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CO2 / CLIMATE REPORT

A Periodical Newsletter Devoted to the Review of Climate Change Research

2000 IN REVIEW
AN ASSESSMENT OF NEW RESEARCH DEVELOPMENTS RELEVANT TO THE SCIENCE OF CLIMATE CHANGE

Winter 2002 Issue

Inside....

1.0 INTRODUCTION

As part of an ongoing literature review and assessment process within the Science Assessment and Policy Integration Branch of the Meteorological Service of Canada (MSC), this issue of *CO_2/Climate Report* provides a synthesis of some 400 key scientific papers and reports relevant to climate change that have appeared within the international peer-reviewed literature in 2000. As with past reviews, this synthesis is not intended to be a full assessment of the state of scientific knowledge on climate change, but rather a brief summary of recent, incremental research highlights. For a more comprehensive assessment of the science of climate change, readers are referred to the *Third Assessment Report* (TAR)[1], released by the Intergovernmental Panel on Climate Change (IPCC, 2001), and to other special IPCC reports published in recent years[2]. Earlier issues of the *CO_2/Climate Report* can also be consulted for summaries of research papers published prior to 2000. 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 2000 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 and regretted.

2.0 Changing Atmospheric Composition

2.1 Carbon Dioxide

2.1.1 Atmospheric Concentrations

Globally averaged CO_2 concentrations reached 368.5 ppm in 1999, an increase of 1.8 ppm relative to the previous year. While annual increases in concentration have averaged 1.5 ppm/year since 1979, this growth rate varies significantly from year to year. Lowest rates of 0.5 ppm/year occurred in 1982 and highest rates of 3.5 ppm (equal to a net source of 6.2 billion tonnes of carbon (GtC)) in 1998. Although changes in human emissions can also be a factor, this variability appears to be primarily due to natural inter-annual changes in atmosphere-ocean and atmosphere-land CO_2 flux processes. Biospheric model simulations, for example, suggest that the unusual warm conditions during the 1998 ENSO anomaly may have induced increased respiration and soil decomposition in regions such as eastern Siberia, northern South America and South Africa. On average, natural processes appear to be a net carbon sink in the Northern

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Hemisphere, particularly over mid-latitude oceans and high latitude land areas. In contrast, tropical oceans and the Southern Hemisphere appear to be natural sources of atmospheric CO_2 (despite evidence for a mid-hemispheric ocean sink). However, ongoing evidence of changes in the ratio of carbon isotopes in atmospheric CO_2 with time suggests that much of the long term increase in CO_2 concentrations is due to the emissions into the atmosphere of CO_2 from fossil fuel sources[3-6].

Detailed analysis of Antarctic ice cores suggest four millennial-scale time periods during the Last Glacial Maximum when CO_2 concentrations rose above background levels by about 20 ppmv, coincident with brief warm anomalies in the temperature record. However, such detailed reconstructions of past CO_2 concentrations from ice cores may be sensitive to artifacts caused by chemical interactions over time within the ice. This appears to be particularly important for the Greenland ice cores, which have higher concentrations of carbonates within them[7-8].

2.1.2 Land Carbon Flux Processes

Recent empirical and modelling studies indicate that net land uptake of atmospheric carbon (including emissions from deforestation) increased from average values of near zero in the 1980s to an average of about 2 GtC/year in the 1990s. During the past decade, emissions from deforestation in the tropics appear still to equal or exceed net regional biological uptake of atmospheric carbon. Hence, it is unlikely that low latitude ecosystems contribute to this global carbon sink. Rather, most of the current global land sink appears to occur in non-tropical latitudes of the Northern Hemisphere, with recent estimates of 0.5 GtC/year over North America, 0.3 GtC/year over Europe and 1.3 GtC/year over Siberia. However, there is high temporal and spatial variability in the net terrestrial fluxes. Regional changes are well correlated with changes in temperature and precipitation (which influence both respiration and net primary productivity), although varying cloudiness (which affects solar insolation and hence photosynthesis) may also be a factor. Such sensitivities of natural CO_2 fluxes to climate variability also have implications for response to long-term climate change[9-17].

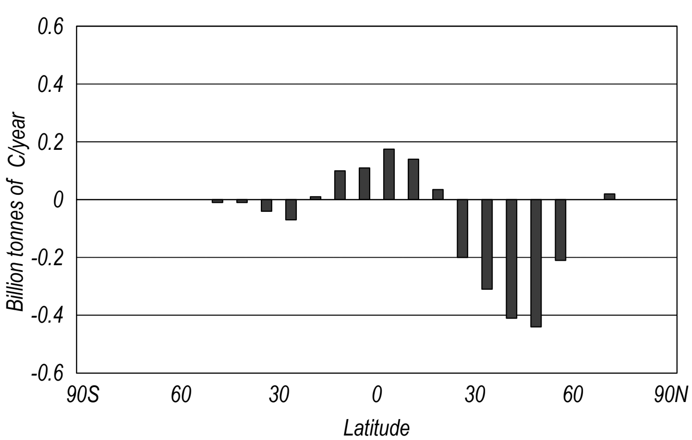

Figure 1. Average annual source/sink per 7.5° latitude band for 1985-95, as estimated by an inverse model. Adapted from Ciais et al. (2000) [11].

