likewise, changes in climate may affect the atmospheric transportation of mineral dust from land surfaces to the oceans. Recent model simulations suggest that atmospheric dust loading could decrease by 20-60% by 2100, relative to pre-industrial levels. Since mineral dust can be an important source of nutrients to ocean ecosystems, such reductions can reduce both ocean carbon sinks and planetary albedo. Both responses are positive feedbacks that amplify the warming already taking place[122-123].

4.1.3 Ocean Processes

The multiple feedback roles of the ocean's circulation system within the climate system are complex and as yet not well understood. Model and paleo climate data studies generally suggest that the ocean thermohaline circulation (THC) system has two stable states, one with a strong THC, the other with that system shut down. The transition from one to the other appears to be strongly linked to changes in continental and sea ice formation and volume, particularly during glacial periods. However, during interglacials, when variations in continental ice volume are weaker, thermal, atmospheric and hydrological feedbacks become increasingly important. Some of these feedbacks tend to enhance ocean overturning (and thus strengthen the THC system), others to attenuate it. These feedbacks may also differ from one part of the ocean system to another. For example, projected changes in the intensity and global pattern of precipitation, runoff, and freshwater flux from both melting sea ice and land ice over the next century and beyond are likely to freshen North Atlantic surface waters (making them less dense) and thus weaken overturning circulation of the Atlantic Ocean. Conversely, changes in the global hydrological system could also cause a concurrent increase in surface water salinity in the Pacific, enhancing meridional overturning in that region. Paleo records suggest that such out of phase changes in Atlantic and Pacific Ocean climates, with the Southern Ocean as the pivot, have occurred in the past. Such changes in relative surface salinity between different ocean basins could be as important to changes in global ocean circulation patterns as the more regional changes occurring in the North Atlantic. Hence, the magnitude of future changes in ocean circulation remains uncertain and model-dependent. Furthermore, changes in the global THC system will, in turn, further alter global atmospheric circulation and precipitation patterns, affecting the role of land ecosystems as sources and sinks of moisture and carbon dioxide. Likewise, a reduced or collapsed North Atlantic THC system could cause an expansion of sea ice at high latitudes and hence in a regional cooling in these regions, rather than a warming. While some of these additional feedbacks are likely modest on a global scale, locally and regionally they may be large. These complex feedbacks between the atmosphere, oceans, ecosystems and the cryosphere, some negative and others positive, significantly add to the challenge of projecting the regional impacts of climate change with confidence[115,124-131].

Other factors may also be important in regulating ocean response to climate change. For example, higher Pacific Ocean tropical warm pool temperatures may increase regional ocean instability, thus inducing stronger El Niños and enhancing the poleward heat export they generate. This, in turn, helps cool the tropical temperatures and return stability to the system. Warmer ocean temperatures can also cause an increase in dimethyl sulfide emissions from ocean surface. Since these serve as cloud nuclei, this may increase cloud cover and thus provide a negative feedback. This feedback will likely be small on a global scale but could be significant at the regional scale, and thus becomes one more factor affecting regional climate patterns[132-133].

Oceans are also an important part of the global carbon cycle. In comparison with those for land ecosystems, physical and biological carbon cycle feedbacks within the global oceans uptake in response to the atmospheric CO_2 concentrations rise and climate change are relatively small. In general, the physical feedbacks relating to weakening ocean circulation and rising water temperatures are positive and dominant over the biological feedbacks. Although oceans are likely to continue to sequester a substantial fraction of excess atmospheric CO_2, the net effect of these feedbacks will likely lead to somewhat higher atmospheric CO_2 concentrations by 2100 than in their absence[134-135].

4.2 Model Simulations and Projections

4.2.1 Model Performance and Climate Sensitivities

Most models, when driven by realistic reconstructions of past changes in the dominant radiative forcings, can now replicate the climate behaviour of the 20th century quite well. These all show accelerated warming for the most recent decades, concurrent with the rapid rise in anthropogenic forcing relative to natural factors. There is still debate about how important forcings from changes in solar irradiance and volcanic aerosols concentrations may have been. Inter-comparison studies also indicate that most models portray realistic relationships between temperatures of different ocean basins but do less well in correctly simulating hemispheric pressure patterns. One of the reasons suggested for the continued challenge in improving model performance, particularly at the regional scale, is the intrinsic level of uncertainty introduced by the non-linear and stochastic aspects of the climate system. This could be addressed by using a collaborative international program involving a hierarchy of models in a probabilistic manner to characterize and quantify uncertainties in each step of the modeling process. Another reason is that the regional patterns in climate response to climate forcings are often more closely related to differences in regional feedbacks than to the global patterns of the forcing itself. For example, high latitude regions and the equatorial Pacific tend to exhibit strong positive feedbacks while other areas have negative or neutral feedbacks[136-140].

Climate sensitivity is the term used to define the magnitude of an equilibrium global surface temperature response to a doubling of atmospheric CO_2 concentrations. Past estimates of climate sensitivity based on climate model simulations have, in general, ranged between 1.5 and 4.5°C warming per doubling of CO_2. This large range is indicative of the large uncertainties that still exist in how to incorporate key climate processes, particularly those related to the hydrological cycle, clouds and aerosols, into climate models. By comparison, while model resolution is important in simulating the large scale pattern of change, it has little impact on estimates of climate sensitivity. Recent coupled climate model simulations, using more realistic descriptions of these processes, have somewhat narrowed the most likely projections for climate sensitivity, but also slightly increased the upper and lower boundaries. Several recent assessments of multiple coupled model results, using different methods, show relatively consistent results. While some still show results similar to previous estimates, most show mean climate sensitivities of about 3 to 3.5°C, and 90% confidence limits of between 2.4 and 5.4°C, per doubling of CO_2. Another study, using a Monte Carlo type multi-thousand simulation approach involving participation of the broader public, generated a plausible range of sensitivity of between 2 and 11°C per CO_2 doubling. Studies comparing simulations of the climate effects of Pinatubo with that observed also suggest a climate sensitivity of about 3°C. Likewise, comparison of Antarctic ice core data against model simulations of past climates suggests sensitivities in the range of 4.4 to 5.6°C per doubling. Hence, while it remains uncertain how likely extremely high sensitivities might be, the collective conclusion of these various studies is that a feeble greenhouse effect now seems very unlikely[141-152].

The length of time it takes for the climate system to reach full equilibrium response to climate forcings is largely determined by ocean mixing of heat. Studies suggest that such response times are different for the Southern Hemisphere than the Northern Hemisphere, for deep oceans versus surface ocean mixing layers, and for cooling forcings versus warming forcings[153].

Regional climate models (RCMs), when nested within or driven by the outputs of global general circulation models, are important tools to help provide added regional details to climate simulations. Although there is continued progress in improving the performance of RCMs, these also have performance limitations and hence their results must still be used with care. The Canadian RCM, for example, shows much improvement in simulation of precipitation compared to that of the GCM it is linked to, but still appears to simulate too much stratospheric cloud. This produces daily minimum temperatures that are too warm. Another unavoidable limitation is the quality of the boundary inputs provided by the GCMs to which they are connected[154-155].

4.2.2 Projections

Advanced coupled climate models, when used to simulate climate response to past radiative forcings, now show much improved ability to accurately replicate the pattern of observed climates, relative to earlier simulations. For projections into the future, ensemble means of model simulations suggest a rise in global temperatures by 2090 of a low of about 2°C for SRES B1 to a high of 3.7°C for SRES A2. These magnitudes are similar to those of earlier studies. However, some models still project much larger changes of more than 5°C. Should all global fossil fuel reserves be combusted and released as CO_2, global temperatures could rise by at least 8°C by AD 2300. Ensemble means for global precipitation increases are about 4 to 5%, although there continues to be significant disagreement between models. In general, those with high climate sensitivity show weaker precipitation response, and vice versa. The atmospheric holding capacity for water vapour increases by about 7% per degree of warming. This implies longer atmospheric residence time of moisture and a slower rate of water cycling. Most models show precipitation increases in the ITCZ, a poleward displacement of the mid-latitude precipitation maximum, and decreased precipitation in the latitude zones centered around 30°N and 30°S. There are indications that, on average, precipitation increases over oceans and decreases over land. However, there is also more disagreement between models over land areas than over oceans. In general, impacts of aerosol emission reduction are also greater for precipitation than for temperature[156-162].

The polar amplification projected by various models for warmer climates ranges between 1.5 and 4.5 times the global mean. Cryospheric feedbacks involving snow and sea ice cover are the dominant factors in polar amplification. However, increased transport of sensible and latent heat from low to high latitudes is a contributing factor. This moisture flux also enhances polar precipitation. The amount of amplification also varies in space and time. For Hudson Bay, for example, regional feedbacks cause two peak periods of amplification, one in the winter because of thinner ice conditions and a second over adjacent land in summer (due to regional reduction in soil moisture and permafrost decay)[163-165].

Most climate models also project equatorial regions will experience enhanced warming relative to that over the sub-tropics, as well as an enhanced annual climate cycle. These enhancements, linked to feedbacks involving surface latent heat flux, shortwave cloud radiation and surface mixing, may be an important fingerprint for attributing future change to causal forcings[166-167].

In general, models also project a decrease in the daily temperature range (DTR) for most parts of the globe. Factors effecting DTR include cloud cover, vegetation cover and soil moisture. Since related climate system feedbacks are as yet poorly understood, the regional magnitude and even sign of the change in DTR remains uncertain. There is, however, no strong evidence for a change in global scale climate variability as temperatures rise[168-169].

Most coupled climate models, including the Canadian version, now show a realistic relationship between Pacific

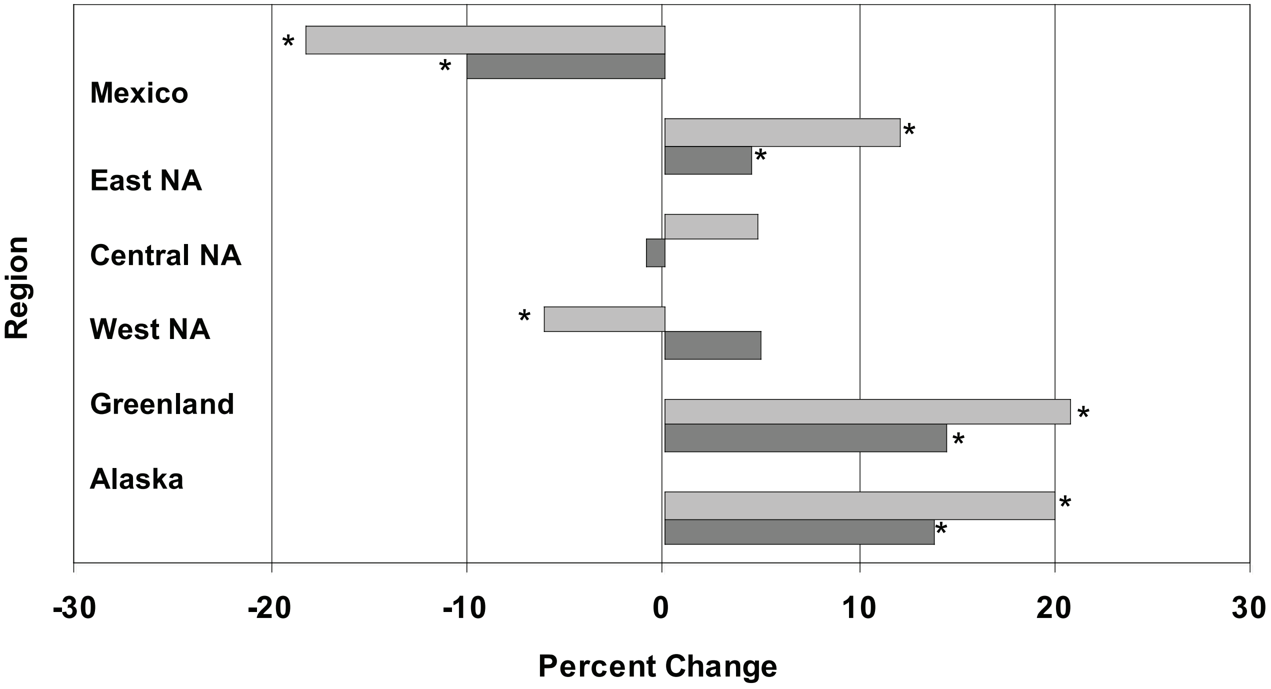


Figure 2: Ensemble projections for future regional changes (%) in wet (dark grey) and dry (light grey) season precipitation over North America and Greenland, based on 20 coupled climate model simulations using the A1B SRES scenario. Asterisks indicate that at least 80% of the models agree on the sign of change. Note that the wet and dry seasons are defined as the six consecutive months with most and least cumulated average regional precipitation, and hence vary from region to region. For all regions shown, except western North America (West NA), the dry season occurred during the colder half of the year (data from Giorgi and Bi 2005, reference #158).

and Atlantic Ocean temperatures and simulate the Southern Oscillation, North Atlantic Oscillation and Arctic Oscillation Indexes reasonably well. However, many still have problems properly replicating the behaviour of the El Niño Southern Oscillation (ENSO), particularly its variability in space and time. While model simulations show mean values for ENSO behaviour under warmer climate similar to that of today, some suggest ENSOs could become more intense, while others project that they may become weaker. However, those projecting more intense behaviour also appear to perform less well in simulating current ENSO behaviour. Analyzing ENSO behaviour in climate models is further complicated by the non-uniform geographical pattern of future global warming. Some model simulations suggest that future warming will manifest itself in an El Niño like pattern. Paleo evidence also suggests a La Nina-like global climate patterns during the last glacial maximum. Most models also project that the Arctic Oscillation and its impact on the Aleutian Low position will intensify under warmer climates. These changes may be important in predicting future regional climates of the Northern Hemisphere[64,104,136,159,170-175].

