Environment Canada / Environnement Canada

CO_2/ CLIMATE REPORT

A Periodical Newsletter Devoted to the Review of Climate Change Research

1999 IN REVIEW
AN ASSESSMENT OF NEW RESEARCH DEVELOPMENTS RELEVANT TO THE SCIENCE OF CLIMATE CHANGE

Spring 2001 Issue

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1.0 INTRODUCTION

As part of an ongoing literature review and assessment process within the Science Assessment and Integration Branch of the Meteorological Service of Canada (MSC), this issue of *CO_2/Climate Report* provides a synthesis of about 350 key scientific papers and reports relevant to climate change that have appeared within the international peer-reviewed literature in 1999. As for past reviews, this synthesis is not intended to be a full assessment of the state of scientific knowledge on climate change, but rather a brief summary of recent, incremental research highlights. For a more comprehensive assessment of the science of climate change, readers are referred to the 1995 *Second Assessment Report* (SAR) prepared by the Intergovernmental Panel on Climate Change (IPCC) and to subsequent special IPCC reports[1-5]. Earlier issues of the *CO_2/Climate Report* can also be consulted for summaries of research papers published subsequent to the SAR but prior to 1999. Recent issues of these reports can be accessed on the MSC science assessment website at www.msc-smc.ec.gc.ca/saib/climate/ccsci_e.cfm.

In the interests of brevity and utility, the 1999 literature review is based on a selection of those papers most relevant to improved understanding of the science behind the climate change issue. It is very concise, but fully referenced. Readers should consult the relevant papers identified for further details on the various topics and results discussed. Undoubtedly, some important papers will have been missed in this review, either through oversight or lack of ready access to the relevant journals in which they appeared. Any related annoyance to the authors of such papers and inconvenience to the reader is unintended and regretted.

2.0 CHANGES IN ATMOSPHERIC COMPOSITION

2.1 Carbon Dioxide

Atmospheric Concentration: By the end of 1999, atmospheric concentrations of carbon dioxide had reached concentrations of about 368 parts per million by volume (ppmv). By comparison, recent analyses of high resolution Antarctic ice core data indicate that atmospheric concentrations of CO_2 during the pre-industrial period of the current interglacial have varied between 280 to 285 ppmv during the past several thousand years and was about 25 ppmv lower some 8000 years ago. Ocean sediment studies suggest a similar slow rise in concentrations during the Holocene. While there is evidence that the interglacial concentrations also fluctuated on decadal to century time scales (for example, concentrations dipped by about 6 ppmv during the Little Ice Age several centuries ago), longer term rates of change appear to have been less than 0.01 GtC/yr (1 ppmv ~ 2.1 GtC). This rate is about two orders of magnitude less than current accumulation rates of about 3 GtC/yr. Measurements involving ^{13}C and ^{14}C isotopes indicate that these low frequency interglacial changes can be linked to gradual changes in land biomass and ocean fluxes in response to deglaciation processes and regional climate shifts[6-11].

On times scales of glacial-interglacial cycles, shifts in carbon dioxide concentrations appear to be well correlated with changes in climate. Recent analyses of high resolution Antarctic ice cores indicate that, at the end of each of the last three glacial terminations, atmospheric CO_2 concentrations increased rapidly by about 80 to 100 ppmv within 600 years after the onset of warming, briefly peaking at around 300 ppmv during the ensuing interglacial. However, the declines in concentrations at the end of the interglacials were delayed by thousands of years with respect to the onset of cooling, with the delay being proportional to the length of the interglacial. Analysis of stomatal frequency (which is inversely related to CO_2 concentrations) in fossil birch leaves suggest that concentrations during the early phases of the current interglacial may have peaked well above 300 ppmv[12-13]. On even longer time scales of millions of years, ocean sediment data indicate that changes in atmospheric CO_2 concentrations can often be out of phase with major climate shifts. This suggests that, on such time scales, other slow geological processes such as continental movement and major changes in concentrations of other greenhouse gases may be important factors[14-15].

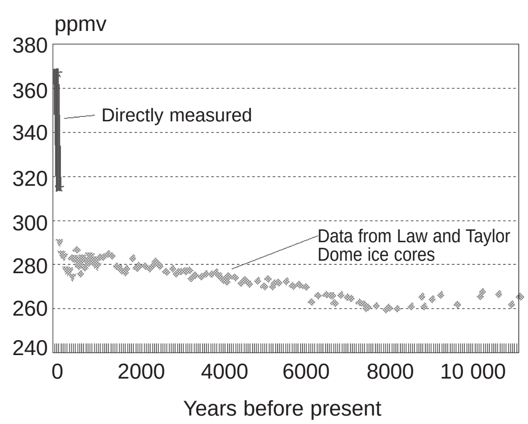

Figure 1. *High resolution Antarctic ice core data show slow millennial scale changes in Holocene CO_2 concentrations between 260 and 280 ppmv, including a slight dip during the Little Ice Age. Recent atmospheric measurements (solid line) are shown for comparison. Adapted from Indermuhle et al. (#10).*

Progress in Understanding The Global Carbon Budget: A variety of analysis techniques using carbon isotopes, O_2/N_2 ratios and inverse modelling suggest that net oceanic uptake during recent decades have averaged between 1.5 and 2.3 GtC/yr. Inverse modelling also implies a stronger ocean sink in the Northern Hemisphere (NH) than the Southern Hemisphere (SH). Direct measurements of partial pressure differences suggest NH oceans take up about 0.86 GtC/yr (highest uptake in spring and least in summer), and that the Indian Ocean is also a significant sink, particularly in mid-latitudes. Continental shelf regions may be a significant contributor to these sinks because of their more rapid surface cooling and hence greater contribution to deep water formation compared to most deeper ocean regions. The ocean uptake also varies considerably from year to year, in response to El Niño and La Niña events and other oscillations in ocean climates. The effects of these variations on carbon fluxes are particularly prominent in the tropical oceans, and can cause year to year variability in net ocean flux of +/- 1GtC[16-24].

In comparison to ocean fluxes, net global flux between the atmosphere and land areas has been relatively small in recent decades. However, its inter-annual and longer term variability is larger because of greater sensitivity to regional climate shifts. Despite the relatively small magnitude of net land-atmosphere fluxes (including the emissions from deforestation activities) on a global scale, there are large regional differences in terrestrial fluxes. Land use change in southeast Asia alone, for example, may have released about 1 GtC/year into the atmosphere during the 1980s, although somewhat less in the more recent decade. There remains considerable controversy as to the distribution and temporal variability of additional sources as well as the offsetting sinks elsewhere. Some ecological models and direct flux measurements suggest direct CO_2 fertilization of ecosystems is a major contributor to terrestrial sinks (particularly in the tropics), possibly accounting for more than 50% of the global terrestrial sink for anthropogenic carbon dioxide. On the other hand, other studies using inversion models or assessing nitrogen fertilization effects suggest a large sink in mid-latitudes of the Northern Hemisphere (NH), perhaps sequestering as much as 1 GtC/year (primarily in North America and/or Eurasia). However, the rate of increase in the magnitude of the NH sink appears to be less than that for fossil fuel emissions. Regional climate fluctuations and shifts in the seasonal climate cycle (e.g. earlier springs) can also be important factors, causing the magnitudes and seasonal cycle of sinks to change with time. Both tropical and NH mid-latitude sinks may actually be involved, but considerable work remains to be done to quantify the carbon flux effects of CO_2 and nitrogen fertilization, as well as other variables such as regional climate change. While isotopic measurements can help to understand the processes involved and thus reduce uncertainties, they in turn must also consider such biases as isotopic dis-equilibrium between land biota and soil matter[16,18,25-43].