There continues to be controversy over the accuracy of regional estimates of terrestrial sinks. For US forest ecosystems, for example, dynamical ecological models suggest that enhanced growth rates due to climate change and CO_2 fertilization may have induced an average net sink in these ecosystems of about 80 million tonnes of carbon (MtC) per year since 1980, and that N fertilization and other environmental factors may have contributed as much again. However, inventory based and inverse model studies indicate this net sink could be 300 MtC/year or higher. Furthermore, inventory based analysis for the eastern US suggest that this region is currently a large carbon sink primarily because of regrowth due to past disturbances, rather that enhanced growth rates due to environmental change, and that this regional sink would be expected to decline significantly as the forests mature. This suggests that ecosystem models as yet inadequately consider forest structure and age, and may therefore significantly over-estimate the effects of CO_2 and N fertilization, or of warmer climates.

For non-forest ecosystems, such as those for northern tundra and peatland systems, the sensitivity of soil carbon fluxes to changes in temperature and to permafrost degradation may be of primary importance. Recent studies show that Alaskan tundra regions changed from carbon sinks to sources in the early 1980s in response to the effects of regional warming on enhanced winter effluxes. They also suggest that future warming will likely enhance the annual carbon cycle, increasing both summer uptake and winter efflux, change its seasonal pattern. This is supported by paleo evidence of past response of Quebec peatlands to changes in climate[18-26].

Dynamical model projections of future response of terrestrial ecosystems to changing environmental conditions suggest land sinks are likely to increase with time during the next few decades, then gradually stabilize or decline by mid-century as CO_2 fertilization effects begin to saturate and warmer temperatures increase soil respiration. At higher Northern Hemisphere (NH) latitudes north of 50^{o}N, terrestrial CO_2 sinks may initially decrease because of increased boreal forest fires . However, they could increase to almost 1 GtC/year by 2050, then stabilize, as a result of northward expansion of forest ecosystems and longer growing seasons (providing summer moisture levels remain adequate). In contrast, some studies suggest tropical regions are expected to become hot and dry, and hence a large net source of atmospheric CO_2. There is significant disagreement between models on the magnitude of net global changes in land sinks beyond 2050. Some suggest CO_2 sinks will stabilize or decline slowly, but others predict that land sinks will begin to decline abruptly by mid-century and even become a net source by 2100 or sooner. A key factor in this disagreement is the inadequate understanding or inclusion of processes affecting soil carbon changes[15,27-32].

2.1.3 Ocean Carbon Fluxes

Studies with inverse and ocean biogeochemistry models suggest that global ocean sinks are of comparable magnitude to that of land areas, but much less variable. They also appear to have declined slightly in recent years. Inter-annual variability in ocean sinks appears to be driven by changes in circulation and in climate, and is dominated by ENSO and other dynamical processes in the tropical Pacific Ocean. Physical changes in ocean circulation may be of particular importance in determining the future role of oceans as a large carbon sink. For example, the southern ocean deep-water formation region could decrease as a major sink for excess atmospheric carbon if climate change reduces surface densities and hence surface water sinking processes. Increasing atmospheric CO_2 concentrations over time also reduces calcite production in surface ocean waters, which can enhance CO_2 uptake. However, this also alters calcium carbonate and hence coral production and other aspects of ocean biochemistry. These possible biochemical and physical responses of the oceans to a changing environment are as yet poorly understood[9-11,33-36].

2.2 Other Greenhouse Gases

2.2.1 Methane

Following more than a decade of declining growth rates, methane concentrations increased abruptly to a peak rate of some 20 ppb/year in 1998, then declined again to a mean increase in 1999 of almost 7 ppb. Analyses of trends and fluctuations provide some support for decline in gas field and pipeline leakage in the Former Soviet Union (estimated to be about 10% of global anthropogenic emissions a decade ago), but point primarily to temperature and precipitation driven changes in wetland emissions and to increased destruction of methane by recent rises in concentrations of OH. Hence it is premature to assume that methane budget is approaching a steady state[5,37-38].

Analysis of methane concentrations and isotopic composition in ice core data for pre-industrial Holocene periods, using a chemical transport model, indicate natural wetlands during this period were likely an average annual source of about 160 Mt CH_4 and have decreased by about 10% since. This provides an improved constraint on past estimates for current wetland emissions, and suggests anthropogenic emissions may have been underestimated. Polar ice cores also indicate that wetland methane concentrations changed significantly (by some 200-300 ppb) during four brief but rapid climate transitions during the 40,000 year period prior to the Holocene. These changes appear to be caused primarily by changes in both tropical and boreal wetlands conditions, which lag the changes in climate. Reconstruction of Amazon River flow histories for the past 14 k support such wetland-methane concentration relationships, but also suggest that wetland variability in the region is related to changes in convective activity induced by summer solar insolation variations[39-44].

Aggregated estimates of methane emissions from the Hudson Bay Lowlands derived from atmospheric models suggest an annual net source in recent decades of 0.23 to 0.5 Mt CH_4, but very sensitive to changes in temperature. While these emission rates are much lower than that estimated from in situ measurements, the high sensitivity to temperature suggests emissions may rise rapidly as climate warms[45].

Land use change can significantly alter the role of soils as a sink for methane, by changing soil moisture content and the phenology and productiveness of ecosystems involved. Conversion of soils from natural states to agricultural purposes usually decreases the magnitude of the sink. Although land use for rice production appears to be increasing in many countries, related methane emissions appear to have been overestimated. Such emissions have already been reduced by increased use of modern rice varieties, but can be further limited by appropriate uses of fertilizers, flooding techniques and other appropriate agricultural practices. Flooding of vegetated landscapes to create water reservoirs may also be a significant but largely ignored anthropogenic source of methane emissions. While such emissions vary a great deal from site to site, depending on reservoir characteristics and age, and global estimates are very uncertain, these reservoirs could account for as much as 20% of global anthropogenic emissions[46-51].