Model simulations also indicate that melting of the Greenland ice sheet and/or enhanced northern river discharge into the Arctic Ocean under warmer climates could introduce a large portion of the fresh water into the North Atlantic Ocean needed to trigger a devastating collapse of the THC system. However, surface heat flux also plays a major role in the circulation system. Hence, while the system could slow down by up to 50% within the next 140 years, complete collapse during that time period does not seem likely. For most of the region, concurrent atmospheric warming of ocean surface would, in general, dominate over any cooling effects of slower circulation. However, there are other complex feedbacks involving the NAO, snow cover, vegetation patterns and the carbon cycle that would modify the effects of a slower THC, particularly over Eurasia. Should the THC shut down completely, much of Europe could cool[176-183].

Models disagree substantially on the magnitude of sea ice response to warmer climates. However, results suggest that ice cover in the Arctic will decrease by more than 10% and ice thickness by 0.3 to 1.8 m at the time of CO_2 doubling[184].

Small changes in mean values for precipitation and temperature can result in large changes in the frequency of their extremes. While Canadian studies project little change in the distribution curves for temperature events for most areas of the globe (and hence variability), those regions with snow and ice cover can expect very large reductions in interannual variability of extreme cold events. Areas with reduced moisture also experience increased variability in annual warm extremes. Increased surface evaporation will increase the latent heat available to invigorate storms, resulting in fewer but more intense precipitation events. Distribution curves for precipitation become flatter and shift towards more frequent intense events, both of which contribute to a doubling of extreme precipitation events by 2100. Intense extra-tropical storms are also expected to become more frequent and severe[161,185-187].

There is also growing evidence that the climate system, when pushed by external forcings, may not change gradually but abruptly switch from one equilibrium mode to another. The likelihood of such non-linear and potentially catastrophic discontinuities in climate condition appears to increase with the magnitude of the forcing applied. Paleo records indicate that such surprises have occurred in the past, primarily during periods of rapid climate change between relatively stable glacial and interglacial states. It remains uncertain whether or not a new stable state might be possible under unusually high CO_2 concentrations[188-190].

5.0 TRENDS

5.1 Million Year Time Scale

While cosmic radiation flux entering the Earth's atmosphere has been hypothesized as a primary driver of the Earth's climate on multi-million year time scales, subsequent assessments suggest that it is unlikely. There is evidence that changes in solar insolation and low CO_2 concentrations were both factors in past ice ages and at the onset of the current ice age some 10 million years ago. It also appears that, some 55 million years ago, an abrupt release of methane from hydrates below the ocean floor (possibly through the release of large amounts of methane rich pore water triggered by submarine landslides) may have triggered a period of greenhouse gas induced warming that lasted for 100,000 years. Both suggest that changing greenhouse gas concentrations have been a factor in climate change for at least millions of years[57,191-197].

5.2 Past 400,000 Years

5.2.1 Glacial-Interglacial Cycles

New Antarctic ice core data now extend the record of atmospheric composition and climate conditions back

740,000 ybp, a time period that included eight glacial-interglacial cycles. Analyses indicate that the variations in climate are essentially homogenous across a large region, and that the amplitudes of the first four of these climate cycles were weaker than the last four. The interglacial of some 400,000 years ago appears to be the most similar to the current Holocene interglacial[9,198-199].

Greenland ice cores provide a much shorter climate record. However, new cores from northern Greenland include the last interglacial period some 125 000 years ago, when regional climates appear to have been about 5°C warmer than that of today. Temperatures in the region slowly declined during that interglacial, but then experienced an abrupt warming prior to the onset of re-glaciation. This warm pulse does not appear in Antarctic ice core records. Comparisons with other Greenland cores also suggest that the regional climate change may not have been as homogenous as that in the Antarctic[200].

While orbital forcings may induce the initial transitions of Earth's climate from glacial to interglacial conditions and stimulate some of the shorter and weaker fluctuations in climate, cloud, land and sea ice, ocean circulation and carbon cycle feedbacks are critical factors that help regulate the length and intensity of the different phases of these variations. The extended Antarctic cores, for example, indicate that changes in greenhouse gas concentrations follow the temperature cycle closely throughout the record. Model simulations indicate that this greenhouse gas feedback process (which can be season dependent) may have contributed, when these gases concentrations were diminishing, 60% of the cooling experienced during the slow transition form the last interglacial to the Last Glacial Maximum. These feedback processes may be different in winter seasons than summer seasons[8,10,43,201-203].

5.2.2 Abrupt Climate Anomalies

Greenland ice core data show evidence of 23 abrupt climate events during the last glacial period, occurring with regularity at intervals of about 1470 years. While the causes of these events are not known, there are indications that they are linked to large changes in the Atlantic THC system and related atmospheric, ice and ocean feedbacks. For example, paleo records imply that one such event that occurred about 19 kybp was linked to an abrupt meltwater discharge during the onset of deglaciation, which in turn induced a large change in the THC. Better data are needed to determine whether or not these circulation changes were responses to changes in other aspects of the climate system. Such abrupt climate anomalies can result in significant although complex interactions with regional vegetation growth. An abrupt cold climate anomaly some 17 to 15 thousand years ago, for example, was accompanied by a rapid increase in precipitation intensity in the Amazonian region of Brazil region – although vegetation response lagged by one to two millennia. Similar events appear to have also caused tree population crashes in Portugal. These studies imply that ecosystems have critical but as yet poorly understood thresholds that affect how they will respond to a regional change in climate[204-208].

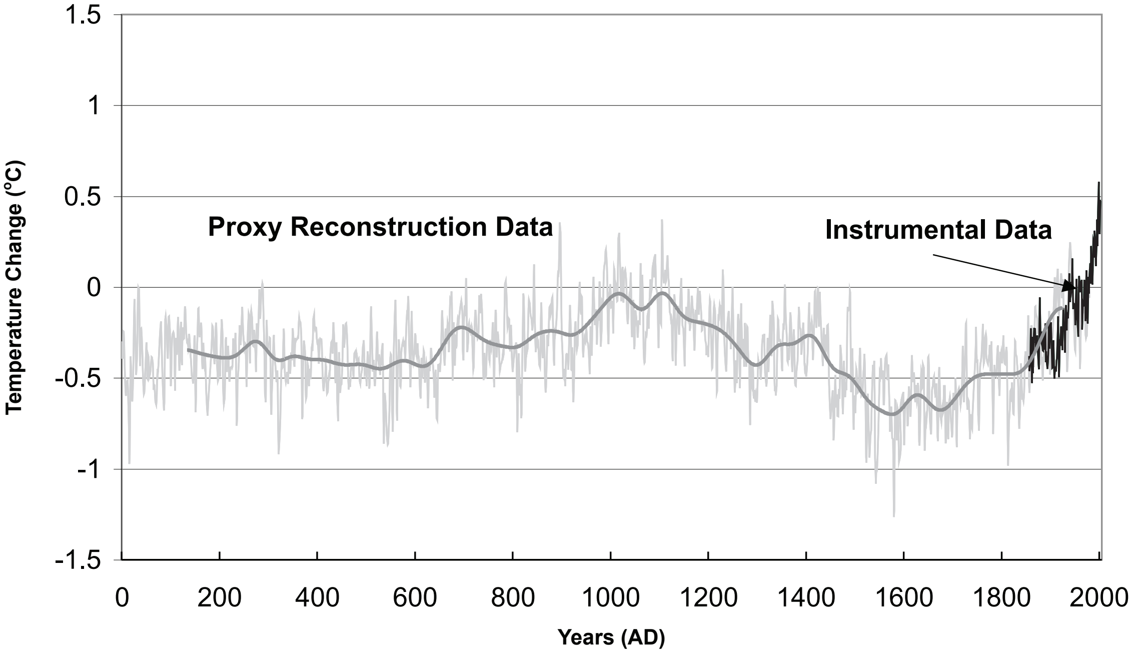
5.3 Current Interglacial

5.3.1 Holocene

Tree ring data from Irish bogs and marine data from the North Atlantic both show that regional climates were dominated by an 800 year cycle during much of the Holocene. However, these cycles do not appear to correlate well with the solar data extracted from the same tree rings. This suggests that, if there is a linkage to solar forcing, it must be through indirect processes. However, there are indications that solar variability on shorter time scales of 200-250 years may have repeatedly triggered THC system feedbacks that could, in turn, affect local ecosystems. Proxy data collected from a large number of Alaskan glaciers also suggest a 200 year periodicity consistent with forcing from solar variability[209-212].

5.3.2 Past Two Millennia

There continues to be considerable debate about whether or not the most recent decades are unprecedented in warmth relative to the past few millennia, particularly relative to the so-called Medieval Warm Period (MWP) some 1000 ybp. Several scientists have argued that, at least in the Northern Hemisphere, regional warm anomalies that occurred between 800 and 1300 AD exceeded temperatures observed in the late 20th century. However, others have countered that these events were local and not persistent, and often occur in coincidence with cool temperatures in other parts of the hemisphere. They suggest that the MWP is actually a poorly defined time period of uncertain scale and magnitude. When averaged spatially over an extended period, mean temperature anomalies during that period appear similar in magnitude to that of the 1900-1970 time period, and hence about 0.35°C cooler than today[213-214].



Source: Moberg et al. 2005

Figure 3: Comparison of reconstructed temperatures for the Northern Hemisphere (gray line) using multi-proxy data, including borehole temperatures, with that from instrumental data collected over the past century (black line). Results show larger low frequency variability that past studies, but continue to indicate the unusualness of recent temperature rise (adapted from Moberg et al 2005, reference #229).

A number of studies using multi-proxy temperature reconstructions that extend the global proxy temperature records back 2000 years have helped to clarify the debate. While there has been considerable controversy about data quality, calibration methods and the statistical analysis techniques used in these studies (often referred to as the 'hockey stick' debate), results from various analyses using different techniques and data sources consistently agree that temperatures during the last few decades of the 20th century have likely been unprecedented throughout the 2000 year period, at least for the Northern Hemisphere. There are also indications that recent behaviour of ENSO and NAO circulation systems may be anomalous in a long term context. A number of model studies used to test the paleo climate reconstructions provide further supporting evidence[213,215-234].

There are also a variety of other studies that demonstrate the importance of understanding the background low frequency natural variability of the climate system in order to better assess the significance of recent regional climate trends. For example, model studies of ocean climates over the past millennium suggest that the present rise in ocean heat content already began in mid-19th century and has been relatively linear since. Ground temperature reconstructions based on bore hole data indicate that only about 20% of the 1°C surface warming detected for the Northern hemisphere during the past 500 years occurred prior to the 20th century. Ice cores records from alpine glaciers in the Himalayas and the Andes also show that these low latitude regions have experienced an unusual large scale warming during the 20th century. In general, the combined proxy and instrumental data records suggest that the warming trend of the 20th century already began before the industrial period, but accelerated during the 20th century. When changes are compared to radiative forcings that have occurred over the past few centuries, results suggest a global climate sensitivity of 0.4 to 0.7°C per W/m^2 increase in net radiation. This is equivalent to about 1.5 to 2.6°C per CO_2 doubling (using IPCC Third Assessment Report estimates for CO_2 radiative forcing). Although at the low end of climate sensitivity estimates based on model studies (see section 4.2.1), these results are significantly higher than previous estimates based on paleo data[140,224,235-240].

Canadian studies show similar results. Recent maximum summer temperatures in the mountain regions of interior

BC have been the warmest of the past 300 years. The devastating drought in western Canada during the 1920s and 1930s was the longest and most wide spread dry spell in the region during the past three centuries, but not the most severe. For example, past changes in diatom composition found in lake sediments in the southern Canadian Prairies and northern US Great Plains indicate a very dry period in the Prairies between 500 and 800 AD, and several centuries later in the US region. Such anomalies may be related to long term shifts in storm tracks that could happen again as part of natural climate variability. Ground surface temperature history for the past 500 years, reconstructed from bore hole temperature data, shows little evidence for a Little Ice Age event across Canada, and only modest warming prior to the past century. Since then, average temperatures have increased by 0.7°C. Across northern Canada, the borehole data imply that most of the 2°C regional warming over the past two centuries occurred before 1940. There are, however, limitations in the reliability of using sparse high latitude borehole data to resolve recent changes in temperature. Finally, paleo data also show evidence of a marked change in precipitation variability in northern Ontario after 1850, possibly due to a change from the Pacific Decadal Oscillation (PDO) to a North Atlantic Oscillation (NAO) domination of the region's climate variability[241-246].