A NH sink is also broadly consistent with studies of American land use change fluxes, which indicate a significant source of CO_2 prior to 1945 that has changed to a large sink due to the combined effects of forest regrowth, wetter climates and higher CO_2 concentrations. In contrast, Canadian forests appear to have been a significant carbon sink between 1920 and 1980, but have changed to a net source of atmospheric carbon dioxide in recent decades due to a major increase in natural disturbances. Although estimates for the size of the carbon pools involved remain quite uncertain, a similar period of ecosystem carbon loss may have occurred prior to 1920. In addition to natural disturbances, biomass productivity and hence the magnitude of the carbon uptake in the Canadian boreal forest can also vary significantly with changes in spring temperatures and precipitation conditions. However, the response can be complex, affecting the flux from upland regions such as aspen groves quite differently from fens within the larger forest ecosystem. Forest management activities can also result in storage of large volumes of carbon in long term carbon reservoirs. For example, the carbon content of Canadian forest products have increased during the 1980s by about 23.5 MtC/year, with about one-third of this pool residing outside of Canada[44-49].

Carbon accumulation in forest litter, which for ecosystems such as eastern US pine forests can represent about 20% of total ecosystem carbon, is an important variable in estimating net ecosystem carbon fluxes. However, litter decomposition rates appear to be sensitive to three key variables of temperature, precipitation and lignin to nitrogen ratios. Temperature and precipitation in a warmer world would likely increase litter decay rates in colder ecosystems such as those of Canadian forests, although lower lignin to nitrogen ratios could partially offset this response. More work is required to ensure that litter decay models properly capture these sensitivities[50-52].

Winter effluxes of CO_2 from tundra ecosystems can also be an important but oft overlooked contributor to their net annual carbon balance, changing some Arctic tundra ecosystem from a net sink to a net source of atmospheric CO_2 . The net annual flux from these and other northern ecosystems such as peatlands are also highly sensitive to temperature and precipitation fluctuations, and thus vary considerably in space and time. Projections for response to warmer climates imply that emissions of CO_2 will increase for at least some of these cold climate ecosystems[53-56].

There remains considerable uncertainty as to how net global carbon flux processes will change in future decades as various global ecosystems respond to changing environmental conditions. Some studies suggest that response of forest biomass, litter and fine roots could be enough to remove up to 50% of projected anthropogenic CO_2 emissions by 2050. However, when allowances are made for nutrient constraints, climate change and other variables, such sinks may be far less significant. Furthermore, changes in soil decomposition rates in response to warmer climate also need to be considered (although past studies may have overestimated this feedback). Experiments with a dynamic vegetation model coupled to two coupled climate models (HadCM2 and HadCM3) and forced with projected CO_2 and N fertilization and IS92a climate forcing suggest net effect may be an increase in global net ecosystem productivity (NEP) to 3.6 GtC/yr by 2030, then a decline to zero growth by 2100. With HadCM3, the decline involves a dramatic NEP collapse ~2050, primarily because of enhanced respiration from drier tropical forests[57-60].

Ocean responses to warmer climates will involve a complex interplay of changes in ocean surface CO_2 solubility, reduced transport of CO_2 into the deep ocean, and an enhanced ocean biological cycle. The first two factors are projected to decrease ocean CO_2 uptake, while the latter increases it. Ocean surface heating effects are projected to dominate initially, but model studies suggest the effect of ocean circulation may dominate by 2100. The behaviour of the Southern Ocean is particularly important in determining the net effect of these three factors on global ocean CO_2 uptake. One recent study suggests a modest positive feedback that will increase projected CO_2 concentrations by a few percent by 2100 and perhaps 20% by 2500. However, the various ocean models involved in such studies still show considerable inter-model differences[61-64].

Given the complexity and uncertainty with respect to the above variables, confident predictions as to how the global carbon cycle will change in future decades cannot be made at this time, although emerging and future results and studies promise to reduce these uncertainties[65].

2.2 Other Greenhouse Gases and Aerosols

Methane. Isotopic analysis of atmospheric methane suggests that 18% of emissions come from fossil fuel sources. Past studies have suggested that emissions from leaky pipelines may be an important source of fossil methane emissions. Measurements during 1996 and 1997 of emissions from Russian natural gas production and distribution systems, estimated to be a significant source of methane in the past, suggest such losses are now only in the order of 1% of production. Emissions from Chinese rice fields may also be decreasing, since mineral fertilizers are gradually replacing the use of organic fertilizer. Direct effects of CO_2 fertilization could further reduce rice paddy emissions, although the magnitude of response may be soil sensitive. Other regional anthropogenic sources include sheep herds in New Zealand, which are estimated to release some 155 kg/ha of methane each year[66-70].

Natural wetlands emissions of methane are highly variable in space and time, and depend on wetland characteristics. Measurements, which can be biased by inadequate sampling control, continue to show beaver ponds as significantly larger sources than other boreal wetlands. Emissions from termites, on the other hand, are found to be largely oxidized by soils within the termite mounds, and are now estimated at approximately 1% of total emissions, significantly less than past estimates. The role of sub-ocean gas hydrates as a potential source of methane remains uncertain, although there is now evidence of massive eruptions from ocean floor hydrate deposits during warm ocean periods millions of years ago[71-74].

Isotopic analyses also indicate that chemical destruction of methane by OH dominates the seasonal cycle of methane in the tropics. However, at mid to high latitudes, seasonal changes in the biological processes to control wetland methane emissions appear to be more important. Model based estimates for the rate of atmospheric methane destruction within global soils suggest a range of 20 to 51 Mt/year, or between 6 and 15% of total methane emissions. Agricultural intensification could reduce this sink by some 10%[74-75].

Nitrous Oxide. Pre-industrial nitrous oxide concentrations in the atmosphere appear to have varied from 210-250 ppbv during the last glacial maximum to 270 ppbv during the current interglacial, with a fairly rapid response during the deglaciation process. Current concentrations are now at about 315 ppbv. Total global emissions, estimated at about 11 million tonnes of nitrogen per year(MtN/yr) in 1850, are now estimated at 18 MtN/yr. Food production processes appear to be that dominant source contributing to this increase, although those from agricultural soils are sensitive to water conditions and thaw processes. New models developed to simulate these emissions appear to capture this sensitivity quite well[76-78].

Halogenated Gases. Emissions of perfluorocarbons (PFCs) appear to have declined during the past decade, with that for CF_4 now about 11 kilo-tonnes per year (Kt/yr) compared to 16 Kt/yr in 1978-90. However, long term business-as-usual prospects suggest PFC emissions may increase by 150% by 2050, and that for sulphur hexafluoride (SF_6) by 210%. This only adds 0.026 W/m^2 to global radiative forcing, but the long lifetimes of the gases involved (>5000 years for SF_6) makes the projected rise a concern[79-80].

The Global Warming Potential (GWP) for the hydrofluorocarbon HFC 245fa, with a lifetime of 7.6 years, has been estimated at about 760. Meanwhile, a new family of halogenated gases, referred to as hydrofluoroethers (HFEs), have recently been identified as potent greenhouse gases. Despite their relatively short lifetimes ranging between 6 and 12 years, these gases are very potent, with GWP values ranging from 3900 to 7000[81-82].

Ozone: Measurement of ozone trends in the stratosphere since 1979 show large losses at all altitudes over NH mid-latitudes, peaking at -7%/decade at some elevations. In the upper stratosphere, where similar losses also show in the SH, chlorine loading is implicated, and the losses should slowly recover as chlorine loading decreases. Changes in the lower stratosphere are more complex, since they also involve transport mechanisms[83].

Aerosols: Concentrations of anthropogenic aerosols have declined over Alert since 1991. Most of these reductions are related to the industrial decline in the former USSR, although lead free gasoline in Europe has contributed to a dramatic decline in lead aerosols[84].

3.0 Radiative Forcing

3.1 Anthropogenic Forcings

Greenhouse gases: A new estimate for the direct effect of decreasing stratospheric ozone concentrations during recent decades suggests a net radiative forcing of 0.10 W/m^2, or half of previous estimates. On the other hand, increasing concentrations of water vapour in the stratosphere may be both adding to the stratospheric cooling caused by ozone depletion and enhancing the greenhouse effect caused by other greenhouse gases. While the cause of this water vapour increase is not understood, it could be due to methane decomposition (hence an indirect anthropogenic forcing) or due to changes in tropopause temperatures (a feedback effect)[85-86].

In the troposphere, net surface radiative forcing due to increasing ozone concentrations may be reduced by as much as 0.1 W/m^2 due to the presence of clouds. Non methane hydrocarbons may also have had some influence on the greenhouse effect, but these effects are estimated at less than 1% of the well mixed greenhouse gases[87-88].