2.2.2 Nitrous Oxide

N_2O concentrations have increased by an average of 0.25%/year since 1978, but slightly more rapidly since 1996. N_2O emissions are highly variable in space and time and hence difficult to scale up to global scales. The use of models of N_2O budgets and other tools, such as the analysis of trends in N_2O isotopic composition, can help to better understand the anthropogenic sources, sinks and pathways. However, better monitoring networks will be needed to constrain model results[52-54].

Soil emissions of N_2O are strongly influenced by soil type and water content, being highest immediately after precipitation events or in water saturated locations, and hence are spatially and temporally very variable. Tropical rain forests may be particularly important but underestimated sources. In cold climates such as that of Canada, a very large pulse of emissions from agricultural soils can occur during spring melt. While effects of nitrogen fertilization of crops may be a secondary factor in determining N_2O emissions on small scales, at a global scale it is an important contributor to anthropogenic emissions, both directly from soils and indirectly through losses from nitrogen leaching or runoff into riparian zones and streams. Such agricultural emissions are expected to increase from about 6 MtN/year in 1990 to 9 MtN/year by 2020. IPCC methods for estimating these emissions do not adequately consider the factors that contribute to high variability, and results differ significantly from those observed in related studies. Hence, they may need significant revisions[55-60].

About one-third of anthropogenic N_2O emissions come from aquatic systems, primarily due to nitrate buildup and increase in oxygen-deficient waters. Most of these emissions come from rivers and estuaries, but a significant and previously overlooked source appears to be coastal ocean waters, particularly over continental shelves[61-62].

Based on laboratory and roadway measurements, N_2O emissions from transportation cause about 1-4% of its atmospheric growth rate. More than 50% of these emissions come from about 10% of transportation vehicles[63-64].

2.2.3 Halogenated Gases

Concentrations of CFC-12 continue to increase in the atmosphere, although less rapidly than a decade ago. Meanwhile, concentrations of shorter life-time CFCs, such as CFC-11 and CFC-113, are declining slowly at about 1% per year and CH3CCl3 much more rapidly at 18%/year. HCFC concentrations, in general, continue to rise, while SF6 (which appears to have no significant natural source) is increasing linearly at about 0.24 ppt/year, or currently about 5%/year[53].

2.3 Tropospheric Aerosols.

Atmospheric measurements show an average 2% per year decline in total aerosol scattering at the high latitude site of Barrow, Alaska since 1980, consistent with a decline in aerosol emissions from Europe and Russia. By comparison, total scattering has increased over the low latitude sites of Samoa and the Mauna Loa[65].

While tropical biomass burning is a large source of black carbon and particulate organic matter, wildfires in boreal and temperate forests can also be significant contributors, particularly during bad fire years[66].

3.0 Radiative Forcing

3.1 Greenhouse Gases

New estimates of life cycles and radiative forcing effects of different greenhouse gases suggest a net global increase in forcing since 1765 of 2.32 W/m^2, similar to past estimates. However, they also indicate that the GWP values and hence the role for short lived greenhouse gases may have been significantly underestimated. Furthermore, exaggerated estimates for pre-industrial concentrations of tropospheric ozone may have added substantially to an underestimation of its radiative forcing role to date. Tropospheric ozone concentrations are currently increasing over southeast Asia. Future emission scenarios suggest its global radiative forcing effects will continue to rise, although negative chemistry feedbacks associated with warmer climates may significantly mitigate this increase. Meanwhile, in the stratosphere, ozone depletion appears to be causing a decrease in radiative forcing in high latitudes[67-70].

An estimated 1% increase in high altitude cloud cover due to jet contrails, which is plausible within the next 50 years, could also increase average global air temperatures by 0.43°C, with larger increases over the Northern Hemisphere at upper levels of the troposphere[71].

3.2 Aerosols

The direct effects of various types of aerosols on atmospheric radiative fluxes depend on many factors, including the nature of the aerosol, their interactions with other atmospheric constituents, and the albedo of the surface below, and hence are very difficult to assess. Hygroscopic aerosols, for example, expand with increasing humidity, causing their albedo values to rise in a complex and non-additive manner. Furthermore, the seasonality of aerosol concentrations is controlled by complex interplays of transport mechanisms, chemistry and deposition processes, all of which vary in time and space. Indirect effects are even more complex, involving changes in atmospheric circulation as well as in cloud properties. Hence, the role of aerosols in radiative forcing and climate change, while significant, remain very difficult to estimate. Recent studies suggest the direct effects of enhanced sulphate aerosol concentrations alone may have induced a negative global radiative forcing relative to pre-industrial periods of -0.56 W/m^2, that indirect effects may have added another -0.4 to -1.78 W/m^2, and that related changes in atmospheric circulations may have displaced the equatorial rainbelt southward. While other studies suggest lower estimates, all suggest that sulphate aerosols have substantially masked the effects of positive radiative forcing from concurrent increases in greenhouse gas concentrations [72-75].