5.4 Past Century

5.4.1 Climate Reconstruction Methodologies

A large variety of data bases are now available to help reconstruct how temperatures at the Earth's surface and in the atmosphere above have changed over the past century. All have interpretation challenges related to spatial coverage, systemic changes in observing methods and instrumentation, and other errors in data collection and analysis. Furthermore, non-climatic factors, such as urbanization and land use change, can also affect local temperature records. Hence meteorological records need to be adjusted to correct for such biases if they are to be used to accurately describe the real behaviour of regional and global climates. Some argue that observed global warming trends may therefore be artefacts of these data errors. However, experts continue to improve adjustments of data records to correct for these errors, with encouraging results. For example, recent comparison of trends in urban and rural subsets of the American adjusted national climate data set indicates that there is no evidence of a residual urbanization influence in the corrected data set. Similarly, comparison of trends on calm days (when urbanization effects should be most pronounced) and windy days show little difference. Thus there is increased confidence that the adjusted data sets now used for global temperature trend analysis are a good representation of past changes[247-255].

5.4.2 Temperature

Updated analysis of global surface temperatures trends using improved global climate observing network data sets for surface air temperatures estimate a global warming between 1901 and 2001 of 0.7°C. While the updated trends for the Northern Hemisphere are similar to those from previous analyses, that for the Southern Hemisphere are larger. Subsequent years have also been amongst the warmest of the record. The eight warmest years of the record have all occurred since 1996, with 2005 being the warmest[256-258].

Satellite-based monitoring systems are now also providing independent confirmation of surface temperature trends. These show recent trends in both ocean and land surface temperatures that are broadly consistent with those estimated from the climatological observing network[259-260].

Past analyses of tropospheric temperatures using satellite based microwave sounding unit (MSU) data have suggested related warming trends since 1979 of about 0.03°C/decade, significantly less than that reported at the surface using climate station and ship-based instrumental data. Furthermore, past studies using data from balloon-borne radiosondes, while indicating a long term warming of the troposphere since the 1950s similar to that at the surface, also reported a weaker warming of the troposphere in recent decades. Such weak tropospheric warming disagrees with climate model simulations of an enhanced greenhouse effect, which suggest the lower atmosphere should be warming more rapidly than the surface. There are various explanations for this discrepancy, including the effect of surface processes such as evaporation and the conversion of energy from sensible into latent heat. Recent studies, however, indicate that these earlier analyses failed to adequately correct for changes in characteristics of satellite orbits (such as altitude, drift and time of day), instrument calibration concerns and contamination from microwave radiation from a cooling stratosphere. In polar regions, seasonal changes in ice cover may also affect the MSU readings. More recent analyses suggest that, when corrected, the MSU data show tropospheric temperature trends very similar to or slightly greater than that reported for the surface data. Likewise, a more careful evaluation of radiosonde data indicate that past analyses have failed to adequately consider the bias introduced by diurnal variations in solar heating of the on-board sensors. When corrected, these data now suggest a warming only slightly less than that observed at the surface. While investigators advise caution in using these results because of others as yet uncorrected sources of error in the radiosonde data, they do note that there is no contradicting evidence from these sensors. The combined corrected data sets also show a recent amplification in tropical regions of both trends and month to month variability of tropospheric temperatures relative to surface changes. Finally, independent evidence of a decrease in thermosphere density is also consistent with that expected due to an enhanced greenhouse effect. Hence there is renewed confidence in the significance and consistency of warming trends, both at the surface and in the lower atmosphere[261-276].

Global daily minimum temperatures have been increasing more rapidly than daily maximum temperatures. This has resulted in a large reduction of, on average, 0.07°C/decade in the average daily temperature range (DTR) over the past 50 years. However, since 1979, maximum and minimum temperatures have been rising at similar rates, resulting in almost no trend in DTR in recent decades. Although the decrease in DTR is unlikely to be due to natural variability alone, models simulations driven with past changes in climate forcings are as yet unable to replicate such a large change. This may be due to the effects of increased cloud cover, which are as yet not well simulated. Rising night-time temperatures have also increased annual frost free periods. For example, the frost free period has increased by 19 days in the western US and 3 days in the eastern half. Most of this increase has occurred since 1980[277-279].

The global ocean-sea ice system is also warming. Average temperatures in the upper 3 km of the oceans, for example, have increased by 0.037°C since 1955, equivalent to added heat content of 14.5 x 1022 J. This is an order of magnitude greater than that absorbed within the atmosphere. Concurrent changes in ocean circulation have caused even greater warming in some ocean regions. For example, in the eastern North Atlantic, temperatures at the main thermocline (the base of the mixed surface ocean layer at about 400 m depth) show a warming during the past decade of about 4°C. This was accompanied by an increase in salinity. Likewise, sea bottom temperatures in the North Sea have recently warmed by 0.24°C/decade. In Arctic regions, the total arctic ice-ocean system has been warming almost twice as rapidly as other ocean systems around the world, likely due to the amplification by sea ice feedbacks. Surface air temperatures in the region have also risen by 1.2°C over the past century. The temporal and spatial patterns of these Arctic trends are complex. Temperature trends, for example, show warm peaks in the 1930s-40s and the 1990s. During the past 20 years, these trends have varied from more than 1°C/decade increase over the North American Arctic to a slight cooling over Greenland. Arctic melt seasons have also increased by 9 to 17 days per decade. The heat taken up by just the consequent enhanced ice melt alone has absorbed an estimated 4 x 1021 J over this period. A strong warming pulse in the Eurasian Basin of the Arctic Ocean in 2004 also appears to be consistent with this gradual transition of the ocean to a warmer state. Researchers suggest that both the long term variability and the recent trends may be at least partially due to a low frequency oscillation originating in the north Atlantic[280-287].

Finally, ground temperature profiles indicate a heating up of the Earth's continental lithosphere. Across Canada, ground surface temperatures have warmed by about 0.7°C over the past century, with greater warming in southern regions. At 20 cm depth, average soil temperatures have risen by 0.6°C. This is smaller in magnitude than the 1.1°C warming for southern Canada indicated in meteorological records for air temperatures. The regional pattern of these increases in soil temperature is complex and diverse, largely because of the buffering effects of snow cover, soil moisture and other factors[241,288].

5.4.3 Hydrological

The global hydrological cycle is complex and regionally variable. Satellite records show a global trend since 1982 towards increased moisture levels in the upper troposphere (Soden/Jackson 2005). Observational data collected since 1998 also indicate that, over oceans, the total precipitable water content throughout the vertical atmospheric column, although strongly influenced from decade to decade by ENSO variability, has been rising by some 8% per degree of rise in sea surface temperatures (SSTs). Trends are regionally less consistent in the lower troposphere. For example, over the past three decades, a significant increase in relative humidity in the lower troposphere has been observed over regions such as the US, the Caribbean and China but not over, for example, Canada. Experts caution that some of these results may be affected by discontinuities in observing procedures and instrumentation[161,289-290].

Observations indicate that, over the past 50 years, average precipitation over tropical land areas has been decreasing. Since the region has also been warming and hence experiencing increased evaporation of surface waters and ecosystem moisture, water resources in this region have been decreasing at a greater rate than precipitation[470]. Likewise, changes in atmospheric circulations caused by warmer surface temperatures in the Indian and western Pacific Oceans, coinciding with cooling in the eastern Pacific Ocean, appear to have contributed to increased aridity in the tropical Sahel region since 1970s and to more recent persistent droughts in mid-latitudes of the Northern Hemisphere, particularly some regions of the US, southern Canada, the Mediterranean and southwest and central Asia. Such patterns may be a harbinger of how future warming may increase drought risks in these mid-latitude regions[291-295].

Within Canada, warmer temperatures and increased snow and glacier melt have changed the seasonality and volume of river flows throughout the mountainous regions of BC and the southern Yukon. Flow volumes of glacier fed rivers in these regions have been increasing, while those for rain-fed rivers have decreased. In the Great Lakes basin, rising lake temperatures and reduced ice cover have enhanced evaporation and lake-effect precipitation. The Great Lakes experienced a record one year drop in lake levels in 1998 and near record decreases in the following few years, largely because of high evaporation rates. Ice cover records indicate that these years also had the least maximum ice cover since 1900. In contrast, record absolute low levels of the 1930s were induced by decreased precipitation, rather then enhanced evaporation[296-300].

Cloudiness has increased across much of Canada since 1953, although cloud cover decreased over BC and the Prairies in winter and over north-eastern Canada in summer. At least in the Mackenzie Basin, the increase in cloud cover in that region is linked to warmer temperatures. The Arctic north of 60°N has become warmer and cloudier in spring and summer since 1982, but winters have cooled and become less cloudy in much of the region. Since these cloud cover changes appear to have caused a negative net feedback, they have helped to moderate the rate of warming that has occurred in the Arctic. There are indications that at least some of these trends are linked to changes in the Arctic Oscillation (AO), rather than local effects[301-303].

5.4.4 Cryosphere and Sea Level Rise

Polar ice sheets continue to change. Altimetry measurements indicate that the high elevation regions in the interior of the Greenland ice sheet have been growing between 1992 and 2003. However, much of the ice sheet below 1500 m has been thinning. Although some of this thinning is due to increased melt rates, changes in glacier dynamics along the margins of the Greenland ice sheet have also contributed. Net balance studies indicate that the total ice sheet volume has therefore been slowly shrinking during the 1990s, adding about 1.5 mm to global sea levels during the decade. Estimates, however, have large error margins[304-307].

The east Antarctic ice sheet also appears to be thickening in the interior, likely due to increased snowfall. The rate of increase is enough to reduce rates of sea rise by 0.12 mm/year. In contrast, the West Antarctic ice sheet appears to be thinning. Paleo data indicate that this ice sheet has been in continuous decline throughout the Holocene and may still be contributing to sea level rise through natural deglaciation processes. However, the rate of decline has recently increased, primarily through drainage by accelerating and widening glaciers. Along the shores of the Antarctic Peninsula, 87% of marine glaciers have been retreating over the 1940-2001 period. For example, glaciers in the Amundsen Sea region of west Antarctica, in particular the large Pine Island Glacier, are thinning and moving faster, accelerating the flow of ice towards the sea. The adjacent ice shelf has also thinned. The surface elevation of the Larsen C ice shelf has lowered by 27 cm between 1992 and 2001, primarily due to basal melt caused by warm ocean waters. This thinning may have made the shelf more susceptible to crevice formation and hence contributed to recent disintegration of sections of the shelf. Meanwhile the recent collapse of the Larsen B shelf has contributed to a rapid acceleration of glacier flow that had been braced by the shelf. Glacier lubrication by meltwater has also contributed to the acceleration. Experts indicate that these coastal zone changes can trigger further changes that propagate far inland to interior glaciers and ice sheets. Although some glacier retreats in the region are not well correlated with temperature trends, suggesting other factors are also affecting the glacier behaviour, most appear to be linked to the effects of the large warming experienced in the region. The recent rapid response of west Antarctic ice dynamics to warmer climates is somewhat unexpected and may suggest related impacts on sea level rise may be underestimated. Continued thinning at current rates could cause its complete collapse within the next century[308-321].

Elsewhere around the world, both winter snow accumulation and summer ablation rates have been increasing across most glaciated areas, consistent with an intensified hydrological cycle. However, since the 1960s, net balance has been predominantly negative. Small glaciers are

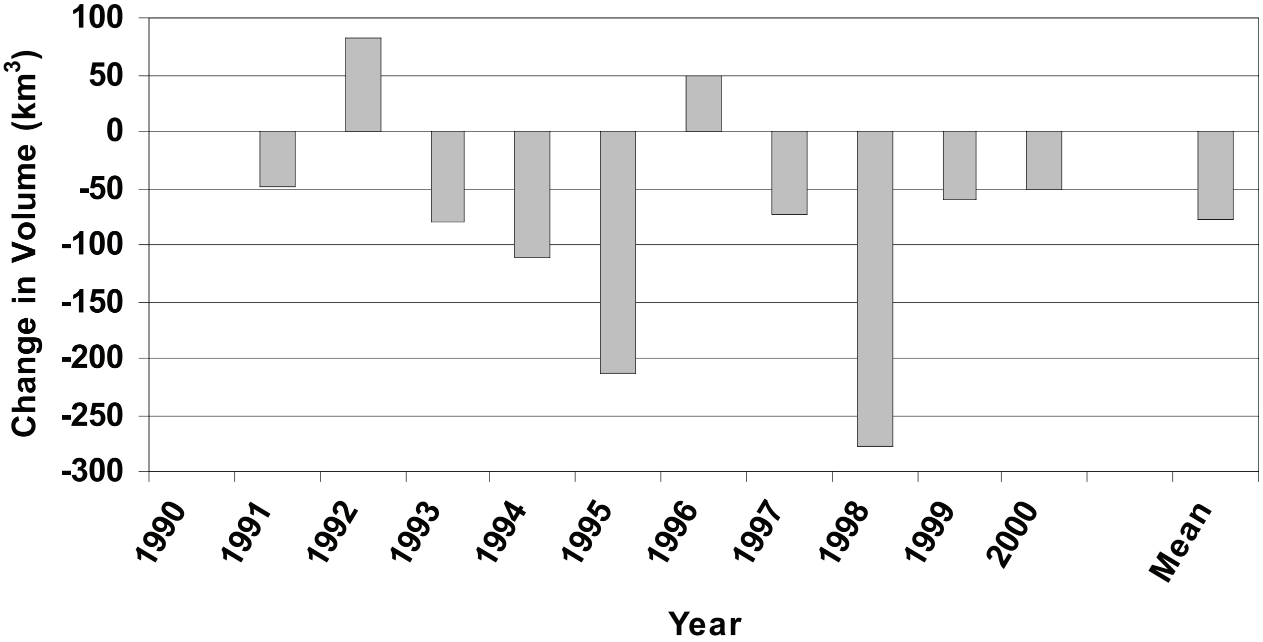


Figure 4: Estimated net annual changes in total mass balance of the Greenland ice sheet, in km^3/year, between 1991 and 2000, based on a combination of in situ data and model simulations. This is equivalent to adding 2.2 mm to global sea levels during the decade. However, uncertainties remain large (Box et al 2004, reference #305).

disappearing and larger glaciers in mid-latitudes are shrinking slightly. In the European Alps, this decline appears to be due to enhanced rate of melt. On the other hand, those on Mt. Kilimanjaro are disappearing rapidly because of increased regional aridity. About half of the variability in these global glacier volume trends can be attributed to atmospheric circulation patterns, but recent trends demonstrate change outside the range of normal variability[322-325].