Aerosols: Both naturally and anthropogenically produced aerosols can have important influences on regional and global climates. Over ocean regions remote from industrial areas, sea salt continues to be the leading aerosol contributor. Human induced aerosols are dominant over and adjacent to land areas. There is new evidence to suggest that physical interaction between sulphate aerosols and other aerosols, including sea salt, can change their properties, including their size, and thus reduce their effectiveness as solar reflectors. Hence, while the direct effects of aerosols remain important in radiative forcing, such effects appear to be very complex. Indirect radiative forcing effects, which are induced by the influence of aerosols on both the number and size of cloud droplets and their lifetime, may be even larger, more complex and more uncertain. Some estimates suggest a net regional indirect aerosol forcing in heavily polluted areas such as the southeast USA of as much as -4 W/m^2, and a global forcing to date as high as -2.1 W/m^2. However, other studies suggest that such estimates may not have adequately considered other offsetting factors, and that the net global indirect effects of aerosols could even be positive. Only integrated programs of modelling and multi-level observations can help reduce these uncertainties[89-95].

In tropical regions, the radiative effect of aerosols from biomass burning can be quite significant, partly because of the high solar incidence angles involved. Recent estimates suggest a net global radiative forcing due to these aerosols of

-0.7 W/ m^2. Meanwhile, north-south surveys of the combined effect of both sulphate and black carbon aerosols (both combustion by-products) suggest a net forcing of +2 W/m^2 over north Africa, -5 W/m^2 over polluted regions of Europe, and +0.4 W/m^2 over the Arctic[96-97].

Aerosols released in aviation flight corridors increase the net amount of cirrus cloud cover over heavily traveled areas. Averaged globally, net positive radiative forcing is currently estimated at 0.02 W/m^2, and projected to increase to 0.1 W/m^2 by 2050. However, over the Great Lakes, these contrails may have increased high level cloud coverage by almost 3%/decade, with a regional radiative forcing effect of ~7 W/m^2 [98-99].

3.2 Natural Forcings

Solar: Recent studies continue to suggest that much of the variability in global climate over the past four centuries can be attributed to solar forcing, although there is as yet little agreement on how to reconstruct these linkages, how to estimate their magnitudes, and by what mechanisms they occur. One possible indicator is change in total magnetic flux leaving the sun, which may be related to both total irradiance and atmospheric cloudiness. This flux, which is somewhat chaotic, has increased by a factor of 2.3 since 1901, and by 40% since 1964. Revised estimates of net solar forcing effects suggest a contribution of between 25 and 50% of the observed change during the past century (i.e., in the range of 0.15 to 0.3°C) decreasing to less than a third of the observed change since 1970. Satellite observations indicate the total irradiance did not change significantly during the past two solar cycles, but that within the cycles, most of the change takes place in the ultraviolet (UV) part of the spectrum. The UV changes, in turn, affect stratospheric ozone concentration and distribution and hence atmospheric circulation[100-110].

4.0 CLIMATE MODELLING

4.1 Climate Model Processes

Atmospheric processes: The radiative effects of changes in water vapour density is about 2.6 times larger in the upper troposphere than in the lower troposphere, and 1.5 times larger for the free extratropical troposphere than in the tropics. Water vapour feedbacks within the climate system are weaker in models that include correlated response of water vapor and clouds, and are stronger for initial surface temperature anomaly of long duration than for brief anomalies (due to deeper penetration of the water vapour response within the atmosphere)[111-112].

Arctic observations indicate that pervasive regional low clouds have a net positive radiative effect in summer. Net Arctic surface radiation is negative in winter, changing to positive in spring and summer, peaking at over 130 W/m^2 in July. The positive summer cloud feedback is caused by the strong thermal blanket effect of the clouds, which exceeds their reflection of incoming solar radiation and hence warms the surface and enhances rate of ice melt[113].

There is increasing evidence of the important roles of stratospheric chemistry and thermospheric-stratospheric-tropospheric coupling mechanisms in climate variability and change, and the need to include these in coupled models of the climate system that extend from the ground to space. Coupling mechanisms include radiative transfer, gravity wave forcing, and transport and mixing[109,114-115].

Land processes: Inter-comparisons of sixteen different land surface schemes currently used within climate models (including the Canadian CLASS model) suggest continued problems with simulation of some key climate variables, and raise concerns about the general reliability of current schemes. For example, magnitudes of simulated sensible and latent heat fluxes over forests and grasslands vary by more than a factor of two. Likewise, there is considerable disagreement between the various schemes on simulated runoff, surface moisture and effective radiating temperatures. However, independent evaluation of the Canadian CLASS scheme in simulating alpine climates indicates broad agreement with observations, although there are some problems with proper simulation of snowfall[116-117].

Coupled climate-vegetation models indicate that mid to high-latitude vegetation response to climate change causes an important regional albedo feedback that is positive in summer and negative in winter. Vegetation response can also have important feedbacks in terms of carbon fluxes and climate response[60,62,118-119].

Ocean processes: Recent studies into the role of the ocean thermohaline circulation (THC) system as an important response mechanism within the global climate system suggest a strong linkage between North Atlantic and Southern Ocean deep water formation processes. Model simulations suggest two dominant stable circulation modes, one with a strong circulation current induced by intense downwelling in the North Atlantic, the other a weak circulation current linked to massive discharge of freshwater into the North Atlantic that decreases surface water sinking in that region but is accompanied by stronger downwelling in the Southern Ocean. However, the feedback processes within the THC system appear to differ between hemispheres, with that for the Northern Hemispheres dominated by processes within the North Atlantic and the Southern Hemispheric response by Pacific Ocean processes. These hemispheric feedbacks appear to be negatively correlated. Wind-induced upwelling in the Southern Ocean may also be a factor in controlling the intensity of the thermohaline circulation system. While simulations of climate response to enhanced greenhouse forcing suggest an initial increased fresh water influx into the

North Atlantic and hence a decrease in THC intensity of a factor of two or more, the long term transient response depends on a number of factors, including the rate of warming, the response of high latitude temperatures and the hydrological cycle and the concurrent change in fresh water flux into the Southern Ocean. Hence simulated responses are highly sensitive to the simulated changes in hemispheric scale fresh water fluxes and the ocean mixing schemes used. Both a full recovery and a complete collapse are within the range of possibilities, with the latter having major implications for a cooler, dryer Europe[120-126].

Ocean variability on decadal time scales has often been associated with various oscillatory features in different ocean regions. Some of these, like the variability of the thermocline in the North Pacific and ENSO, may in turn be generated by interacting forcing mechanisms such as wind stress and surface buoyancy anomalies that affect vertical and horizontal ocean circulation patterns. However, there is now evidence that these regional oscillations may be all inter-linked as part of a single, dominant global mode of decadal variability that is independent of a global trend signal[127-129].

4.2 Model Evaluation

Coupled climate model simulations appear to capture interannual variability as well as oscillatory behaviour of features such as ENSO and NAO (including their interdecadal fluctuations) reasonably well. Reductions in systematic errors and improved resolution in recent model experiments appear to improve such model performance. However, the linkages between these oscillations and SST patterns are as yet inadequately understood. For example, while model simulated ENSO oscillations for the climate optimum some 6000 years ago show patterns similar to that of today, their teleconnections with ocean temperatures and tropical precipitation patterns are different. Hence, current climate teleconnections may also not persist under future climate change. Chaos within the climate system also introduces multiple non-linear responses within the climate system that are as yet poorly understood, but which can add significantly to the uncertainty of the climate system response to climate forcings of the past century. Hence, they need to be incorporated into model experiment design. Ensemble experiments with the GFDL coupled model do suggest that response of climate to the much larger forcings projecting for the next century are relatively insensitive to the start time of the experiments, and hence that the chaos error may be much less significant for such experiments[130-136].

While use of asynchronous schemes within coupled models can help to reduce computational time of experiments, such schemes need to be developed carefully to avoid significant problems. Regional climate models (RCMs) also continue to be successfully improved to enhance their fidelity in projecting GCM outputs onto local landscapes. However, systematic errors in boundary conditions simulated by GCMs and other problems constrain their potential, and recent experiments continue to show some deficiencies in the seasonal distribution of precipitation[137-139].