In contrast, dark aerosols appear to add to the positive radiative forcing of greenhouse gases. New forcing estimates for black carbon aerosols suggest values in the range of 0.3 to 0.6 W/m^2 (depending on how these interact with other aerosols). Studies related to the south-east Asian INDOEX project also suggest that such aerosols cause local heating affects that can reduce day-time cloud-cover, further adding to the warming effects. Since these aerosols have short life-times, emission reduction efforts could reduce their contributions to radiative forcing much more quickly than that for longer lived greenhouse gases[76-78].

Stratospheric aerosols from major volcanic eruptions also periodically cause significant negative radiative forcing effects. These can influence global climate for several years after such eruptions, thus further increasing the difficulty in detecting the human effects on the climate against background climate system noise. Statistical analyses of major eruptions (causing temporary negative radiative forcing of -1 W/m^2 or more) over the past 600 years suggest a 37% probability of such an event, and a 15% probability of two such eruptions, within the next decade[79].

3.3 Solar

Establishing possible linkages between solar activity, cloud cover and climate requires both good correlations between the variables involved and plausible mechanisms to explain such correlations. Linkages between solar uv radiation, changes in stratospheric ozone concentrations and climate variations have been proposed as one such possible mechanism. Although possible effects of cosmic ray activity on global cloud cover has also been suggested as another mechanism, analysis of trends in observed regional and global cloud cover between 1986 and 1993 show strong linkage to the ENSO signal, but little evidence of coupling with cosmic ray activity[80-82].

4.0 Climate Modelling and Model Results

4.1 Climate Processes

4.1.1 Atmospheric Processes

Water vapour concentrations in the atmosphere can vary by four orders of magnitude, with highest values in humid climates near the surface and lowest values in the lower stratosphere. There continue to be large discrepancies between various types of field measurements of these concentrations, and of their radiative effects. Furthermore, inadequate understanding of atmospheric temperature-moisture-cloud relationships make it difficult to confidently model water vapour feedbacks. For example, NCAR model studies using a tight temperature-moisture relationship with non-convective cloud schemes produced a much drier upper troposphere and higher climate sensitivity to radiative forcing than experiments using deep convective cloud schemes and weaker temperature-moisture relationship. Hence uncertainties about the role of water vapour in climate feedbacks, and therefore in climate sensitivity to radiative forcings, continue to be very large. However, there is good evidence to suggest that climate response to a doubling of CO_2 is unlikely to be less that 1°C, and is probably significantly greater[83-84, 237].

Simulations of clear sky solar radiation with climate models using advanced radiation schemes and aerosol effects continue to underestimate observed values, although the discrepancy has decreased substantially from previous studies. Both observations and model simulations suggest that all-sky absorption of solar radiation is not significantly different from clear sky absorption[85].

There is good evidence to suggest that the troposphere, stratosphere, mesosphere and thermosphere are coupled and that upper atmospheric chemistry and other features such as gravity waves, winds and tides are important in simulating the global climate system. Earlier versions of climate models have

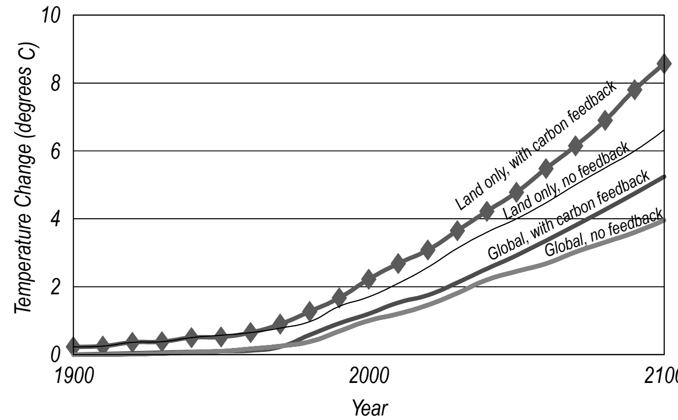

Figure 2. Projected responses of global and land area temperatures to changing concentrations of greenhouse gases estimated under the IS92a emissions scenario. Solid curves are for responses when a dynamic carbon budget model is fully coupled to the climate model, while dashed and dotted curves represent temperature responses without full carbon budget feedbacks. Adapted from Cox and Betts (2000) [88].

either excluded or inadequately described the upper layers of the atmosphere. However, a number of middle atmospheric models (such as the Canadian Middle Atmosphere Model) are now able to satisfactorily replicate many of the features of upper atmospheric processes and are now available for inclusion in climate models[86].

4.1.2 Land Processes

Biogeophysical and biogeochemical processes can have important influences on radiative, hydrological and other fluxes between the biosphere and the atmosphere, and hence on climate. A significant number of dynamic global vegetation models that describe many of these processes, including the Canadian Land Surface Scheme (CLASS), are now being developed and evaluated. Experiments conducted with vegetation models linked to simple GCMs are providing useful insights into some of the non-linear responses of the climate system to climate forcing. For example, some of these studies suggest that the combined effects of climate change and CO_2 fertilization feedbacks on hydrological processes, while regionally variable, tend to cause more arid conditions, particularly in the tropics and mid-latitudes. This is contrary to common views on the hydrological effects of CO_2 fertilization. Although it is still difficult to fully couple vegetation models to complex coupled climate models, one such study projects that climate-carbon cycle feedbacks in response to rising greenhouse gas concentrations may eventually cause large land areas to revert from current sink role to that of source (despite CO_2 fertilization effects). This would further enhance atmospheric CO_2 concentrations and could add about 10% to the climate effects simulated without this feedback[29,87-92].