Merged paleo and tidal gauge records indicate that global sea levels have been rising for at least the past 700 years, but that the rate of rise began to accelerate in the late 19th century, coincident with the onset of warming conditions. Since 1950, average rates of rise are estimated at 1.8 mm/year. Satellite records indicate this may have increased to 3.1 mm/year since 1993. While the recent trends in land ice melt have contributed to this rise, the larger contribution is likely linked to warming ocean waters. Observed warming of the upper 3000m of the world's oceans imply a related rate of steric sea level rise of 0.4 mm/yr since 1950, but tripling between 1993 and 2003. However, multi-decadal oscillations in ocean climates may be a significant element of the recent acceleration. Furthermore, uncertainties in these estimates remain large. Although analysis of ocean freshening could put some boundaries on these uncertainties, there is a need to carefully consider this source of freshening[216,326-331].

Arctic sea ice extent has declined by an estimated 2.5% per decade since 1973. Minimum summer ice cover in the region set new record lows during 2002, then again in 2005, likely due to the combination of warm summer temperatures and ice transport from anomalously warm summer winds. Between 1987 and 1996, mean ice thickness also decreased by 60 to 90 cm. Model studies suggest that thickness may have recovered slightly in subsequent years. Changes in thickness are not uniform across the basin, being greatest in the central Arctic and East Siberian Sea, the least adjacent to the Canadian archipelago. Ice passing through Fram Strait into the North Atlantic, for example, has decreased in thickness by a more moderate 45 cm between 1994 and 2002. The fraction of old ice within the Arctic sea ice pack has, on average, decreased by 11% since the 1960s, and total ice volume by 32%. Earlier break-up, which has advanced by 3 days per decade since 1971, has also helped lengthen the ice free season in southern Hudson Bay. While some of these changes may be linked to the behaviour of the Arctic Oscillation, model studies suggest that thermal forcing and enhanced summer solar insolation also appear to be important factors. Some suggest that the system may now have passed a critical threshold, where positive feedbacks will progressively accelerate the reduction of sea ice volume, and that a return to the old regime would only happen if a prolonged cool period were to occur[332-340].

In Antarctica, sea ice extent decreased dramatically during the mid 1970s but this decrease has been partially offset by a slow increase in extent since 1978. Although these Antarctic trends are significantly influenced by regional ENSO and NAO events, the net 20% decrease in sea ice in the region since 1950 appears to be without precedence at least since 1841[332,341-342].

There is a significant trend towards longer ice free season and earlier ice break-up in lakes across southern Ontario[343].

In recent decades, many high latitude regions of the Northern Hemisphere are experiencing significant warming and/or degradation within the upper layers of permafrost. The magnitude of warming varies from as much as 1-3°C/decade in colder permafrost along the Arctic coastal plains of Alaska and in the Canadian high Arctic to very little change in regions with warmer permafrost, such as the southern Mackenzie Basin. The latter may be due to increased use of heat energy for melting ice within the permafrost. The effect of these rising ground temperatures on ground ice varies from region to region. For example, in much of the Alaskan and Mackenzie Valley regions, there is little evidence that the active layer above the permafrost has become deeper. On the other hand, in the peatlands along the east shores of Hudson Bay, the alpine regions of Europe and across much of Siberia and the Canadian high Arctic, extensive permafrost decay has caused erosion of coastal shorelines, significant changes in land hydrology, lake and wetland area, and enhanced land instability. These changes also alter the regional carbon budget, although net effects are difficult to estimate. In some regions, complete disappearance of permafrost is likely within decades. Such a rise in ground temperature and related permafrost decay can be due to both increased snow cover and rise in air temperature[344-355].

5.4.5 Circulation and Variability

Over the past five centuries, North Atlantic climate has been significantly influenced by a 60 to 100 year Atlantic Multi-decadal Oscillation. Periodic progression of significant low salinity anomalies across the North Atlantic sub-polar gyre over the past 50 years is also indicative of shorter term natural ocean variability. However, while models can simulate these natural variations reasonably well, they are unable to reproduce the recent trend towards a persistent strong positive phase of the NAO without including greenhouse gas forcing. Hence the recent NAO trend appears to be at least partly attributable to human influences. Similar conclusions have also been found for other changes in global circulation. For example, the recent trend in the Arctic Oscillation appears to be without precedence since at least AD 1650. Likewise, while the La Nina stage of the ENSO activity has been quite stable since at least 1856, the El Niño phase has occurred more frequently preceding and during periods of rapid global warming[356-361].

Run-off from high latitude glaciers, melting sea ice and increasing precipitation in high latitudes are increasing the flux of fresh water into the Arctic Ocean, the Nordic Sea and the north Atlantic. Observations indicate that, together with increased salinity in the tropical-subtropical waters caused by enhanced evaporation, this freshening of north Atlantic surface waters is changing Atlantic Ocean salinity and temperature patterns and contributing to a weakening of the North Atlantic thermohaline circulation (THC) system, particularly during the past decade. Some studies suggest the meridional circulation in the region may have slowed down by as much as 30% since the 1950s. Models also suggest a further positive feedback process whereby weaker THC reduces meridional freshwater divergence. However, other feedbacks, such as the reduced flux of sea ice from Arctic waters could be offsetting these influences. Furthermore, these factors may affect surface waters differently from deep waters. Although the observed trends are broadly consistent with model simulation results, the accuracy of related measurements is limited. Hence, the relative magnitudes of the various processes involved, and hence the net consequences for ocean overturning, are not well known[177,362-369].

Changes in atmospheric circulation patterns affect temperature variability, winds and other aspects of regional climates. For example, they appear to have caused a northward shift in storm tracks across North America during the past half century. This has resulted in a decrease in cyclone activity in mid-latitudes since the 1960s, but a significant increase in areas north of 60°N. Along the west coast of Canada, a change in the Pacific Decadal Oscillation (PDO) behaviour appears to also have caused more frequent calm periods and less frequent intense winds since 1970. Over the past 50 years, Canadian winter temperature variability has also been significantly affected by changes in the NAO index[370-372].

Within the stratosphere, cooling over polar regions in recent decades has been an important factor in the recent decline in total ozone concentrations over these regions. While the cause of the cooling is not well understood, it is likely due to a combination of factors, including enhanced greenhouse gas warming, decreases in stratospheric ozone concentrations and changes in the dynamics of the polar atmospheric circulation[373-374].

5.4.6 Extremes

There are many areas around the world that have experienced unusual behaviour in terms of temperature extremes. For example, in Canada, winter temperature anomalies during the past 50 years show a trend towards more frequent and longer warm spells across most of the country, and fewer, shorter and less intense cold events in western Canada. In contrast, cold winter spells have become more frequent in eastern Canada, perhaps due to changes in NAO behaviour. The extreme summer experienced by Europe in 2003 was unprecedented in regional historical records. In general, these trends and events are consistent with those expected in a warmer world[375-377].

There appears to be a widespread increase in very intense precipitation events (upper 0.3% of events) over many land areas in the extratropics, in keeping with model projections for warmer climates. The magnitudes of such events over the United Kingdom (UK), for example, have doubled since the 1960s, causing large flooding disasters. However, studies for similar events over the US indicate that intense events today occur with frequencies that are similar to those of a century ago, with a more benign period in between events. Likewise, major summer flooding events along the Elbe and Oder Rivers of central Europe show no significant trend over the past 150 years, and indicate that winter events have actually decreased – likely because of the impacts of warmer temperatures. Researchers note that these trends may be affected by significant river engineering and land use change influences as well as changes in climate. Paleo studies also suggest that storms over oceans (which account for a significant part of observed increases in precipitation) were not strongly linked to temperature variability until the past 50 years or so, and do not show a significant long term trend over the past five centuries. Such results are a reminder that caution is needed in attributing recent trends in extreme extratropical precipitation events to external forcing factors[185,378-380].

Most hurricane experts also agree that it is too early to suggest that climate change is causing the recent flurry of intense tropical Atlantic hurricane activity. There appears to be no strong evidence, for example, that the duration or timing of the cyclone season or the dominant cyclone tracking in the tropical Atlantic and Caribbean has changed significantly over the past century. Furthermore, variabilities of these parameters are also not clearly linked to regional SSTs or global temperature trends. Some experts argue that such activity is dominated on decadal time scales by the multi-decadal Atlantic Oscillation, and that we may be in an active phase for the next few decades. However, others note that this trend may be at least partly offset over the next few years by opposing effects of a concurrent decadal oscillation. There are indications that the frequency of category 4 and 5 storms relative to weaker storms has significantly increased across all tropical ocean basins in recent decades. Likewise, trends in an index of total dissipation of power by all hurricanes show a marked increase since the 1970s that is highly correlated with a rise in regional ocean temperatures. However, other climate variables such as wind shear and sub-surface ocean temperatures may also affect hurricane behaviour. Furthermore, there is as yet no strong evidence of upward trends in the dissipated power of hurricanes that make United States land-fall[381-391].

The insurance industry also reports that both the number of natural disasters – primarily weather related – and the damage they caused in recent years are unprecedented since the 1960s. While demographic factors contribute significantly to the increase in damages, so do the meteorological factors[392-395].

5.4.7 Ecological

Experts note that changes in behaviour of biological species may be useful indicators of climate change and hence encourage the development of related phenological monitoring networks. Fortunately, there has also been a resurgence of public interest in participating in such networks. Although site specific in nature, when coupled with satellite data, the information provided by such networks can provide a broad indication of how ecosystems are changing. Several recent studies have reviewed the results of many related research projects that have used such phenological data to assess the behaviour of a very large number of different biological species. Experts note that about 80% of the reported ecological changes (most from the Northern Hemisphere) were consistent with changes in climate. On average, species assessed had moved poleward by up to 6 km/decade, and the phenological onset of spring had advanced by 2 to 6 days/decade. As expected, changes were greater at high latitudes than low latitudes, and for animals and birds than for trees. The large number of species involved has helped to enhance the confidence in the link between biological trends and climate[396-400].

Recent reports of biological trends in Canada include:

- A coherent pattern of change in the physical-biological system across the Arctic, linked to three dominant factors: interdecadal variability; a regime shift since 1989 and a long term linear trend[401];
- The loss of a rare ice lake ecosystem when an ice dammed lake on northern Ellesmere Island drained following the recent break-up of the Ward Hunt Ice Shelf[402];
- Unprecedented chlorophyll production and widespread changes in species composition and ecological organization in a number of high arctic lakes during the past two centuries, relative to the preceding 5000 years, consistent with regional changes in climate[403-406];
- A 98% decline in Peary Caribou populations in the western Queen Elizabeth islands since 1993, likely caused through die-off during heavy snow and ice winters in the mid 1990s[407];
- Changed distribution of polar bears along the western shores of Hudson Bay, connected to altered ice break-up patterns[408;]
- A recent change in diet of local bird colonies in Northern Hudson Bay, with increased content of capelin and sandlance in their nestling diets, relative to Arctic cod. This is indicative of a change from Arctic to sub-Arctic fish in the local waters[409];
- Recent declines of salmon stock in the North Atlantic appears to be linked to a climate induced range contraction[410];
- Spring arrival of bluebirds and swallows into Alberta about two weeks earlier than in the 1960s[411].

Elsewhere, rising temperatures in two large African lakes (Lake Tanganyika and Lake Malawi) have caused a sharp drop in lake primary productivity. That in Lake Tanganyika has decreased by 30% since 1975, threatening the survival of many unique species within it[412-414].