4.3 Model Results

Results from a number of new coupled climate models simulations of future climate continue to show common characteristics but also significant differences. For example, the Hamburg ECHAM4/OPYC3 model, using the IS92a greenhouse gas and aerosols forcing scenario (including indirect aerosol effects) suggests a 0.2°C/decade warming during the next century, a poleward shift in mid-latitude westerlies, an increase in high latitude precipitation, and drier conditions over many NH land areas. Aerosol effects tend to reduce the enhancement of the global hydrological cycle. New GFDL model projections also show increased poleward transport of moisture and dryer summer conditions in mid-latitudes of the Northern hemisphere, although such changes may be harder to detect against climate noise than the concurrent temperature changes. Experiments with the NCAR CCM3 coupled climate model to climate forcings show a 2.3°C warming at the time of CO_2 doubling and hence a decreased climate sensitivity relative to their CCM1 version. This is largely due to enhanced turbulent atmospheric mixing, more effective transfer of latent and sensible heat to the upper atmosphere through use of a different deep convection scheme and a more complex slab ocean with reduced ice cover sensitivity. A slight decrease in sensitivity was also noted in experiments with the GISS equilibrium GCM model when new improvements in the cloud parameterization were added to the model. The GISS coupled model, starting from equilibrium conditions (i.e., a 'cold start'), projects a global warming of about 1.4°C at about the time of CO_2 doubling, with areas of cooling within the Atlantic and Pacific Oceans. The cooling areas are in response to circulation changes that reduce the net global sea ice feedback effect and hence climate sensitivity. However, researchers caution that most models have only included a subset of the forcing factors at work within the climate system and that the understanding of factors such as aerosols are still very uncertain. Hence, the results of these model experiments must still be used with caution[140-145].

Simulations with a 2D version of the GISS GCM to assess upper and lower limits of climate sensitivity to external forcings suggest a 95% confidence range for equilibrium response to doubling of CO_2 concentrations of 0.7°C to higher than 5.1°C. Comparable transient response of the system at the time of CO_2 doubling is projected at 0.5 to 3.3°C, compared to a range of 1.4°C to 2.5°C simulated by the current generation of coupled climate models. Hence, the possible range of response may be significantly higher than that often cited[146].

Most climate model simulations continue to project a significant weakening of the THC system in response to climate warming. The GFDL model, for example, suggests an initial 50% reduction in intensity at $2XCO_2$ which takes 500 years to recover, and a complete collapse under $4XCO_2$ scenarios, with minimal recovery within the first millennium after collapse. The response of the total climate system, and particularly oceans however, significantly lags the change in CO_2 concentrations, with the magnitude of delay sensitive to the rate of CO_2 increase. The new HadCM3 model experiments, which do not include flux adjustments, show a 25% reduction in THC system by 2100, primarily because of a complete collapse of the deep water formation in the Labrador Sea within the next few decades. The threshold for complete collapse of the THC system may be between atmospheric CO_2 concentrations of 650 and 700 ppmv (i.e., between doubling and tripling of pre-industrialized levels)[122,147-150].

The Canadian coupled climate model suggests that greenhouse gas forcing during the past century has caused Arctic and Antarctic Oscillation indexes to become increasingly positive because of a change in the background climate. The changes do not appear to favour one phase of these oscillations over another, nor appear to involve a stratospheric response. The GISS model also shows similar response in the AO index, although only if the model includes a realistic representation of the stratosphere and its dynamics. The Canadian model also projects an amplified climate response with elevation over alpine regions because of albedo feedbacks. Meanwhile, simulations with the Hamburg coupled model appear to underestimate ENSO sensitivity to climate change with coarse resolution experiments, but suggest the ENSO cycle becomes more energetic under warmer climates when high resolution versions of the model are used. When the model is linked to a high resolution tropical ocean model, results show more frequent and more intense El Niño and La Niña conditions under enhanced CO_2 forcing[151-156].

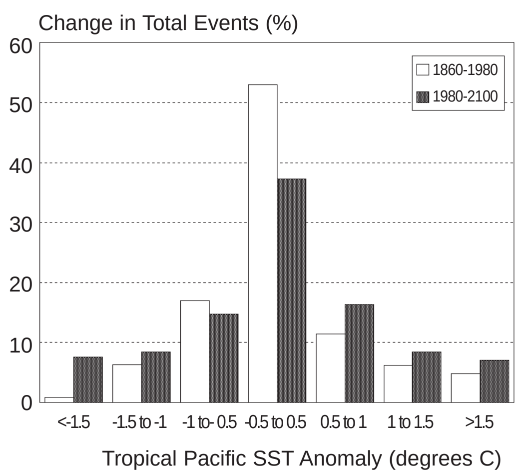

Figure 2. *Projected changes in El Niño and La Niña behaviour as simulated by one coupled climate model experiment. Results suggest that both intense El Niños and La Niñas could become more frequent, with neutral conditions becoming less prevalent. Adapted from Timmermann et al. (#155).*

Each degree of atmospheric warming is also estimated to increase the earth's angular momentum and thus slightly reduce the Earth's rotation speed and hence increase the length of Earth's day[157].

5.0 Climate Trends

5.1 Paleo Climates

Glacial/Interglacial Climates: Extended Vostok ice core records indicate that the current interglacial may have provided the longest stable warm period of at least the past 420 thousand years (ky). By comparison, all three preceding interglacials, while lasting between 10 and 20 ky each, only experienced stable warm periods of 4 ky or less. Each interglacial appears to have been preceded by orbital forcing, amplified by response in greenhouse concentrations and subsequent changes in albedo as the climate warmed. While changes in eccentricity is generally accepted as the likely cause of the 100 ky orbital forcing cycle, spectral analysis of ice core isotopic records suggests it could also have been triggered by a harmonic of changes in orbital precession[158-159].

New sediment core records continue to suggest tropical SST temperatures during the last glacial maximum about 5-6°C below that of today. This is up to 2°C cooler that past paleoclimate data estimates have implied. The Gulf Stream also appears to have been weaker at the time, but sub-tropical gyre centers appear to have remained stable. Climate models driven by these changes in SSTs also project similar changes in temperatures of the tropical atmosphere, but suggest that these changes varied considerably throughout the tropics[160-164].

Coral records indicate that ENSO behaviour during the last interglacial some 125 kybp was quite similar to that of recent centuries. However, that for recent decades appears to be distinct from the paleo record, supporting hypotheses that the current behaviour is anomalous[165].

The Last 15,000 Years: Various data sources continue to show evidence that abrupt climate transitions to periods of cold, dry conditions in mid to high latitudes have occurred at approximately 1500 year intervals during the current interglacial, and perhaps throughout the past 130 ky. The Little Ice Age of about 400 years ago was the most recent of these. These anomalies appear to be weaker during the Holocene than during glacial and deglaciation periods, and at least some show coincident warming in polar and tropical regions. Other climate anomalies appear to be linked to ice sheet dynamics. Catastrophic draining of Laurentide glacial lakes and a consequent massive flow of freshwater into the North Atlantic, for example, appear to have been important factors in at least one of two distinct climate reversals between 9 and 8 kybp. Other abrupt climate anomalies, including the Younger Dryas-Holocene transitions and the warming over Greenland about 14.7 ky ago, also imply a North Atlantic rather than tropical triggering process. These data lend support to arguments that long term climate change can occur as sudden jumps, rather than gradually, and that the climate system is very sensitive to very small changes in climate forcing factors. There are also indications that these events are often linked to abrupt changes in ocean circulation, which in turn may be triggered by forcings such as solar variations or ice sheet surging[166-175].

The transition of the Saharan climate from a vegetated region to desert conditions may also have been triggered by a change in monsoonal rains induced by orbital forcing and amplified by biospheric feedbacks. Meanwhile, in the Palliser Triangle region of the Canadian Prairies, warmer summers and less rainfall during the mid-Holocene (similar to some model projections for $2xCO_2$) resulted in long intervals of severe aridity. During the past 5000 years, more humid and cooler conditions have returned, but include periods of drought much more severe than those evident within the instrumental record[176-178].