There are also other variables and feedbacks that may be important in properly simulating vegetation-climate interactions. For example, the albedo effect of the earlier retreat of spring-time snow cover in the Northern Hemisphere since 1979 may have caused a positive seasonal feedback of 2 W/m^2 over the areas affected. Likewise, while land use change may not have significant effects on global scale climate, winter albedo effects of historical land use change in mid-latitudes of the NH may have contributed to a northward shift of a wider but weaker westerly jet stream. Conversely, reforestation activities in mid to high latitudes could significantly decrease albedo effects and cause significant regional warming influences[93-96].

4.1.3 Ocean Processes

Sea ice plays an important role at the atmosphere-ocean interface in polar regions and, together with sea surface temperatures, may be an important driver for precipitation changes in these areas[97-98].

Sensitivity experiments and model simulations indicate that surface ocean warming and related feedbacks are the dominant factors in the weakening of the North Atlantic thermohaline circulation system in response to warmer climates. By comparison, the effects of increased freshwater fluxes into the North Atlantic may be partially offset by increased export of freshwater from the Atlantic Ocean to the Pacific and Indian Oceans. Hence the freshwater flux only contributes to about 25% to the thermohaline circulation change. The weakening of the THC system is relatively insensitive to the details of model flux adjustments, and hence considered a robust conclusion. By comparison, the process and nature of recovery is much more sensitive to changes in model parameterizations, and hence has lower confidence[99-100].

Increased UVb radiation due to stratospheric ozone depletion may also affect ocean surface chemistry and the flux of dimethyl sulphide (DMS) and other gases into the atmosphere. This may possibly impact on the climate system in as yet poorly understood ways[101].

4.2 Model Validation

The newest generation of coupled climate models show good progress in performance, and generally replicate annual and decadal variability for most regions of the globe quite well. Hence they now appear to be sufficiently advanced to be useful in climate change detection studies and in providing advice on future climate to policy makers. Intercomparison studies with these models, with and without flux adjustments, indicate that all appear to simulate the amplitude of the average global seasonal cycle well, although all have problems over some land areas. In general, flux adjusted models as yet capture basic climate parameters such as surface temperatures more accurately and have smaller regional discrepancies than the unadjusted models. Major challenges include improved methods for properly scaling up small scale climate system processes and effective inclusion of mesoscale, eddy-induced advection mechanisms to help reduce model drift[102-106].

Evaluations of individual models show varied results. For the flux adjusted Canadian CGCM1, the broad features of mean climate quantities and variability over land are simulated reasonably well, but the variability over the tropical oceans and in the extratropical storm track regions is underestimated. This model suggests that much of the variability in the Northern Hemisphere can be characterized as two distinct variants of the Arctic Oscillation. Analysis of variability in three other coupled models (GFDL, HadCM2 and Ham3L), using long control simulations, indicate that the multi-decadal variability observed in instrumental and proxy records of hemispheric temperatures is captured quite well. Performance for regional variability in the tropical Pacific, which is critical for ENSO behaviour, was less satisfactory, with one model overestimating and the other two underestimating the variability. Results also suggest the warming over the past century exceeds long term natural variations. In a 15,000 year control simulation, the GFDL model also simulated a natural abrupt cooling event near southern Greenland, triggered by a wind generated, multi-decadal shut down of North Atlantic convection processes. This event was very similar to abrupt cooling events reported in the paleoclimate literature, suggesting the latter may be due to natural variability rather than an external forcing.

The UKMO has now developed a coupled model (HadCM3) with a higher resolution ocean and improved simulation of heat budget and fluxes. This model now maintains a stable globel climate without flux adjustments[107-110].

Tests of GCM performance against paleoclimate conditions such as those for 6000 and 21000 years ago indicate that these models, in general, continue to show considerable disagreement with reported paleo data in simulating past surface mass budgets for most ice sheets, primarily because of the high sensitivity of snow and ice melt to relatively small differences in summer temperatures. There are also indications that the climate system has a very long memory and that current climate conditions may still be under the influence of climate forcings from the past 6000 years. Hence model that have been span-up using forcings of the past 150 years only may not be in proper quasi-equilibrium comparable to the real climate today. This may, in turn, affect their performance in transient climate simulations[111-112].

Some argue that use of the same observational data to both force and test model performance can involve a circular logic that affects credibility of performance tests. The use of only well quantified forcings and more detailed observations for testing can help avoid such risks. Finally, there are also legitimate concerns about attempting to validate the performance of models in experiments that inadequately include forcings at work simply because they are poorly quantified[113-114].

Tests with the Canadian Regional Climate Model, nested within CGCM2 and coupled to an interactive lake ice model, show good model performance in simulating the seasonal evolution of surface temperatures and ice cover on the

Great Lakes, as well as lake induced precipitation. However, it underestimates ice concentration[115].

4.3 Model Simulation Results

Coupled climate model simulations using historical changes in greenhouse gas and aerosol concentrations generally show good agreement with observed changes in global temperatures. Some also perform well at the regional level, although the differences at this scale between various models using similar forcing scenarios continue to be large. Several simulations also indicate a change in temperature patterns from a La Nina like condition to an El Niño pattern after the 1960s, suggesting that recent El Niño behaviour may be at least partially linked to climate change. However, there are still difficulties in reproducing observed Arctic Oscillation patterns in anthropogenic forcing experiments, either because of model deficiencies or because these changes are caused by non anthropogenic forces. Simulations with improved ocean mixing schemes also suggest less asymmetry between North and South Hemisphere warming than suggested in past model studies, and closer to that observed[116-120].