Changes in climate also affect the local, regional and global carbon cycle. Since 1982, the net primary productivity (NPP) of global land ecosystems has, on average, increased by 6%, adding 3.4 GtC to the land based ecosystem carbon reservoir. Largest increases occurred in the tropics perhaps due to reduced local cloudiness and related enhancement of solar radiation. However, increased respiration and fire loss may have offset the enhanced tropical NPP, resulting in little net ecosystem change at these latitudes. In northern forests and tundra regions, the enhanced carbon uptake appears to be primarily linked to warmer temperatures. In contrast, NPP in the global oceans has decreased by 6% since the early 1980s. Some 70% of this decline occurred at northern high latitudes, with warmer temperatures and reduced iron deposition being possible factors. In Antarctic regions, wind stress may be the dominant factor. There are also indications that, at least in some regions, warmer water temperatures are beginning to induce significant seasonal shifts in biological activities, such as the timing of plankton blooms and turtle nesting[25,415-420].

5.4.8 Detection/Attribution

Experts now generally agree that the Earth's climate and ecosystems are undergoing large and potentially disruptive changes, and that these changes have accelerated in recent decades. Some argue, based on time series analysis of data from the past few millennia, that recent changes can be entirely explained by natural factors. However, simulations with a coupled climate vegetation model, constrained by ice core data for past CO_2 concentrations, suggest that global temperature variations over the past millennium have been within 1°C. This small range of variation is inconsistent with the large solar forcing-climate feedback that would be required to explain recent trends on the basis of natural forcing only. Furthermore, while trends prior to 1970 show a significant solar-temperature connection, the warming since 1970 is clearly dominated by non-solar factors. To attribute past changes in climate to the combination of factors involved, both in space and time, is a complex process that requires a range of Earth system models to describe and explore the complex array of processes and feedbacks at work within the climate system. These models can be used to study both how the internal climate system varies in the absence of forcing and how external climate forcings, both natural and anthropogenic, may have affected the climate system in space and time, individually and together. Numerous studies of this kind continue to add to the growing knowledge base and confidence in attributing past changes in climate to such causes[421-423].

Some studies have used such models to investigate the evolution of climate response to external forcings over the past few millennia, hence including periods that significantly predate industrialization. Results indicate that the largest short term climate anomalies over the past few millennia occurred after large volcanic eruptions during periods of solar sunspot minima. However, the long term (multi-decadal) regional influences of such eruptions are modest and tend to be less than that of natural variability. In contrast, solar forcing creates long term regional influences, like the Little Ice Age, that exceed variability in an unforced system. Between the 1950s and the late 1980s, the amount of solar radiation reaching the Earth's outer atmosphere declined slightly. Furthermore, the fraction of this incoming energy reaching the Earth's surface has also been decreasing. This solar 'dimming' at the surface has been attributed to direct and indirect effects of rising aerosol concentrations, and has been stronger in polluted regions than in other less polluted areas. Model studies suggest that this has impacted the regional pattern of heat and moisture fluxes in the lower atmosphere and hence on precipitation patterns over the past 50 years. During the past few decades, however, the sun has become somewhat brighter, and pollution control measures have help improve atmospheric transparency. However, there appears to be debate amongst experts as to how significant these trends in solar insolation are in terms of net climate forcing. On the anthropogenic side, key historical forcing factors have been deforestation through human land use change (a significant cooling factor during the 19th century) and the gradual rise in greenhouse gas concentrations in the atmosphere (a warming influence). Rising greenhouse gas concentrations became an increasingly important factor during the 20th century, although their effects were partially offset by the cooling effects of land use change. Inclusion of all of these forcings can significantly improve the ability of models to simulate past climate trends and variability[424-429].

Numerous simulations with advanced coupled climate models have now been used to explore in more detail which of the above climate forcings may have played dominant roles during the 20th century. When all key natural and anthropogenic forcings factors are included, most simulations now agree remarkably well with observed conditions, including the decade to decade variability. This suggests that the models can replicate observed conditions with considerable confidence. Furthermore, on a global scale, they all agree that increasing solar radiation and decreasing volcanic dust loading in the atmosphere were dominant contributors to the warming observed during the first half of the century. However, despite indications that solar irradiance may have increased again in recent decades, net solar and volcanic forcings were small and likely negative during the second half of the century. In contrast, anthropogenic forcings increased rapidly. Hence the evidence continues to build that most of the warming during this period is attributed to rising greenhouse gases, partially masked by the effects of human aerosols emissions[91,430-431].

Numerous studies have also used the patterns of climate change, vertically, horizontally and over time, as a means for 'fingerprinting' the cause of past changes in global and regional climates in greater detail. Such studies are based on evidence that each type of forcing imposes its own unique spatial and temporal pattern on the different parts of the climate system. They also often use combinations of different climate variables as indicators of change, rather than single variables. The simulated patterns of temperature change are, for example, different for the spatially variable solar induced warming than for that due to well mixed greenhouse gases. The differences in precipitation patterns are even more pronounced. Most studies now indicate that detection of the anthropogenic influence (through emissions of greenhouse gases and aerosols and through ozone depletion) on climate in recent decades can be made with confidence in both the global troposphere and stratosphere. Attribution of recent change to human factors can now also be made at continental scales, such as that of North America and Europe. A significant short term role for volcanic forcing can also be detected. Likewise, multi-decadal natural variability is an important factor in explaining past climate change. However, there is greater difficulty in detecting the net effects of solar variability. Some experts suggest that models may underestimate the effect of solar forcing in their simulations and overestimate that due to greenhouse gas and volcanic forcings, thus somewhat biasing results against detection of the solar forcing role[432-442].

There are still some that contend that, while models generally project that greenhouse gas forcing of the climate system in recent decades should have caused the troposphere to warm more rapidly than the Earth's surface, satellite data suggest that the reverse is true. However, as noted in section 5.3.2, recent corrections of the satellite data have resulted in good agreement between model simulations and observed climates, thus adding confidence to the performance of models in simulating climates. Such corrections are a reminder that discrepancies between model and observations may also be due to observational error[438-443].

Changes in global precipitation patterns during the 20th century are too large to be explained by internal climate system variability, but consistent with model simulations driven by both natural and anthropogenic forcings. Much of these changes appear to be connected to solar forcing during the early part of the record. However, enhanced greenhouse gas forcing appears to have been a significant contributor to increased precipitation in the tropical west Pacific Ocean since 1940, and hence to changes in extra-tropical winter circulation patterns. Increased discharge of freshwater from European rivers into the Arctic Ocean also appears to be best explained by regional hydrological effects of warmer climates[444-447].

The short-term climate impacts of large volcanic eruptions are clearly detectable in sea level rise and ocean subsurface data. However, like that for the atmosphere, the complex pattern of trends in ocean temperatures over the past 40 years cannot adequately be explained by natural forcings or internal variability. Rather, the recent pattern of change is best explained by surface warming induced by rising greenhouse gas concentrations, modified by ocean advection processes. Cooling effects from both volcanic and human aerosol emissions have delayed the ocean heat uptake that would have occurred from greenhouse gas forcing alone during the past century by about two-thirds[280,448].

There are also an increasing number of other aspects of climate response to radiative forcing that add to the confidence of climate fingerprinting. For example:

- The height of the tropopause has been rising in recent decades, consistent with an anthropogenic-induced tropospheric warming[449-452];
- Rising European temperatures, the 2003 intense European heat wave, trends in European spring and summer temperatures and changes in extreme warm and cold night temperatures around the world since 1950 have all been significantly linked to anthropogenic forcing of the global climate system[453-456];
- About one third of the rise in long-wave downward radiation over central Europe between 1995 and 2002, linked to rising humidity, has also been attributed to rising greenhouse gas concentrations[457];
- The pattern of changes in sea level pressure around the world are simulated well by climate models, and can only be explained by anthropogenic forcing factors[458];
- Although some model simulations capture the Arctic Oscillation behaviour and its effect on Arctic climate variability quite well, these are only able to replicate the recent trends in AO behaviour if anthropogenic forcings are included in the simulations. The same has been found for the recent changes in decadal ENSO behaviour[459-460];
- While regional changes in climate from one year to the next can be dominated by the effects of oscillations such as the NAO and AO, the large scale features of global warming trends over the past 30 years cannot be explained by these natural fluctuations[461];
- While experts agree that single weather events cannot, in general, be attributed to a specific global cause, the use of methodologies similar to those used in epidemiological disciplines can help determine how the risk of such events can be linked to causal factors[462].

There are other regional climate trends that are still difficult to link with confidence to specific climate forcings. Recent patterns in summer precipitation over Europe, for example, appear quite similar to that projected by models forced with natural and anthropogenic forcings, but the magnitudes of changes differ. Hence the observed changes cannot as yet be linked to causal factors. Furthermore, although changes in atmospheric circulation have also been suggested as appropriate indicators of climate change (and an important factor in attributing such change at the regional level), recent trends in behaviour of circulation features such as the winter NAO do not agree well with most model simulations forced with rising greenhouse gas concentrations. One of the reasons may be inadequate resolution of global circulation models. Investigations indicate, for instance, that higher resolution models can resolve important local surface heat and moisture flux feedbacks that are otherwise not included in model simulations. Hence, attribution of changes at the regional level may continue to be a problem until models include greater detail with respect to climate feedbacks[171,463-467].

There are also indications that the human fingerprint may be detectable in ecological responses to climate change. A study of forest fire activities across Canada indicate that the trend in area burned between 1922 and 1999 is closely related to observed trends in summer temperatures in the burn regions. These, in turn, have been attributed to greenhouse effect forcing. Likewise, significant changes in Arctic vegetation along the tundra/taiga interface in north-western Canada are also consistent with large regional changes in climate and related feedbacks that are attributable to anthropogenic forcing[468-469].

6.0 IMPACTS

6.1 Hydrological Resources and Events

In general, current generation coupled climate models are more consistent in their projections of future response of regional hydrology to warmer climates than those of earlier studies. On a global scale, they tend to project increased water resources in regions that already have plenty and decreased water supply in regions that are already dry. They imply significant decreases in soil moisture and runoff (10-30% below 20th century levels by 2050) in large areas of South America, East Asia, Africa, Australia, the Mediterranean and the western US. These decreases can be particularly large in areas where rising temperatures are accompanied by decreasing precipitation. In contrast, soil moisture and river discharges appear likely to increase in many mid-to-high latitude regions. Regional climate model studies, however, suggest that the coupled climate model studies may have inadequately allowed for the negative vegetation evapotranspiration feedbacks during periods of regional drought and hence over-estimated related risks[470-474].

Within Canada, rain driven streams in British Columbia are projected to experience both more frequent (but not necessarily more intense) floods and longer periods of low flow conditions in summer. In contrast, for snow and glacier driven streams, summer floods become more frequent and intense while low flows occur less often (since warmer temperatures increase winter runoff). In southern Manitoba, projections imply drier summers, reduced ground water recharge and lower water levels. In the Great Lakes Basin, a poleward displacement of atmospheric moisture transport will likely cause areas north and south of 42°N to become wetter and drier, respectively. Recent ensemble model results, averaged across the entire basin, suggest that annual increases in precipitation will exceed any increase in evaporation loss. Hence, everything else being equal, this implies a net annual increase in water supply to the basin. However, net water supply decreases in summer. These results appear to differ from those derived in past studies and need further investigation[475-478].

Other regional studies project that warmer temperatures coupled with increased heavy precipitation events will increase the prevalence of both dry periods and flooding conditions across the US. Changes in atmospheric circulation induced by reduced Arctic sea ice cover and other factors play a role in the risks of such extremes. Furthermore, paleo records for the western US, in addition to providing supporting evidence for a linkage between warm temperatures and severe droughts, indicate that severe droughts of the past century are modest compared to extremes of the past 1200 years. Thus the risks of such droughts within the context of natural variability may also have been underestimated. For England and Wales, projections indicate more intense precipitation events, rising seas and increasing social vulnerability. These could collectively increase related economic losses by up to 20 times current values by 2080[479-482].

6.2 Agriculture

Some studies indicate that world-wide food production during the next century should be adequate to feed global population, but that there will likely be an increased imbalance in food distribution, thus increasing food prices and risks of hunger in the poorest countries of the world. Others caution that projections for enhanced risks of major droughts during agricultural growing seasons, particularly in much of SW North America and in tropical regions, may also cause periods of net global food shortages. Furthermore, studies with high resolution Regional Climate Models suggest that analysis based on coarse General Circulation Model outputs may underestimate the regional warming and overestimate precipitation. Hence they may be too optimistic in estimating net impacts on agricultural production[483-486].

In most international studies, Canadian agriculture is generally seen as one of the major beneficiaries of future climate change. Canadian studies into regional and crop specific impacts of climate change have been less optimistic, suggesting both significant benefits and liabilities. However, a recent assessment using an econometric model to assess land values under warmer climates also implies that, with adaptation, all provinces will benefit, with largest gains in the Canadian Prairies. Researchers do note that the study does not address physical constraints to adaptation, and that many existing government policies such as crop insurance and other support programs would need to be dismantled[487].