The Past Millennium: While several studies based on proxy data of Northern Hemispheric climates for the past millennium suggest that the past few decades are anomalously warm, there are concerns that these analyses have underestimated the uncertainties inherent in these data[179].

Caribbean sediment cores indicate well defined decadal variability in regional ocean climates, and significant inter century variability over the past 825 years. A shift in regional climates appears to have occurred about 700 years ago[180].

5.2 Climate Trends Of The Past Century

Data Collection and Analysis Techniques: Both radiosonde and model based reanalysis data have significant biases, and hence may not be reliable data sources for validating satellite data estimates of temperature trends in the free troposphere, particularly in data sparse areas. There may also be biases in satellite data because of record discontinuities, possible changes in atmospheric lapse rates and other factors and in surface data because of urbanization and other influences. A comparison of global surface temperature trends derived from some 7000 observing stations around the world with trends based on a subset of several thousand rural station suggest that the residual urbanization bias in the global data set may be quite small. However, several independent studies comparing soil temperature records with adjacent rural climate station records for the first half of the 20th century indicate that there could also be some bias in rural stations. Land use change may be an important factor in these differences[181-185].

Both slow growing cliff-dwelling trees and changes in mountain station pressure have also been suggested as useful proxies for trends in local air temperatures[186-187].

Temperature Trends: Analysis of North American radiosonde data between 1975 and 1994 show maximum surface warming of up to 0.5°C/decade in high latitudes and least warming of 0.1°C/decade at mid-latitudes. In contrast, the troposphere shows least warming at high latitudes and greater warming than at the surface in mid latitudes of the Northern Hemisphere. The lower stratosphere cools in all regions. Analysis of differences between estimated trends in tropospheric temperatures based on radiosonde and satellite data and those for surface temperatures indicates a low frequency variance in the difference, possibly related to changing lapse rates[188-189].

Trends towards decreased daily temperature range (DTR) in many regions of the world appear to be linked to increased cloudiness and an intensified hydrological cycle. Over all of Canada, the decrease in DTR is associated with a total increase in minimum temperatures since 1946 of 0.4°C, compared to 0.3°C for maximum temperatures. The trend in DTR for southern Canada since 1895 is even more pronounced[190-191].

At the regional scale, ground borehole studies indicate a regional warming of 2.5°C in the southern Canadian Prairies since about 1850, with almost half of the warming occurring prior to 1900. Vegetation transformations may have been a factor, but do not adequately explain the pattern of seasonal temperature changes that have occurred during the past century. In the oceans, observations suggest a slight warming of deep waters in the Norwegian Sea during the past decade, apparently due to changes in ocean circulation. Reconstruction of North Pacific sea surface temperatures since 1750, using coastal tree ring data, show both a relationship of regional temperatures to the Pacific Decadal Oscillation and a 20th century warming relative to preceding centuries[118,192-194].

Attribution of Temperature Trends: Various analyses of the observed surface temperature trends of the past century,

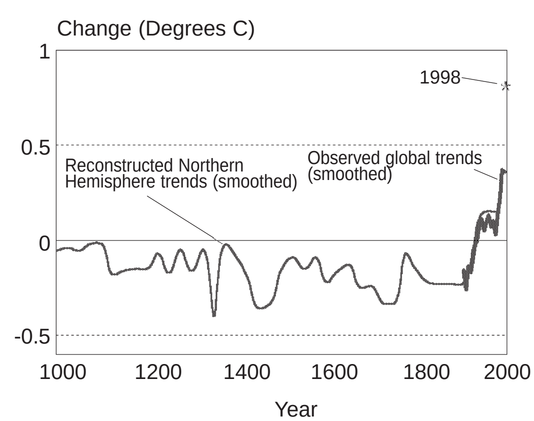

Figure 3. *Comparison of instrumental surface temperature data with estimated temperature records for the past 1000 years based on various proxy data sources suggest that the past 100 year period has been the warmest century of the last millennium, the 1990s were the warmest decade, and 1998 the single warmest year. Adapted from Mann et al. (#202).*

when compared to proxy data for previous century climate variability, suggest that they are unprecedented in at least the last millennium and hence unlikely to be due entirely to natural causes. Comparisons with model simulations of natural variability show similar results. However, there are still significant differences in the spatial patterns of model projections of change due to anthropogenic forcing versus that observed. These differences are also model sensitive. Best correlations between model simulations and observed or reconstructed temperature trends suggest anthropogenic, solar and volcanic forcings may all be involved in recent trends, but with solar forcing a secondary factor in recent decades. Some studies suggest that climate response to radiative forcings may, in fact, occur as a change in modes of natural variability or as global scale change superimposed upon natural variability. Hence, direct attribution of recent climate change to specific causes remains difficult[104,105,195-205].

Climate change and stratospheric ozone depletion are also closely linked. An enhanced atmospheric greenhouse effect causes stratospheric cooling and hence can contribute to ozone depletion. Conversely, stratospheric ozone depletion reduces the net greenhouse effect and hence is an important contributor to surface cooling[206].

Trends in Hydrological Variables: Global mean cloud cover over oceans has increased by 1.9% since 1951, with the greatest increase in low clouds. Although the pattern of change is inconsistent with aerosol effects, it is unclear what the underlying cause of this trend may be[207].

Across North America, the extent of snow cover increased between 1930 and 1980, then subsequently declined. Data collected on ice stations in the Arctic Ocean also suggest a slight decrease in snow depth since 1954. Both regions show strong negative trends in spring. Minimum and median streamflow in American rivers have also increased, although there is no evidence of increasing maximums. This is not inconsistent with reports of more frequent intense summer precipitation events, since most stream maximums currently occur during spring snow melt and run-off, not in summer. In the Canadian Prairies, total precipitation and the number of low precipitation events have both increased since 1961[208-212].

Tropospheric humidity and dewpoint temperatures across most of the US have also increased since 1961, particularly at night[213].

Large Scale Circulation Change and Variability: A sudden shift in the volume and temperature of Atlantic waters entering the Arctic Ocean since 1990 appears to be unprecedented in at least the last 50 years. Likewise, the absence of icebergs in Atlantic shipping lanes in 1999 appears to be without precedence since observations began in 1912. These anomalies may have been caused by an extreme amplification of the NAO. Model studies suggest that the NAO may have a natural low frequency of about 50 years. There are also indications of decadal scale oscillations in the Atlantic climate. However, there appears to be an underlying positive trend to the NAO variability that may be linked to anthropogenic forcing. Improved and longer term observations will be required to verify such causal mechanisms and linkages[214-217].

The Southern Ocean also appears to have experienced a recent reduction in deep water formation that may be linked to North Atlantic processes. Meanwhile, SST oscillations in the North Pacific may be contributing to variations in the intensity of ENSO events on multi-decadal times scale, which in turn appear to be linked to variances in the climate of the Indian and Atlantic Ocean basins. Coral isotopic data also provide evidence of a long term warming trend as well as a 35 year oscillation in south central Pacific Ocean temperatures. The latter is associated with concurrent changes in regional cloud cover and precipitation[169,218-222].

Variability and trends in the Arctic and Antarctic Oscillations may both be important in explaining much of the variability in extratropical climates, particularly with respect to recent surface temperature trends. There are indications that variations in the Aleutian low, for example, are linked to the AO, although Pacific oscillations also seem to be a factor. Warmer climates in the tropics may also have reduced upper tropospheric temperature gradients and contributed to fewer outbreaks of warm air from the troposphere into the stratosphere during the past decade. This in turn cools the stratosphere more rapidly than expected due to radiative processes alone, and may have contributed to Arctic ozone loss[153,223-225].

Mean monthly maximum wind speeds appear to have increased across the USA since 1961, while minimum speeds have decreased. The causes of these changes are not clear[226].