Model simulations of the possible effects of recent increases in greenhouse gas concentrations on temperatures in the upper reaches of the atmosphere show similar patterns but much smaller magnitude of cooling to that observed. This suggests that other factors such as ozone depletion may also have contributed substantially to the cooling trend in this region[121].

Simulations with the Canadian coupled climate model, using mid-range IPCC projection (IS92a) for future greenhouse gas and aerosol emissions, suggest a further averaged global surface warming by 2050 of 1.7°C, increasing to 4.4°C by 2100. Both polar sea ice cover and ocean thermohaline circulation decrease, while precipitation increases globally, but with a change in pattern similar to that of an El Niño. UK coupled model simulations, using a more optimistic emission scenario (SRES B2), projects a global warming of 3°C by 2100, while US DOE coupled model and NCAR Parallel Climate Model suggest warming by mid century of 3.5 and 1.3°C, respectively. By comparison, the NCAR climate system model (CSM) projects a much lower warming of 1.9°C by 2100. The NCAR model also suggests a reduction in the amplitude of decadal scale climate variability but an increase in amplitude of oscillations with return periods of less than 20 years. Models generally agree that warming is greater than global averages in winter and over land, and that daily temperature range (DTR) will decrease[122-127].

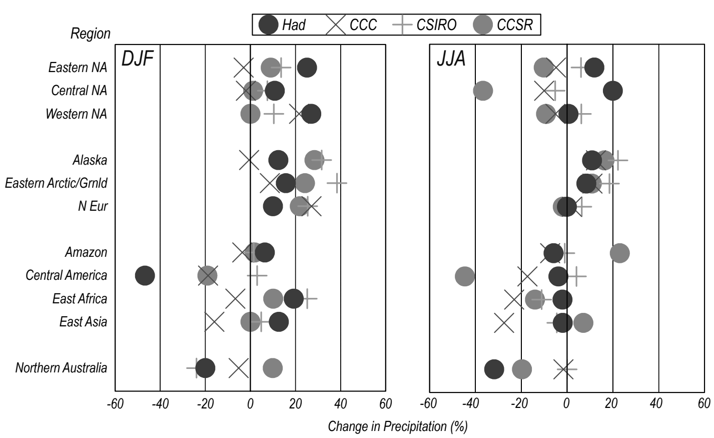

Figure 3. Percent changes in winter and summer precipitation by ~2085 (relative to simulated values for 1961-90) for selected land regions as projected in experiments with four different coupled climate models. While there is considerable disagreement between models for such regional projections, most suggest Arctic regions will become wetter, and tropical regions and central North America somewhat drier, particularly in summer. Adapted from Giorgi and Francisco (2000) [120].

A recent study has used the good agreement between observed and simulated changes in global temperatures in response to past anthropogenic forcings to estimate the current sensitivity of the climate system to forcings. This sensitivity is then used to project a 90% probability that future forcings under a mid-range SRES scenario will cause a further warming of 1 to 2.5°C by 2040. However, although such probability projections can be very useful for the policy community, other researchers suggest they need to be accepted with considerable caution. One study, for example, indicates that climate system sensitivity (which involves a fast response atmosphere-surface ocean component and a slower component dealing with the deep ocean) may not be constant but can increase on century time scales as the climate responds to human forcings. Another study reports that failure to include ecosystem feedbacks within coupled climate models may result in underestimated changes. It projects that future climate change will cause a dramatic collapse of the Amazonian forests by mid century, causing large incremental emissions of CO_2 into the atmosphere and increasing projected global warming by 2100 from 4°C without this feedback to 5.5°C when it is included. Such feedbacks are still poorly understood and their magnitude very uncertain. Although stabilization of future CO_2 concentrations at 550 to 750 ppmv could help reduce the ultimate magnitude of such projected changes, large changes appear to be unavoidable[88,128-132].

While models disagree significantly on the regional response of precipitation to future warming, there are indications that some regions will experience a drastic shift to more extreme conditions, with related implications for both soil erosion and ecosystem stress. Most suggest significant increases in precipitation in mid to high latitudes, as well as in most of the low latitude regions of Asia. Weaker land-sea contrasts may cause the Asian winter monsoon as well as the winter northeasterly winds along the Eurasian Pacific coast to weaken, while enhanced contrasts in summer are likely provide stronger but more variable summer monsoons in these regions[133-134].

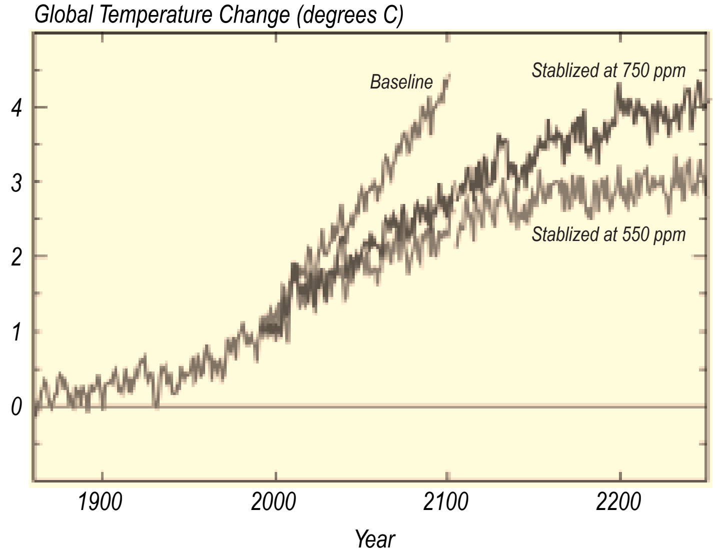

Figure 4. Projected impacts of stabilization of carbon dioxide at 550 and 750 ppmv, as simulated by the HadCM2 coupled model. Adapted from Mitchel and Johns (2000) [129].