6.3 Natural Ecosystems

The response of global forest ecosystems to climate change will be complex. In the central region of their range, forest species may initially be resilient to change – until certain thresholds are exceeded. Once exceeded, change can become rapid and result in a dramatically different combination of species within the ecosystem. Unless these relationships are well understood, it will be difficult to predict with confidence how climate change will affect such ecosystems[206,208,488].

For Canadian natural ecosystems, projected changes in climate are likely to negatively affect boreal forest regions but enhance biological activity in many tundra regions. Forests will also expand into the tundra, and the species in emerging ecosystems will change in composition, become more diverse and more productive. The tundra ecosystem response will be determined as much by hydrologic factors as temperature change, and will have complex effects on the physical properties of the landscape, including surface albedo and carbon fluxes. Because both photosynthesis and respiration will likely increase, these changes will involve an enhanced rate of carbon flux in and out of the ecosystem. Much of the increased tundra productivity will arise from the proliferation of woody species. Fire, disease and insect outbreaks will increase. This will be particularly important for the boreal forests. Large forest fires represent only 3% of all Canadian fires, but account for about 97% of forest area burned each year. Although annual losses currently average about 2 million ha, but can exceed 7 million ha, current fire frequencies at many Canadian sites (particularly in Quebec) are likely lower than historical levels during the 19th century. However, future warming will likely once again increase fire risks, particularly in the boreal forests and peatlands of the Yukon, northern Ontario and Quebec, with annual burn area across Canada likely to double by the end of the 21st century. Fires caused by human activity will also play an important role in this increase. Enhanced rainfall may mitigate these increases in risks in some regions of Canada, but none of the regions are likely to see decreases in risks. Such fires could result in large emissions of carbon dioxide into the atmosphere. Appropriate forest management could help reduce these risks[489-495].

Forest ecosystem productivity is also significantly dependent on the amount of summer precipitation. On the Canadian Pacific coast, for example, a 10% decrease in rainfall or 6% increase in evapotranspiration would reduce marketable timber production over a stand life-time by 10-30%. Many model-based studies have assumed that the direct effect of higher CO_2 on leaf stomata density would help reduce evapotranspiration per unit leaf area and thus help mitigate the possible effects of reduced rainfall. Related experiments on 15 different types of plant species, however, showed stomata aperture decreasing only slightly under higher CO_2. More importantly, there was no noticeable change in stomata density[496-497].

With a dramatic reduction in Arctic sea ice cover in summer and a significant shift of the entire Arctic climate to temperatures above freezing, the entire high arctic physical-

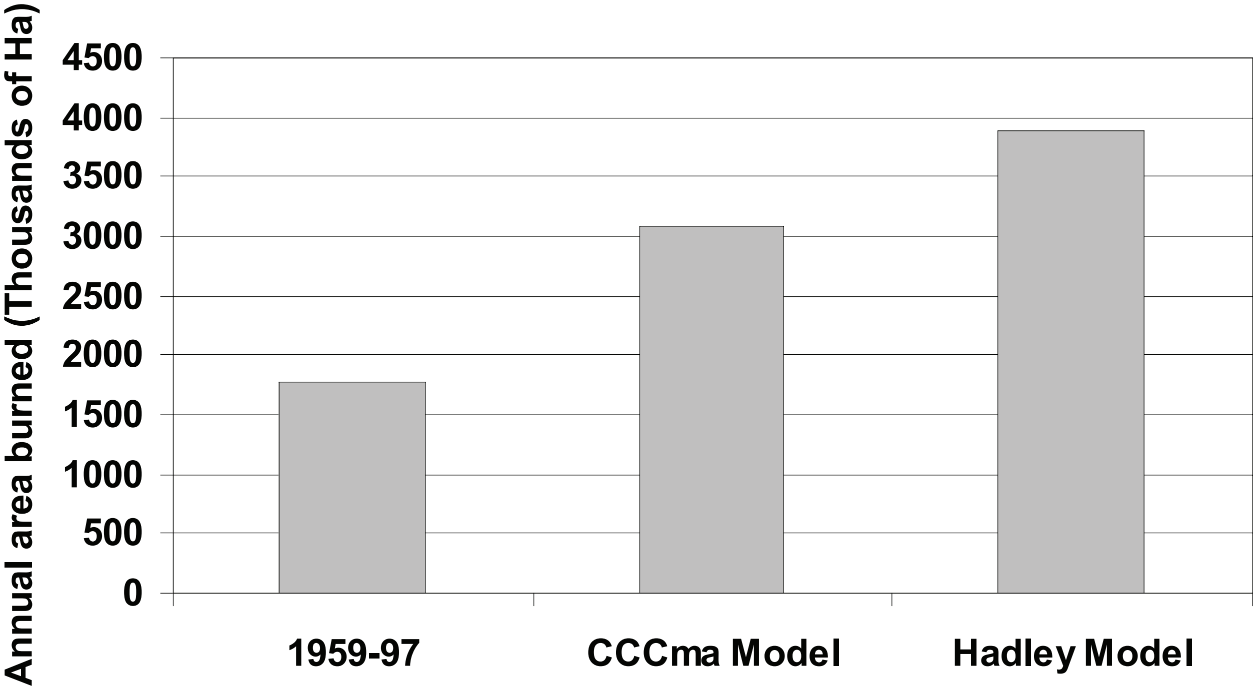


Figure 5: Based on historical relationship between weather, fire weather index and area burned applied to regional climate projections from two different climate models, total annual fire loss in Canada's boreal forest could increase by 70 to 120%, relative to current loss rates, under warmer (3xCO_2) climates expected near the end of the century (Flannigan et al. 2005, reference #491).

biological system will also change dramatically. However, many aspects of this complex and interconnected system remain poorly understood. Some species will be at risk. For example, increased frequency of warm rain events will increase risks to ringed seal populations established along Arctic coastal areas by collapsing lairs and increasing exposure of seal pups to thermal stress and predators. Reduction in seal numbers in turn affects the bears that feed on them. Likewise, increased risk of heavy snow and rain-on-snow events under warmer, wetter winters could have serious impacts to Arctic ungulates such as the Peary Caribou herds, already devastated by recent events. For many of the Arctic flora and fauna species, the dominant response will be relocation, rather than adaptation. For others, relocation may not be an option[407,498-502].

Ocean primary productivity is projected to increase globally by up to 8%. However, the oxygen content of the sub-surface ocean will gradually decline. Should the thermohaline circulation system break down, an extensive deep ocean anoxia could slowly develop, with local oxygen levels declining by 20-40% within six centuries. In the marginal sea ice regions of the sub-polar oceans, sea ice retreat will likely cause the highly productive regional ocean biomes to contract significantly in area (42% in the Northern Hemisphere). Furthermore, at low latitudes, the low productivity zone will increase slightly in area. Some of the coral reefs in these regions are likely to experience extensive bleaching and die, while others may develop new symbiotic relationships with heat tolerant algae that help prevent bleaching. Although this suggests that coral may be more adaptive to climate change than previously thought, the composition of corals could change dramatically. Higher ocean acidity would further exacerbate the effects of rising temperatures. Some suggest that these stresses on corals could, by mid-century, have devastating effects on reefs and the biodiversity and societies that depend on them[167,503-507].

Experts caution that, when assessing the impacts of climate change on ocean ecosystems, the very strong regional impacts of multi-decadal oscillations must also be considered. This is exemplified by the large impacts of the multi-decadal changes in Pacific Ocean climates over the past 50 years on the varying abundance of anchovies and sardines in the region. Furthermore, the relationship between the abundance of the lower levels of the food chain with temperature is modified by ocean dynamics, and hence complex. This relationship is positive, for example, in the more turbulent, nutrient rich cool waters of the north Atlantic and negative for warmer, stratified equatorial waters. Hence the response of ocean ecosystems to future climate change will be complex[508-509].

Within freshwater systems, local fish diversity may decline by up to 75% by 2070 in rivers with reduced discharges – most of which are located in poor countries. However, regional changes in water and ecosystem management could help reduce these losses. Future warming will also constrain the period of time for the annual migration inland of certain fish species. This may, for example, threaten sockeye populations at the southern end of their range off the coast of British Columbia. Within European lakes, a 1°C warming could be enough to cause the overturning of waters in deep lakes to cease. The consequent lack of oxygen supply to deeper waters would break the nutrient cycle and irreversibly destroy the deep lake biota species. In contrast, warming in shallow lakes, while negatively impacting cold water species, would likely penetrate through most of the vertical water column and thus help retain overturning. In alpine lakes, such changes would likely result in a shift towards smaller species and increased risk of invasion by exotic species[510-513].

There could also be a sharp increase in species extinction probabilities by 2050 on global scales. One study, for example, indicates that, on a global scale, a 2°C warming might commit as many as 37% of the more than 1000 species examined to eventual extinction. Some suggest the risks of extinction could be even greater if other pressures on species composition, distribution and abundance as well as increased habitat fragmentation are also considered. One such example of such ecological impacts already taking place is the dramatic decline and extinction of many frog species in the American tropics, likely a result of the break-out of a pathogenic fungus triggered by increased night-time temperatures and daytime cloud cover. Other examples relate to the different rates of ecological response along the migration corridors of bird species such as the pied flycatcher, and to the decrease in Prairie wetland habitats required by migrating water fowl in North America[514-519].

6.4 Cryosphere and Sea Level

Projected changes in the precipitation-melting balance of the Greenland ice sheet under warmer climates are expected to cause the ice sheet volume to continue to shrink. However, because of poor model resolution and uncertainties in projected climate change, the rate of such decrease is not well defined. In Antarctica, on the other hand, the projected increase in precipitation may exceed enhanced melt rates, resulting in a positive ice balance that could offset the Greenland deficit. When added to long-term background depletion trends, the net impact of ice sheet response in both polar regions to warmer climates on sea level rise over the next century may be close to zero. However, the related rise in sea levels is expected to be increasingly positive in subsequent centuries. If, for example, a warming of 3˚C or more is sustained beyond 2100, the Greenland ice sheet could completely melt within the next one to three millennia. Fully depleted, the ice sheet would add 7 m to global sea levels. Once this process begins, feedbacks would likely make the process irreversible[520-525].

Other small ice caps and glaciers around the world will also continue to melt, adding to global sea level rise. Total ice volume stored in these smaller land ice masses is estimated to be equivalent to a sea level rise of 24 cm. When glaciers linked to Greenland and Antarctic ice sheets are included, this potentially increases to 50 cm of sea level rise equivalent. This will add to rises caused by ocean thermal expansion. The direct effect of such sea level rise on coastal communities and ecosystems will be exacerbated by coastal erosion. Some estimates suggest the combined impact of both processes on fixed coastal structures could be double that due to sea level rise only[526-527].

Warmer climates will significantly degrade permafrost in high latitude and alpine regions. Increasing winter snow cover or ice crusts due to rain-on-snow events will enhance this degradation in some areas by insulating soils from cold air temperatures, while in other areas the effects of warmer air temperatures may be partially offset by a projected decrease in winter snow depth. Land area currently experiencing rain-on-snow events could increase by 40% by the late 21st century. Recent projections indicate that the depth of the thaw layer across most of the Arctic permafrost region is likely to increase substantially. This could also significantly change the hydrology and stability of affected land masses. Melting ground ice would add to the enhanced freshwater discharge into the Arctic Ocean caused by increased high latitude precipitation. While such permafrost retreat would allow a significant increase in tundra soil carbon fluxes and a northward migration of shrubs and boreal forests, the net impact on surface and subsurface hydrology and carbon cycles are not well understood[500,528-529].

Climate models do not as yet capture well the complex interplay between atmospheric, ocean and sea ice processes in polar regions. Hence, there is still significant disagreement between different simulations with respect to polar sea ice response to warmer climates. Those models that show thick Arctic ice in control simulations also tend to show less global warming than those with thin ice, while the opposite is true in the Southern Ocean. All models, however, project a large decline in polar sea ice. While such a reduction may ultimately lead to much easier shipping in Canadian Arctic waters, the reverse may hold in the next few decades. While warmer temperatures are expected to cause a thinning and more extensive break-up of the relatively smooth ice between the Queen Elizabeth Islands, such break-up will allow very thick and hard old ice from the Arctic Ocean to pass through these channels and enter the North West Passage. This would make shipping in the region more hazardous until the old ice disappears from the Arctic Ocean[530-532].

6.5 Extremes

There are a number of climate variables that influence the frequency of extreme temperature events, including changes in atmospheric circulation, global surface temperature gradients and local feedbacks. Since these variables do not always change linearly with mean temperature, predicting how such extremes will respond to global climate change is difficult. However, model simulations consistently indicate that warmer climates will cause heat waves over Europe and North America to become more intense, more frequent and longer. This will have greatest impact on those regions where such events are currently relatively unusual, since populations in these areas are less well adapted. A good example of such events is the heat wave in Europe in the summer of 2003, an event with a statistical historical return period estimated at between once every 9,000 and 46,000 years. Model simulations also continue to show that warmer climates will likely increase the variability of temperature extremes in areas now covered by snow and ice and where soil moisture is reduced. In parts of the tropics, increases in both mean temperatures and temperature variability could cause current 1 in 20 year seasonal extremes to become almost yearly events by 2100[533-537].