Sea Ice Trends: Analysis of passive microwave satellite data indicates a 14% decline in concentrations of multi-year sea ice in the Arctic since 1978, and a 3% decline in total winter ice extent in the Northern Hemisphere. Late summer mean ice thickness has decreased by 42% since the late 1950s. This decline also has important implications for heat and freshwater exchanges as well as stratification in the Arctic ocean. Observations during the recent Beaufort Sea research project SHEBA also indicate much thinner ice and margins much further north than during the 1970s. Experts suggest it may be partially attributable to altered ENSO behaviour, and to the recent shift in NAO and its effect of penetration of Atlantic waters into the Arctic, but model studies indicate it is very unlikely that such changes are entirely natural[227-232].

Sea Level Rise: Climate model simulations of trends in snow deposition and ice melt between 1950 and 1991 suggest a net increase in the mass balance of the Greenland ice sheet. Similar results are shown for the Antarctic ice sheets. While these results imply that neither ice sheets were

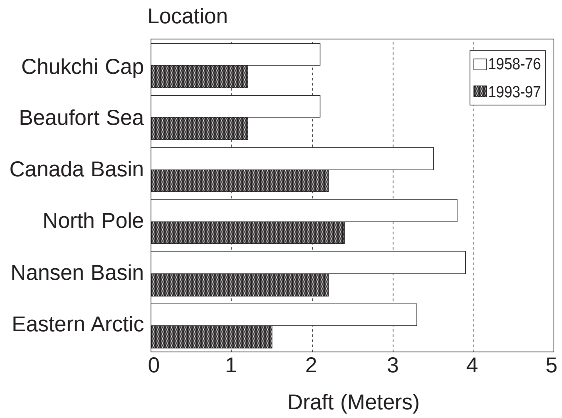

Figure 4. *Measurements of Arctic Ocean ice draft taken during submarine cruises over the past 40 years indicate that average summer ice thickness in the region has decreased by 42% during the period. Adapted from Rothrock et al. (#231).*

significant contributors to sea level change prior in the long term, the net mass balance of the Greenland ice sheet during the last decade appears to have been negative.

Both surface and laser altimetry measurements since 1993 show that the total Greenland ice sheet above 2000m elevation is currently in approximate balance, but that considerable mass loss has taken place at lower elevations due to ice creep[233-235].

During the past 5 years, sea levels in the south Pacific have risen by about 25 mm/year, largely as a result of ENSO behaviour. This rise, together with more frequent intense storms in the region, have contributed to significant erosion of island coastlines in the region and the disappearance of several uninhabited islands in Tuvalu[236].

Extreme Weather: Analysis of tide data in northwestern Europe as a proxy for regional storminess indicates considerable interannual variability but no overall trend over the past century. Extratropical storms over the North Atlantic, on average, also appear to have experienced no significant long term trends since 1885, although some significant changes are apparent over smaller areas within the region. However, there is evidence of an increase in significant wave height in this region since 1964, likely due to higher swell induced by high frequency synoptic processes. Atlantic hurricane frequencies over the past century show a slight increase in east coast USA landfall frequency, but a fairly constant intensity level for these events. A multi-decade period of lower activity level may now be changing back to a higher activity period. Changes in tropical North Atlantic SSTs appear to be the primary cause of these long term (as well as shorter term) variations, suggesting a strong local SST-storm feedback[237-241].

Economic losses due to extreme weather events in the USA have increased significantly during the past 25 years, although most of this increase appears to be attributable to social rather than climate factors. The exception may be for intense winter storms, which appear to have increased at least partly due to more frequent nor-easters. There is also evidence that short duration precipitation events (<7 days) in the region exhibit low frequency variability, with above average occurrence in the 1940s, early 1980s, and the 1990s and a net upward trend of 3%/decade (possibly linked to century scale variability). Trends in continental USA drought severity, based on tree ring proxies, indicate that the 1930s represent the most severe regional drought period of the past 300 years[242-244].

Multi-decadal variations in the intensity of the North Atlantic Deep Water formation alters the intensity of the thermohaline circulation (THC) system and affects the intensity of upwelling in the Indian and western Pacific Oceans. When the THC intensifies, it causes an increased heat release in the eastern hemisphere, and an inverse response in the frequency and intensity of El Niño events within 5-6 years. A possible period of a stronger THC in the next few decades due to long term natural variability could thus result in a period of relatively weaker El Niño events[245].

Other trends: Various studies have noted recent shifts in distribution and behaviour of biological species. In England, for example, bird species have migrated northward by an average 19 km during the past few decades, and at least 19 of UK bird species are laying eggs earlier, largely in response to warmer spring temperatures. During the past century, distributions of almost two thirds of some 35 species of non-migratory European butterflies studied shifted northward by up to 240 km, while only one of the species showed a southward shift. In Costa Rica, 40% of frog and toad species in the highland forests have disappeared. This populations crash appears to be part of a larger shift in bird, reptile and amphibian communities in this region, and is linked to a rise of the base level of orographic clouds in response to warmer temperatures, thus reducing the frequency of dry season mists. Meanwhile, in the Hudson Bay region of Canada, the health of polar bears has declined during the past two decades, largely due to warmer temperatures and earlier break-up of sea ice on the Bay[246-250].

The frequency and number of disease epidemics among corals and marine animals have recently increased in many regions of the oceans. These trends appear to associated with shifts in the range of both known pathogens and the affected species. The rapid rise in temperatures during the 1998 El Niño event also caused extensive coral bleaching, causing mortality of up to 90% in some shallow Indian Ocean regions[251-252].

Analysis of fire years in Canadian forests indicate that the five highest years occurred since 1975, and the five lowest all before 1974. The shift in intensities appears to be linked to a shift in weather patterns immediately over and upstream of the burn areas[253].

6.0 IMPACTS AND ADAPTATION

6.1 CO_2 Fertilization Effects

Past studies of the direct effect of CO_2 enrichment on plants, using both open top chambers and free air experiments, have repeatedly shown a strong enhancement of growth and increased water use efficiency of many plant species. The exposure also induces an increase in surface temperatures of up to 1˚C due to reduced cooling of evapotranspiration. However, some of the open top chamber experiments may have been biased by inadvertent warming of the air within the chamber. Unfortunately, development of appropriate process based models to accurately predict the effects of enhanced CO_2 on vegetation is still hampered by inadequate understanding of the mechanisms for carbon partitioning within ecosystems and the failure of experts to disassemble their theories of CO_2 fertilization effects into testable hypotheses[254-256].

A number of recent studies have examined how plant species and natural ecosystems respond to sustained exposure to enhanced CO_2 concentrations, with and without other environmental stresses. Several tree species in the vicinity of natural CO_2 springs in Italy, for example, showed an initial high growth enhancement of more than 150% that declined rapidly with time to about 10-20% after 30 years. Sustained response will also be sensitive to nutrient availability and the concurrent changes in species composition of the ecosystem. Experimental studies with young Douglas Fir plants also show that, when the effects of climate change are added to those due to enhanced CO_2, respiration from root systems, soil organic matter decay and litter decomposition are all substantially enhanced. Some experts argue that direct CO_2 effects should also increase plant water use efficiency and reduce plant evapotranspiration, thus increasing the amount of water available for runoff (particularly in dry climates). However, several studies suggest that atmospheric and other ecosystem feedbacks tend to mitigate these direct effects, resulting in much lower response at the ecosystem scale[257-266].

Increased carbon dioxide concentrations within tropical ocean surface waters will significantly decrease the saturation state of the carbonate mineral aragonite and hence increase its biogenic precipitation. This may seriously decrease the accumulation of calcium carbonates in coral reefs and threaten their future development[267].

6.2 Methods for Improved Impact Analysis

Predicting regional climates for use in impact studies involves a composite of factors that create uncertainties, including imperfections of the GCMs used as the basis for downscaling methods used, uncertainty in the nature of external forcing factors applied in the predictions, and internal chaos of the climate system itself. The use of multiple forcing scenarios, ensemble experiments, and an integrated climate system model that includes vegetation feedbacks can help reduce these uncertainties. However, there are also uncertainties introduced by the method used for downscaling. For example, while recent studies have successfully used both multi-regression equations and regional climate models (RCMs) to relate synoptic scale features to surface climate, and thus generate more detailed climate data for impact studies, the results can differ significantly according to the method used. In general, the regional scenarios are an improvement over the coarse scenarios provided by the GCMs, with statistical techniques showing skills comparable to that for RCMs. However, statistical methods may be compromised by the assumption that all local climate conditions are driven by synoptic forcing rather than local processes, while RCMs are biased by errors in the boundary inputs from the GCM to which they are coupled. Hence continued effort is needed to improve these techniques[268-273].