Both models and paleo data suggest that the Atlantic Ocean thermohaline circulation (THC) system is inherently non-linear, and that changes from one state to another can have large regional climate impacts. However, while a total collapse of the THC may be possible over longer time scales, such a collapse within the next century appears unlikely. One new model study suggests that advection of high salinity waters from the tropics to the North Atlantic waters may at least partially offset the fresh water flux effect and hence reduce the net effect of this factor in altering the THC system. Likewise, if climate change also induces an upward trend in the Arctic Oscillation/NAO index, as observed in recent decades, related increases in wind intensities and surface heat losses over the Atlantic may tend to enhance surface water sinking and hence also contribute to mitigating projected reductions in the THC. Inter-annual and interdecadal variability in sea ice export into the North Atlantic, as well as in the location of ice melt and the related impacts on ocean convection (which currently play important roles in shorter term variations in the thermohaline circulation system and hence in the NAO signal) will likely decrease significantly as sea ice extent is reduced under warmer climates. This may in turn reduce the climate variability of the North Atlantic[135-139].

The severity and frequency of many climate extremes will change significantly as the climate warms, often disproportionately with changes in mean temperatures. Extreme maximum temperatures are expected to increase, particularly in areas of decreasing soil moisture, while minimum temperatures become less severe. The change in minimum temperatures are expected to exceed maximum temperature rises, especially in areas of snow and ice retreat. In high latitudes, by 2100, heating degree days could decrease by 25-50%, while cooling degree days in the extra-tropics may more than double. While intense precipitation and related wet extremes are expected to become more frequent almost everywhere, drought frequency and intensity are also expected to rise. Thus, soil moisture conditions may become more variable in many regions. Some models suggest climates may become more El Niño-like, while others do not. Such differences may be linked to how the models deal with clouds. Implications for storminess is still uncertain and difficult to model. Cyclone activity over the NE Atlantic and Europe is likely to shift north-eastward and become more intense, while less sea ice cover will also tend to increase winds over Hudson Bay and the Greenland Sea. In contrast winds in the Mediterranean are projected to weaken. Meanwhile, while some past studies have suggested hurricanes could become more intense under warmer climates, at least in some basins, a new GFDL model study suggests increased upper tropospheric warming relative to that at the surface will enhance atmospheric stability. This negative feedback, together with that due to surface ocean mixing, could fully offset the positive effect of higher surface SSTs on hurricane intensity[124,140-144].

Climate simulations indicate that sea levels will rise as the climate warms, and will continue to do so for centuries after global surface climates have stabilized. Recent model estimates suggest a rise of 33 to 48 cm by 2100, with 60% of this due to ocean thermal expansion. While the Greenland ice sheet is not expected to be a major contributor to sea level rise during the next century, subsequent slow melting could cause a 10% loss in volume during the next millennium, adding 70 cm to rises from other sources. A predicted slow-down in the thermohaline circulation system could also enhance the rate of sea levels rise. However, the magnitude of sea level rise remains highly uncertain, and regional differences are large. In the Arctic Ocean, for example, rises are expected to be significantly greater than the global averages because of the influx of less dense freshwater, while that in the Southern Ocean is expected to be less because of projected delays in warming in that region[129,145-149].

5.0 Climate Trends

5.1 Paleo Climates

5.1.1 Past million years

Although geological factors other than CO_2 (e.g., continental drift) appear to have often dominated global climate variations over time scales of millions of years, both tropical ocean sediments and Antarctic ice cores show a very strong agreement between changes in Antarctic air temperature, tropical deep ocean temperature and CO_2 concentrations during at least the last 400,000 years. In contrast, changes in polar land ice volume appear to have lagged temperature and CO_2 changes by several millennia. Furthermore, the onset of warming at the end of the last glacial period appears not to match that for solar forcing. These results suggest that the deglaciation process may be directly linked to changes in CO_2 concentrations and Southern Hemispheric ocean processes (rather than to changes in solar forcing and ice volume). This contradicts common theories employing Northern Hemisphere processes are drivers of glacial-interglacial cycles. While the changes in CO_2 concentration and ocean processes may have been caused indirectly by changes in solar forcing, mechanisms for such linkages are not well understood. Earth system models of intermediate complexity, such as the McGill Paleoclimate Model, have become important tools for exploring such earth system feedbacks and interactions on long time scales, and hence can help to study the intricacies of such forcing linkages and improve their understanding[150-157].