Simulations with both global coupled climate models and the more detailed regional climate models project that changes in extreme precipitation will be highly correlated with future trends in mean precipitation and that the probability of heavy precipitation will increase in most regions of the world. This increase is influenced by a shift in rainfall distribution towards more intense events as well as an increase in precipitation variability. Simulation results suggest, for example, that, around the world, the intensity of the 30 yr precipitation extreme would, on average, increase by 14% by 2085, with larger increases of 10-30% over the tropics. Extreme monthly rainfall events in the UK that now occur once in 20 years could occur once every 3-5 years by the end of the 21st century. However, the probability of such events can also be influenced by local factors, including vegetation feedbacks. For example, the intensity of severe convective storms in summer may be weakened by the direct effects of higher CO_2 on plant evapotranspiration. Alternatively, changes in crop seasons will affect evapotranspiration patterns, which may in turn alter the onset of severe summer weather seasons[186,538-541].

There are indications that, under warmer climates, the total global number of tropical storms may decrease, although not over all ocean basins. However, multiple simulations using various convection schemes and models indicate that, under nearly all scenarios, hurricane wind intensity increases (by an average of 6%), as does the precipitation rate within 100 km of the storm centers (by an average 18%). A 10% increase in wind power would increase the power dissipated by a hurricane by 40-50%. Hence, the risk of occurrence of extremely destructive category 5 hurricanes is expected to gradually increase with time[383,384,542-543].

The total number of cyclones occurring annually outside of the tropics will also likely decrease as climates warm, but intense cyclones will become more frequent. Estimates suggest that intense Southern Hemisphere extra-tropical cyclones will increase in number by more than 20% in both winter and summer, while increases of this magnitude in the Northern Hemisphere are limited to the summer season. Average daily maximum winds are also expected to rise. These increases, which are linked to changes in lower tropospheric baroclinicity and to feedbacks between precipitation and storm intensity, are projected to be greatest along the east coasts of North America and Asia. Storm tracks are expected to shift poleward[187,393,544-546].

Increased intense cyclone activity and more intense positive NAO patterns also affect the frequency of extreme wave heights. For the Atlantic Ocean, these are expected to become more frequent in the northeast and in the southwest in fall and winter, but less frequent in mid-latitudes[547].

Very few studies to date have considered the socio-economic and ecological consequences of abrupt and rapid changes of global climate from one equilibrium state to another. Yet both paleo records and computer simulations suggest that the earth's climate system has and can again undergo such potentially catastrophic discontinuities. Furthermore, the likelihood of such events appears to increase during times of rapid change in mean global climates. Experts caution that related risks also need to be factored into assessments of the long term risks associated with climate change[189,190].

6.6 Socio-Economic Impacts

Many experts consider the impacts on the health and well-being of people as one of the most worrisome aspects of climate change. Greatest increases in related risks will likely occur in Asia and Africa, although many of the poor countries in these regions are already so vulnerable that the added relative risk may be small. Increased water stress may be particularly problematic. In many regions, some already stressed, annual water supply will decrease. These include the Mediterranean, parts of Europe, central and South America and southern Africa. Although other regions such as south and eastern Asia will likely see increases in water supply, this may not occur during the dry season when it is most needed. Therefore, between 370 and 1.7 billion people could experience increased water stress by 2020, increasing to 670 to 2.8 billion people by 2050. Another concern is increased exposure to UVb radiation. Related investigations indicate that continuing stratospheric cooling induced by an enhanced greenhouse effect may increase the vulnerability of Arctic regions to severe ozone loss events. Thus the expected recovery of the Arctic stratospheric ozone layer as ozone depleting substance emissions are reduced under the Montreal Protocol may be prolonged. Similarly, the success of measures to improve air quality in industrialized regions like those of eastern North America may be partially offset by the secondary effects of local climate change on related atmospheric chemistry[268,548-551].

The economic implications of future climate change are difficult to assess, since related metrics vary with societies around the world. Related studies disagree on methodologies, and hence on the quantification of aggregate costs and benefits. They also tend to ignore the complexity of the impacts on humans, particularly the inequitable distribution of adverse versus beneficial effects involved. Related research lags that of the physical sciences. Qualitatively, there is general agreement that net costs become increasingly negative with higher and more rapid rates of warming, and that, if the warming exceeds 3-4°C, all economic sectors other than possibly forests are increasingly likely to be adversely affected. Numerous studies already show that poor people and poor countries are most vulnerable and adversely affected, while much of the benefits accrue to wealthy countries. Equity weighting approaches may help address these biases. Adverse impacts of climate change on developing countries may also increase potential for conflict and disruption of populations in these countries and cause related pressures for migration and emigration. Authorities in recipient countries such as Canada need to anticipate and prepare for such mass migrations. However, lack of related research makes such linkages between climate change, poverty, ethnicity and the politics of conflict somewhat theoretical[552-556].

There have also been a number of recent studies that have considered how climate change may affect local and regional socio-economic activities in Canada and elsewhere. Projections include:

- an increase in social vulnerability to heat stress during high temperature events, particularly in densely populated areas[557];
- increased stress on the ecosystems of coastal regions such as that of the north-west Pacific that will challenge managers of water, forests, salmon habitats and other natural resources[558];
- a decrease in cargo ship load capacity and hence potential increase in costs of marine shipping goods by up to 29%, should water levels in the Great Lakes drop significantly[559];
- less international travel by temperate latitude tourists, and a growth in mid to high-latitude and altitude tourism, relative to regions with hotter climates. For the ski industry in southern Ontario, warmer winters may reduce the season by between 60 and 90% by 2050, and hence adversely affect related industries[560-561];
- increased land instability in alpine regions due to permafrost decay, with related impacts on regional socio-economic activities[346];
- little net economic loss imposed by climate change on Canadian agriculture before 2020, providing adaptation options are fully utilized at no cost and there no increase in extreme events[562];
- demographic factors, rather than trends in weather behaviour, appear to be the dominant cause for rising weather disaster related economic losses in the US[563].

7.0 MANAGING THE RISKS OF CLIMATE CHANGE

7.1 Science-Policy Debate

The debate about climate change within the science community is gradually shifting away from whether it is happening and how serious it will be to how to deal with it. The general consensus is that global warming is already occurring, that fossil fuels combustion is the primary cause, and that the negative impacts of weather and climate events will get much worse. Although there are some who continue to argue that attribution of climate change is not yet possible, such conclusions appear not to be supported by the scientific literature. Furthermore, there is the real and significant risk that the climate system, when undergoing large changes, can become unstable and hence respond abruptly once it passes a critical threshold. This argues against a wait-and-see position, since it is too late to respond once we pass such thresholds. While science cannot provide the political will to solve these concerns, it can help to overcome social, economic and political resistance to change[189,214,564-572].

Part of the remaining scientific challenge is to understand how climate change will affect local weather and surface conditions, as yet an elusive goal. Various researchers have identified critical threshold beyond which harm to ecosystems or societies may be considered unacceptable. However, there is also considerable debate about how such knowledge can be used to determine what constitutes 'dangerous interference' with the climate system as described in the United Nations Framework Convention on Climate Change (UNFCCC). This is partly because as yet little research has been invested in understanding public perception of what is and is not dangerous. A variety of studies have added to the range of criteria that might be considered. Disintegrating polar ice sheets, rising sea levels, coral reef dieback and increased risks associated with extreme weather, for example, are dangerous to the survival and hence sovereignty of atoll countries. They also pose serious risks to other countries. Furthermore, the scientific community may have seriously underestimated climate instability and the related risk of catastrophic surprises. Addressing such vulnerability through policy regimes will require a precautionary approach that also addresses principles of justice, sovereignty and security. However, there is also danger involved in waiting for more detailed assessments, since this may result in missing the window of opportunity for cost-effective mitigation. In regions with long indigenous traditions, use of traditional knowledge may help in assessing vulnerabilities[189,434,564,573-579].

The IPCC assessments continue to be the primary process for developing thorough overviews of the current state of scientific knowledge relevant to the climate change issue – including what aspects of the science is well known and what needs further investigations. Several economists have argued that the economic methods used by the IPCC in developing future greenhouse gas emission scenarios are seriously flawed. Others, however, have countered that some aspects of their arguments are misinformed and that the primary emission scenarios used by IPCC remain robust. Various scientific societies and academies such as the American Meteorological Society have issued declarations of support for the IPCC assessment process and its conclusions to date, but have also acknowledged the need for more research on improving climate model projections, particularly at the regional scale. Similar statements were also made by editors of leading scientific journals. However, sceptics have argued that international assessments undertaken by IPCC and others should not be accepted without relevant debate. Furthermore, they caution against marginalizing or dismissing those who disagree with the plurality of the scientific research community[566,580-588].

In addition to reducing uncertainties, scientists have the major challenge of effectively communicating with decision makers about the science of climate change and the related risks of danger. One complicating factor is that, unlike the use of exposure to harmful UVb as the metaphor for danger that helped science-policy interactions on stratospheric ozone depletion, there is no such metaphor yet developed to exemplify the risks of climate change. Experts have argued that, as a pre-requisite to better communication, the science community must first better describe scientific uncertainties in risk language and terms that non-scientists can understand. They note that this will require, among other things, more formal, published analysis of climate and economic models used in projections, the solicitation of expert opinions where key uncertainties remain un-quantified, a broader involvement of organizations other than IPCC in science assessment and communication, and a better understanding of which climate indicators are important to policy makers and the average citizen. The IPCC method of using relative shades of likelihood may not be the best way to communicate such risks, since the concept of likelihood has different interpretations and applies to probability of occurrence only, not its intensity. Surveys indicate that terminology needs to be developed that relates to the concerns, interests and activities of average citizens, thus providing practical knowledge that can be tested against collective and individual experience of the citizen. Furthermore, some experts caution against too much focus on the socio-economic aspects of climate change risks, since that could result in the climate policy debate becoming hostage to the necessity of dealing with other non-climate related equity issues[589-594].

While better understanding and communication of uncertainties about climate change science are important, there is also a need for improvement in ***how*** scientists communicate with decision makers and other citizens. One of the challenges noted is to enhance direct contact between researchers and other interested parties, including the media, in order to ensure quality reporting of science. Scientists also need to challenge journalists on their tendency to seek "balanced reporting" by presenting opposing views of a topic with equal weight, without considering or reporting the credibility or marginality of these views. Such reporting can create a significant bias in communication – a bias that some argue is particularly apparent in high profile North American media. This requires related training for scientists and the active encouragement of scientists to communicate with non-scientists through media and popular articles[595-597].

While the international policy community has made progress on some short term goals under the Kyoto Protocol for reducing the risks of climate change, experts caution that success ultimately depends on long term mitigation strategies that involve far more stringent actions to reduce greenhouse gas emissions. However, because of vastly different perspectives and vulnerability of nations to long term climate change, policy makers developing such strategies need a portfolio of tools and estimates. One such tool often used to assess risks of danger due to future climate change is that of cost-benefit analyses. Results suggest that, although ecosystems may already be significantly affected once temperatures rise by more than 1 to 2°C, aggregate costs may not become pervasively negative until temperatures rise by 3-4°C. However, many argue that such analyses are seriously flawed because they inadequately address issues of large regional inequities, where major damages in the tropics are offset by gains in mid to high latitudes. Furthermore, the delay in realization of impacts relative to the emissions that causes them raises concern about economic discounting practices used in such analyses. One option to address such inequities might be to compensate those adversely affected[554,598-602].

There are alternative approaches that can add insights into policy response options not addressed in most cost-benefit analysis. One is to identify a range of critical danger thresholds and determine the probability of exceeding these. Some experts, with the help of integrated assessment models, suggest an absolute temperature change threshold in the range of 2 to 3.5°C. Such a threshold would still have a greater than 50% likelihood of being exceeded if CO_2 concentrations are stabilized at levels below doubled CO_2, and has a 17% probability of being surpassed if we were to maintain concentrations at current levels. It is also argued that uncertainty adds urgency to the need for early action, rather than for inaction[603-606].

Another concept which can help guide policy thinking on action strategies is the Tolerable Windows Approach. Also based on integrated assessment model outputs, this approach seeks action alternatives that both avoid dangerous climate change and consider economic tolerance criteria. Again, results from such studies suggest that, for example, significant ecological transformation in 25% of the world's protected nature reserves by 2100 may already be unavoidable. They also indicate that mitigative actions taken by one country will have international repercussions on other countries that need to be considered[607-609].

Some experts also call for the need to introduce concepts of environmental justice, which encompasses all justice issues including that of equity, into the policy response debate. They note that this concept may be the key to developing workable policies on climate change that will help resolve the risks posed by climate change. Studies suggest that many of the poor and most vulnerable people are actually quite resilient and adaptive providing they have adequate room to manoeuvre (referred to as 'head room'). Hence policies that promote more 'head room' may be effective in improving local adaptation potential and addressing equity issues. However, much work needs to be undertaken to identify and study the relevant issues involved in environmental justice. Furthermore, just and equitable climate change policies should be undertaken fully within the context of sustainable development action, rather than as an add-on[610-615].