6.3 Water Resources and Ice Cover

Projections based on several UK Hadley coupled model experiments suggest annual runoff will increase at high latitudes, in equatorial Africa and Asia, and in southeast Asia, but decrease in mid-latitude and subtropical regions. In colder climates, changing snow fall and melt conditions will also result in decreased snow packs and a change in the seasonal pattern of runoff[274-275].

Within North America, net water supply will decrease in many regions (e.g., the western USA), but others will see an increased supply. Warmer temperatures will also generally tend to degrade water quality. Lakes risk becoming more anoxic in southern and south-central regions in mid summer, but less anoxic in winter in northern regions due to drastically reduced ice cover. Boreal lakes could become less productive.

In the Great Lakes basin, significant changes could already occur within the next few decades, with a variety of transient scenarios all suggesting reduced water resources. In the inner Bay of Quinte, a rise in water temperatures of 3-4°C could double total phosphorus concentrations and undo many of the benefits achieved under past control measures. However studies for the Grand River Basin suggest that adaptive measures can help to cope with most of the related impacts[276-281].

6.4 Natural Ecosystems

Forest Ecosystems: The modeled response of central Canada's boreal forest ecosystems to the combined effects of climate change, CO_2 fertilization and fire disturbances shows significant variations from region to region. Most regions show an increase in net primary productivity. However, possible changes in fire disturbance severity was not considered in the study[282].

Montane cloud forests are expected to become increasingly stressed, particularly during the dry seasons, as humidity isolines shift upwards in response to climate warming. Since these forests harbor a high proportion of endemic species, often at the tops of mountains or ridges, many of these species will be threatened with extinction[283].

The combined effects of enhanced CO_2 concentrations and warmer climates could cause VOC emissions from continental US ecosystems to increase by more than 80% above current levels. However, as ecosystems gradually change in response to climate change, high VOC emitting species are likely to decrease. Eventually this could result in a net reduction in emissions[284].

Prairie Landscapes: Studies into the behaviour of the Palliser Triangle region of the Canadian Prairies during past changes in Holocene climates demonstrate that dry regions such as this are highly vulnerable to changes in climate. While sand dunes in the region are currently relatively stable, they have frequently been active during the droughtier periods of the late Holocene and could become active again with relatively small changes in regional climate. Response of the landscape, including runoff systems, to further climate change will be complex, both because it is still in a state of inequilibrium due to past changes and because anthropogenic land use factors may play a dominant role as well[179, 285-286].

Polar/Alpine Systems: Permafrost degradation under warmer climates will have important implications for regional hydrology, ecology, greenhouse gas fluxes and social infrastructure in the high latitudes. This includes the effects of increased land disturbances on the salt content of surface runoff in the Arctic. Such salinization of runoff, which can continue for several decades after the disturbance, can cause high salt accumulations on land surfaces that may have significant negative impacts on local arctic ecosystems[287-288].

Marine and Aquatic Systems: Higher precipitation predicted by the Canadian GCM under equilibrium $2XCO_2$ climates would cause a significant increase in export of dissolved organic carbon from Canadian ecosystems into streams and lakes. This export peaks in spring in southern Canada, and in summer in the north[289].

Flora and Fauna: Since ecosystems are complex systems where impacts on one component of the ecosystem can subsequently cause significant secondary impacts on the entire system, climate change may cause cascading effects that far exceed the primary impact. Other pressures on such ecosystems will also influence how they respond. For example, while walruses expanded rapidly northward into new territories off the coasts of Canada during the last deglaciation, populations and hunting pressures may make it more difficult for them to respond to changing conditions today[290].

Predictions are that, under projected changes in climate for 2080, some 75% of bird species in the UK will advance their egg laying time in spring by up to 18 days [246].

Climate change as well as direct effects of human activities are likely to increase the range and accelerate the transport of both pathogens and marine species at risk to diseases. This could significantly increase the frequency and number of disease epidemics amongst marine animals and corals. Coral bleaching from intense temperature anomalies may further stress these ecosystems, although geological records suggest that corals have resisted extinction during large climate swings of the past[251,252,291].

6.5 Agriculture

Global food production estimates based on Hadley coupled model projections suggest increased yields in mid to high latitudes, but a decrease at low latitudes, putting an additional 80 million people at risk of hunger by 2080. Most vulnerable are the arid and sub-humid regions, particularly those for Africa. However, studies have not as yet adequately addressed the concurrent effects of changes in water resources, adaptive response and other important factors in an integrated manner. Furthermore, few assess the implications of climate variability or extremes. Hence results must still be used with caution and are not as yet a good basis for adaptive policy decisions.

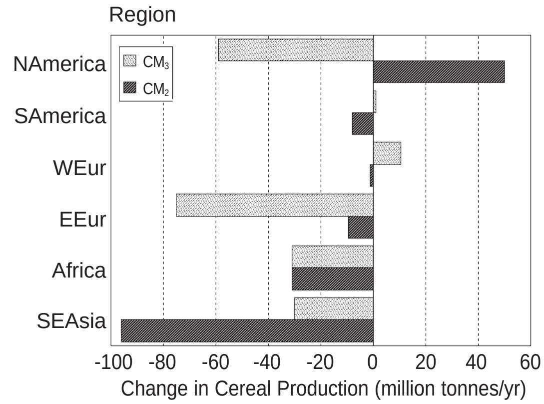

Figure 5. *Estimates for changes in cereal production in different regions of the world based on climate change projections for 2080 using the Hadley Centre HadCM2 and HadCM3 coupled climate models. Estimates include mitigating effects of* CO_2 *fertilization. Results are very sensitive to projections of changes in water supply, but suggest that greatest crop losses due to climate change may occur in the developing countries of the world. Adapted from Parry et al. (#293).*

The competitive interaction between crops, weeds, insects and diseases will also change, creating additional challenges to agricultural systems[292-295].

In regions such as Europe, the effects of climate change on agricultural production may be difficult to detect against background noise before mid-21st century, both because of model uncertainties and the coincident effects of interdecadal natural climate variability[296-297].

6.6 Extreme Weather

Studies using climate model projections of future changes in temperature under enhanced CO_2 conditions suggest that the frequency of intense 5-day heat spells will increase dramatically. One study suggests events will become 6 times more frequent in Berlin, while another projects an 8 fold increase for Toronto. This has important implications for direct heat stress, space cooling power demands and air quality[298-299].

Lightning activity may also increase, perhaps by as much as 40% per °C in the Northern Hemisphere[300].

Studies using the GISS GCM output together with a simple cyclone genesis model and spectral analysis of vorticity suggest a significant increase in cyclogenesis in the North Atlantic, the Gulf of Mexico and particularly the North Pacific. The intensity of hurricanes is also strongly affected by interaction with the upper ocean mixed layer, which induces a negative SST feedback. While this feedback is minor for rapidly moving hurricanes, it can reduce the intensity of slow moving hurricanes by as much as 50%[301-302].

Although extratropical storms are intermediate agents between atmospheric circulation and surface water resources and hence important to understand in the context of warmer climates, climate models are as yet too coarse in resolution to properly assess the consequences of climate change on their characteristics[239].

Increased transport of water vapour into the stratosphere, both due to a projected warming of the tropopause and decomposition of methane, could have important implications for ozone chemistry and the stability of the Arctic vortex in winter and spring. This factor has not been adequately addressed in past studies of the impacts of climate change on episodes of intense ozone depletion over the Arctic[303].

6.7 Land Ice/Sea Level Rise

Multi-century simulations of polar ice sheet response to global warming suggest that, during the 21st century, decreases in the mass balance of the Greenland ice sheet will largely be offset by increases in Antarctica (which will still be dominated by background ice sheet evolution). On longer time scales, ice dynamics could also cause the Antarctic sheet to add to sea level rise, although not as much as that due to Greenland melting processes. Maximum contribution to sea level rise from these ice sheets would be about 85 cm/century, mostly from Greenland[304].

The Hadley coupled model suggests that thermal ocean expansion may add 38 cm to sea levels by 2080, independent of any contributions from polar or temperate glacier ice melt. Such a rise, when considered with concurrent coastline subsidence, would create a five fold increase in global populations vulnerable to flooding by storm surges and cause up to 22% of coastal wetlands to disappear. A higher rise of one meter would affect many major cities through flooding and salt water intrusion, would put 30% of the world's total cropland at risk, and threaten many coastal structures, including nuclear power plants. Hence it would have devastating impacts on societies around the world. Among the most vulnerable are small island states, which have few resources to help them adapt[305-307].

6.8 Economic and Health Impacts

Predicted changes in global water resources under various climate change scenarios suggest a likely increase in the number of people living in water stressed areas by 2025, but less certain consequences by 2050. There will also be an increase in climate change related discomfort and stress due to combined effects of temperature and humidity. This will be greatest in those parts of the world that are already warm and humid, such as the tropics and summer extratropics[274,308].

Models disagree on how climate change will affect regional water resources. For the USA, for example, the Canadian coupled model projects much drier conditions by 2030 for all regions but California, while the Hadley CM2 model projects wetter conditions for more than two-thirds of the region. Implications for cost of water resource management are thus difficult to estimate. Likewise, there is disagreement between models as to how precipitation extremes will change region by region. However, models do in general agree that future climate change will cause more frequent and intense heavy rain events. This implies an increase in stream flow extremes and risk of flooding. However, the implications for flood damage is influenced more by human factors than by such hydrological changes[211,309-310].

In addition to direct costs in terms of human health and suffering caused by extreme weather events, the effects of the spread of disease and other factors may be large. For example, increased risk of heavy rains and more humid climates will increase the likelihood of water and mosquito borne diseases, while changes in ocean climates can increase the spread of toxic substances and destroy corals. Increase in population at risk of malaria alone could exceed several hundred million. Climatologists will need to work much more closely with biomedical scientists to identify the risk factors and mechanisms for disease response to climate change, and thus better assess the above health risks. OECD has recently estimated that the net global costs of climate change, including some of the above health effects, may approach $1 trillion. This suggests that delays in mitigating these risks may be short sighted[311-315].

7.0 POLICY

7.1 Policy-Science Debate

Surveys amongst 400 climate scientists in North America and Germany suggest a consensus that the knowledge of the risks of climate change is sufficient to warrant initiation of mitigative action, despite the fact that they also agree that the detrimental effects of climate change cannot be adequately specified. Likewise, the American Geophysical Union recently adopted a position statement on climate change that acknowledges the considerable uncertainty in current understanding but states that such understanding already provides a compelling basis for legitimate public concern, and that the uncertainties do not justify inaction. These views imply that the call for action is based not only on scientific knowledge but also normative judgments. Some argue that such forays into socio-scientific perspectives of the climate change issue should be undertaken with caution, and in collaboration with social scientists and stakeholders. This collaboration is needed to more effectively and openly assess the consequences of climate change, grasp the need for action, and develop appropriate response strategies. It is also important in putting scientists in touch with social value systems that are equally or more important to decision making processes and helps to restore public trust in scientists. Traditional knowledge from aboriginal people, who are very conscious of natural cycles and the interplay of climate and ecosystems, can also be of considerable value. Furthermore, climate scientists should avoid publishing results too quickly, hence risking the need for retraction of incorrect results. They should also point out the need for adaptation, since even limiting greenhouse gases to a doubling of pre-industrial levels will not avoid the risks of serious impacts. Finally, climate experts should heed the example set by other expert communities such as the medical and legal professions by better communicating the concepts of probabilities, risks, and uncertainties associated with the advice they provide in terms that lay audiences can understand, and in general improving public and media scientific literacy with respect to climate change[316-326].

Various policy analysis tools and institutional mechanisms are available to assist in this work, including cost-benefit analysis and tolerable windows approach. However, these tools can be easily misused or misunderstood and should therefore be used collaboratively to help provide input to the policy decision making process rather than to prescribe policy actions. New tools may also need to be developed. For example, integrated assessment models can provide a means for better relating climate model results to those aspects of society more relevant to the decision making process. Model uncertainties can be factored into these analysis, but will generally lead to stricter mitigation policies. Alternatively, some argue that cost-benefit analyses that seeks to optimize a social welfare function by including all relevant quality of life factors may be the best method to determine optimal response strategies[327-334].

Science assessments and advice based on closed door discussions amongst a select group of scientists provide effective and timely policy making input in the short term, but become less effective in the long term because of lack of support from both the broader science and policy communities. Hence consensus based mechanisms such as the IPCC, although cumbersome and ridden with conflicting interests and perspectives, provides a better long term advisory process. However, while the IPCC process appears to be honest about uncertainties in its assessments, too much focus on consensus is contrary to the adversarial nature of scientific investigation and hence can be dangerous if it ignores minority views[335-336].

Participation by scientists from developing countries in both the scientific research and assessment is important to ensure that their countries have a proactive role in the development of global mitigative policies. However, in many of these countries the endogenous capacity for participating in such research and assessment is lacking[337].

A number of scientists continue to argue that there are significant discrepancies between observed trends in climate and that projected by climate models, and suggest that there is cause for skepticism about the risks of climate change. For example, while models suggest the Arctic will warm more than low latitudes, some areas of the Arctic have cooled in recent decades[338].

7.2 Mitigative Response

While hydro-electic power generation provides a renewable source of energy that can displace fossil fuel generation of electricity, studies indicate that some hydro-electric reservoirs that flood large amounts of biomass can be major sources of methane during the first few decades after flooding. Renewable ethanol fuels developed from corn and cellulosic biomass can also significantly reduce net CO_2 emissions from energy use, although production costs for cellulose ethanol are as yet prohibitive[339-340].

Efforts to reduce greenhouse gases emissions from the agricultural sector, which contribute 10% to Canada’s total emissions, can have important complementary benefits both to the local environment as well as to the long term sustainability of the industry itself. Related mitigation strategies, however, should simultaneously address carbon dioxide, nitrous oxide and methane, since their emissions are inter-linked[341].

Protecting and expanding the carbon content in global forests and coastal wetlands are another effective means of reducing the rate of growth in atmospheric CO_2 concentrations while generating many co-benefits. Forest harvest-regrowth cycles tend to be net sources and are not effective means of reducing emissions unless the harvested products are used in long term storage applications and forest regrowth is rapid[342-344].

Capture and disposal of smokestack CO_2 is an alternative method of reducing emissions. Processes for binding the captured CO_2 into mineral carbonates through reaction with magnesium or calcium may have potential. Dumping of liquid CO_2 into the deep ocean is another alternative for disposal, although studies suggest the CO_2 will pool at the ocean floor and react with sea floor sediments to generate hydrates, a process that releases large amounts of heat and may have significant local environmental implications[345-346].

Emissions of SF_6 and PFCs could be reduced by 25% at relatively low costs. Accounting procedures are not as yet well established, and hence reported reductions based on altered reporting techniques could be fraudulent[80].

7.3 Adaptive Response

Some argue that it may be far simpler to delay mitigative action until better energy technologies are available, and that future developments in science and technology will help us to adapt the changes that do occur. However, others caution that the most vulnerable countries are those who lack the resources to deal with the impacts of climate change, and that the global population of environmental refugees (which numbered 25 million in 1998) could increase six fold by 2050. Preparing communities to deal with climate change related disasters will need to rely primarily on providing appropriate resources and infrastructure at the community level, with assistance from international relief organizations[319,324,347-348].

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Abbreviations for references: *BAMS = Bulletin of the American Meteorological Society; CC = Climatic Change; GBC = Global Biogeochem.Cycle; GCB = Global Change Biology; GRL = Geophysical Research Letters; JGR = Journal of Geophysical Research; JAWRA = Journal of the American Water Resources Association; 23rd ACDPWS = 23rd Annual Climate Diagnostics and Prediction Workshop, Miami, FL, Oct. 1998.*

1.0 INTRODUCTION

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