7.2 Mitigation

Limiting future climate change to less than a 2°C warming threshold – regarded by many as a critical danger threshold – would require stabilizing atmospheric CO_2 concentrations to less than 2x CO_2 (~560 ppm). There is a two in three chance that CO_2 concentrations can be stabilized at 2x CO_2, which would likely commit the Earth's surface to a warming of 2.9°C. At a minimum, this would require that emissions fall well below current levels and that some 75% of energy production by 2100 would need to come from carbon free energy sources – a challenge that would require immediate efforts to develop the required technology. If CO_2 emissions are maintained at current levels, a warming of 2 to 6°C and a sea level rise of 25 cm per century would likely occur over the next four centuries. Even if all greenhouse gas emissions were immediately stopped, the change in atmospheric composition due to past emissions may already have committed the Earth to an additional, as yet unrealized warming of as much as 1°C. Some argue that the best compromise may be a hedging approach that takes enough action in the near and medium term (by 2020) to keep open the option for stabilizing at 450 ppm, should the results of future studies into critical thresholds prove that to be necessary[616-622].

Early action through, for example, a carbon tax, could be one near term action that could significantly reduce the risk of exceeding critical thresholds for danger. However, such economic action may already be too late to avoid danger if global climate sensitivity is high. While useful, such market driven solutions are not enough. Binding commitments are also needed. Consequently, the current reluctance of some developed countries to commit to such actions is reason for concern. There also appears to be inadequate effort in most countries to prepare for the changes that are already inevitable[574,569,604,606].

A number of technological alternatives to fossil fuel combustion have been promoted as means for achieving large emission reductions. For example, fuel switching from fossil fuels to hydro electric energy sources can largely eliminate related direct emissions of greenhouse gases into the atmosphere. However, such alternatives also need to consider indirect greenhouse gas emissions from flooded reservoirs used in such power generation. Reservoir emissions are relatively modest for most northern hydro-electric systems (up to 10% of that avoided by eliminating the use of fossil fuel combustion for similar energy production), but those for shallow tropical systems can negate any avoided direct emission reductions. Wind energy is another attractive option, aggressively promoted by a number of European countries. Although progress in North America is much slower, new improvements in design could make wind energy production as economical as conventional gas fired electricity production. Furthermore, there are other co-benefits of wind energy related to non-greenhouse gas air pollutants. Environmental risks associated with wind energy include small seasonal heating of surface temperatures associated with the heat energy released by the turbines. A third alternative is the use of renewable biomass as an energy source. However, such conversion may also have negative side effects from the release of aerosols during biomass combustion that need to be considered. Finally, some promote a move towards a hydrogen economy as an option that simultaneously improves air quality and mitigates the risks of climate change. However, much more work needs to be done to understand the total life cycle impact of this approach, including the effect of leakage of free hydrogen into the atmosphere on the chemistry of other greenhouse gases in the troposphere and stratosphere (e.g. methane, water vapour and ozone), and the effect of up stream emissions of greenhouse gases during hydrogen production[53,623-628].

Particulate black carbon and organic matter emissions are major contributors to past changes in temperature. Because the residence time of these aerosols in the atmosphere is very short, dramatic reduction in their emissions would quickly reduce their atmospheric concentrations and could therefore be one of the quickest and efficient ways of effective early action on climate change. Some argue that their lack of inclusion in the Kyoto protocol may therefore be a major oversight. However, the related science is complex and there is still considerable debate about how important these aerosols really are[629-634].

Sequestration of carbon through biological sinks, although controversial, is an alternative approach to reducing the rate of growth in atmospheric CO_2 concentrations, and hence the risks of climate change. Many of the land resource management practices required to achieve such sinks also provide additional benefits, such as reduced soil erosion and more productive agricultural soils, particularly in regions with badly degraded soils. Hence, carbon 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, while there is considerable evidence to suggest that such sinks are achievable, unless carefully managed, these sinks are not permanent. One option is to address the non-permanence liability in mitigation protocols through economic models that optimize the costs of CO_2 disposal against the risk of subsequent re-emission into the atmosphere. Such economic criteria, however, often rely on questionable assumptions, particularly with respect to discounting, and inadequately address non-economic considerations. Furthermore, some of the carbon removal induced by sequestration projects would have been removed any way because of natural sequestration increases under high atmospheric CO_2 concentrations[635-641].

Within the North American agricultural sector, past changes in land use practices appear likely to have already contributed to significant carbon storage in soils, although the confidence in the magnitude and even sign of this number is low. Projected land use change in the Canadian agricultural sector, particularly through conversion of tilled soils to grasslands and no-till, reduced summer fallow and spring application of nitrogen fertilizers, may increase this sink to 2 Mt CO_2 per year by 2008. With enhanced sink measures this could be increased to much larger values. Conversion of all US corn and soybean production to no-till operations could potentially generate a sink of 22 MtC/yr. These studies underscore the complexity of successful enhancement of carbon sinks in soils, and the challenge in developing accounting methodologies that are transparent and verifiable[642-646].

There are also other environmental concerns related to carbon sinks. For example, while afforestation may help remove and store carbon dioxide from the atmosphere into biological sinks, these measures also contribute to changes in land albedo (with reduced albedo causing a local warming influence in mid- to high latitudes) and evapotranspiration processes (a local cooling effect). Model simulations indicate that, if all land vegetation were converted to forest cover, the net global effect of these two processes would be a 1.3°C warming. Hence, climatic benefits of such sinks measures in reducing atmospheric CO_2 concentrations may be more than negated by other climatic impacts. Likewise, while the ocean carbon sink can be enhanced through iron fertilization of ocean surfaces, there may be related environmental implications for marine ecology. Recent experiments have not been encouraging in terms of the amount of actual carbon removed into the deep ocean through iron fertilization, although this may be because of the limited scale of the experiments. Finally, rising surface ocean acidity caused by the update of excess atmospheric CO_2 may in turn reduce the upper ocean carbon sink capacity[40,42,647-650].

Injecting vast quantities of liquefied CO_2, extracted from smokestacks of fossil fuel combusting industry, into the deep ocean can also provide a long term carbon sink. The effectiveness of such measures depends significantly on the rate of leakage back to the atmosphere. If less than 0.001 per year, this process can be an effective means of avoiding greenhouse gas emissions. If leakage rates are greater than this, the additional emissions generated during the capture and storage processes may actually make the process counter-productive. There are also environmental concerns about how large scale injection of CO_2 into the ocean might affect ocean acidity. However, the pH impact on water in the area of injection can be mitigated by techniques that maximize dispersion rates. Studies of organism behaviour near CO_2-rich ocean floor vents also suggest their adaptive capacity may be greater than previously assumed[651-654].

A third approach to CO_2 sequestration is the deposition of liquid CO_2 into deep geological reservoirs, such as saline aquifers and alkaline mineral strata, where the CO_2 is chemically immobilized. While costly (about \$40 to \$60/tonne of CO_2), this could eventually be feasible at about \$30/ton of CO_2, and may be environmentally more acceptable than other sequestration alternatives[655-656].

Verification of the reported success of national efforts to reduce CO_2 emissions and/or sequester carbon under the Kyoto Protocol involves a periodic audit process. Regional trends in atmospheric C^{14} concentrations may provide an independent method for checking the accuracy of such audits. Particularly challenging is the verification of carbon sinks claimed as offsets by reporting countries. To ensure this process is fair and open, an internationally coordinated monitoring system and international research into accounting concerns would be required[657-658].

7.3 Adaptation

Given that significant climate change is already unavoidable, regardless of how successful efforts to reduce greenhouse gas emissions might be, there is also a need for decision makers to develop and implement adaptation strategies. Indeed, some argue that mitigation and adaptation should be pursued together in an integrated strategy. However, community vulnerability to climate change is determined by both exposure to risks and the capacity to deal with such risks. There has been increasing research focus on understanding adaptive capacity and the need to mainstream adaptation to current and future climate into current decision making.

Climate related disasters have been viewed as an opportunity to incorporate adaptations to future climate change in the rebuilding efforts. In reality, particularly in developing countries, much of the response to climate disasters currently focuses on disaster recovery, rather than building increased capacity to deal with disaster. This can actually result in a reduced ability to adapt, or an increase in what some call the "adaptation deficit". A change in focus of aid agencies towards a coherent and effective adaptation regime that integrates the risks of climate change into development measures would be more effective in promoting sustainable development in these regions. Some of these countries are making progress in this direction, but related actions are generally inadequately ensconced in national policy making[659-667].

Projected changes in climate over the next few decades will also pose major challenges to regional management of natural resources, including water, forests, coral reef ecosystems and fish migration routes and habitats. Resource managers will need to develop plans that include a suite of options so as to maximize the adaptive capacity and improve the resiliency of these resources and the communities that rely on them. They will need to do so in collaboration with multiple stakeholders affected by changing resources. Investigators indicate that, for land ecosystems, coping with and adjusting to forest disturbances while maintaining genetic diversity and resilience is a priority. Once forest ecosystems exceed certain critical ecological thresholds, change in their composition can become rapid and result in a dramatically different combination of species within a short period of time. Since these trigger thresholds are amenable to management, adaptive policies can help to influence how these transitions evolve. As illustrated in the response of west Greenland communities to the collapse of cod in the region many decades ago, diversification, foresight and political effectiveness can also improve community resilience to such changes. Yet few governments or communities have plans in place to do so[488,512,558,668-671].

Canadian agriculture could benefit significantly from warmer climates provided appropriate adaptation measures are taken. Various studies suggest that a clairvoyant approach to adaptation, where appropriate actions are optimized, may be more effective in mitigating negative impacts and capitalizing on potential benefits than a slow approach that ramps up with time then saturates. Currently, changing management practices such as increased crop specialization, increased production of water dependent crops, less grazing, more tile drainage and greater water competition may actually be making Canadian agricultural production more vulnerable to climate extremes. Experts note that stakeholders need better understanding of trade-offs if they are to become more receptive to adaptive options and reverse such trends. However, this may also require the dismantling of many existing government agricultural support programs, such as crop insurance[487,672-675].

Irrigation is one possible adaptive response to increased risk of agricultural drought. Model projections, though, suggest that many global regions, particularly areas such as NE China, will experience reduced water resources and hence reliability of irrigation. Many areas of the world, including most regions of Canada, also have inadequate reservoir capacity to deal with projected changes in snow-rain ratios and the impacts this will have on seasonal stream flow. Much of the excess run-off may be lost to these reservoirs. These factors could limit the role of irrigation as an adaptive measure[676-677].

Adaptation can also help to mitigate some of the impacts of warmer winters on other Canadian industries. For

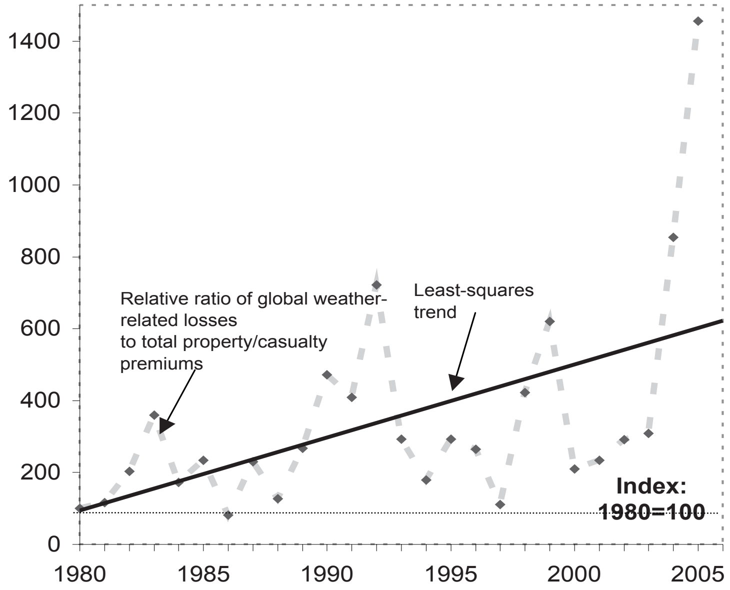


Figure 6: Over the past quarter century, the ratio of insured losses caused by weather-related disasters to insurance premiums. This indicates that the capacity of the global insurance industry to absorb such large losses is in decline (Mills 2005, reference #682).

example, snowmaking for down-hill skiing can reduce losses of 60-90% in season length in southern regions of Ontario to a more modest 7 to 32%[561].

With the increased risk of extreme weather events associated with warmer climates, potential damage to property and loss of life increases as well. Community infrastructures may be particularly vulnerable. Researchers argue that the science, community and insurance industry leaders need to improve collaboration in quantifying risks, identifying the gaps in capacity to cope and considering adaptive measures that reduce the risk of harm at minimum cost. One measure of successful adaptation is reduced death relative to hazardous weather events. For example, a heat alert system recently adopted in Philadelphia has helped reduce heat related deaths by an estimated 2.6 lives per day. However, individual responses to the risks of climate change vary significantly because of differences in risk perception and adaptive capacity. In order to enhance effective adaptation at the individual level, policy makers also need to address these cognitive barriers[678-683].

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Abbreviations for references: BMAS = 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, IJC = International Journal of Climatology

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