Failure to adequately consider the effects of enhanced regional warming due to Northern Hemisphere ocean feedbacks may have resulted in an over-estimation of the global scale intensity of the interglacial some 400 thousand years before present (kybp). However, this event appears to have been longer and warmer than subsequent interglacials, and too intense to be explained by solar forcing only. There are also indications that sea levels rose during three separate stages of the interglacial, eventually reaching some 20 m higher than today. This implies distinct episodes of rapid ice sheet break down, each lasting one to three centuries, that ultimately caused the collapse of both Greenland and West Antarctic ice sheets and some loss from East Antarctica as well. During the last interglacial (the Eemian, some 135 ka bp), strong vegetation feedbacks, an amplified sea ice feedback and a slower ocean circulation system all appear to have been factors in producing average temperatures slightly greater than the current interglacial. The vegetation feedbacks alone may have amplified Northern Hemisphere summer warming over land by as much as 7°C. A more modest sea level rise of 3-5 m during the Eemian appears to have been caused primarily by a reduction in the Greenland ice sheet, rather than changes in the Antarctic ice sheet. Although similar changes could occur in the current interglacial, model studies suggest that it may differ significantly from preceding events. Even without human interference, it could last another 50 thousand years, with the next glacial maximum in about 100 thousand years. With altered ice sheet dynamics due to human interference with the climate, this timing may change dramatically[158-164].

The combined evidence from models and paleo data now indicate that tropical ocean temperatures during the Last Glacial Maximum (LGM) were, on average, some 2.5 to 3°C cooler than today, and accompanied by enhanced transport of water vapour into the western Pacific. Tropical air temperatures at the time were some 3.5 to 6.6°C colder. This is consistent with a climate sensitivity of 3°C equilibrium warming in response to a doubling of carbon dioxide concentrations[153,165-167].

Studies using climate models and Greenland borehole records indicate that the magnitude of some 21 Dansgaard-Oeschger warm events during the last glacial period, previously noted in ice core and North Atlantic ocean sediment records, may have been underestimated. Other records, including those from tropical ocean sediments, provide supporting evidence that these and other abrupt climate events may be associated with oscillations in the polar fronts, changes in the thermohaline circulation system (and hence deep ocean ventilation) and glacial and hydrological discharges associated with ice sheet dynamics. The Younger Dryas event some 11 kybp, for example, may have been linked to non-linear feedbacks between the glacial Lake Agassiz and the Laurentide Ice Sheet. However, these linkages are not well understood, and it is not clear whether the changes in tropical oceans follow or lead those at high latitudes[43,168-172].

In addition to the Dansgaard-Oeschger events, Greenland ice cores records and other data suggest a 1500 year global scale climate cycle through at least the past 30,000 years, the last of which reached a minimum during the Little Ice Age that ended in the 19th century. The cycle appears to be linked to fluctuations in ocean circulation, but may also result from a stochastic resonance between two or more weak forcing mechanisms. Variability in solar forcing and changes in tidal forces caused by resonances in earth-moon interactions on millennial times scales have been suggested as possible mechanisms. Alternatively, it could be an artifact of ice core analysis techniques caused by aliasing, and hence not a real climate oscillation[173-177].

5.1.2 The Holocene

Ice core data suggest that the Antarctic region experienced three distinctly warmer periods during the current interglacial, or Holocene (each peaking in a different part of the region), and that changes in North Atlantic sea ice cover over time caused climates in that region to be more variable during the early and late parts of the Holocene than during the mid-Holocene period. High late Holocene summer temperatures, associated with changes in regional ocean surface temperatures, have also been noted in Tasmania. In contrast, models suggest global ENSO activity was likely less intense during the early and mid Holocene than the later Holocene[178-183].

Within North America, early Holocene temperatures in southern British Columbia were some 4°C warmer than today, while atmospheric circulation in the Arctic appears to have been more intense. For eastern North America, the residual influence of the Laurentian ice sheet caused dry summers during the early Holocene, changing to wet summers and dryer winters in mid Holocene (as Atlantic air mass movement over eastern Canada became more stable) and dry summers once again in the late Holocene (as dominant regional air masses changed to dry Pacific and cold Arctic air masses) [184-186].

5.1.3 Past Millennium

In some regions of the Northern Hemisphere, such as parts of Siberia, the Medieval Warm Period (MWP) of about 1000 years ago appears to have been as least as significant as recent warming. Recent assessments, however, suggest that the MWP was not global in scale (although sparseness of data makes it difficult to be certain). The subsequent Little Ice Age (LIA) also appears to have been more complex than previously thought. While most areas of the world underwent a significant LIA-type cool period at some point in time between the MWP and today, both timing and characteristics of such a cool period vary from region to region. For example, at the time that the Caribbean cooled by as much as 2-3°C, other regions were actually warming. Although model studies still have difficulty in properly simulating such long term climate variability, they suggest that, until 1850, solar and volcanic forcing can explain between 41 and 64% of it, with the remainder being similar to model simulated internal nature variability. However, the 20th century, and particularly the past 50 years are the warmest of the millennium and hence difficult to explain on the basis of natural variability, whether externally forced or internal to the climate system[187-192].

The MWP and LIA also appear to have had significant effects on regional hydrology. Eastern Africa, for example, was dry during the MWP and predominantly wet during the LIA. However, the latter was interrupted by several shorter dry periods that were more intense than any during the past century. Likewise, a number of past droughts in much of North America during past centuries, possibly linked to the Pacific Decadal Oscillation, appear to have been more severe than any of the 20th century. Hence such severe droughts could occur again in future decades entirely due to natural variability. When added to related risks associated with climate change, droughts could have far more serious implications in the future than any changes in temperature[193-195].

5.2 Climate of the Past Century

5.2.1 Temperature

Surface observational records indicate a Northern Hemispheric warming of about 0.5°C during the past 50 years. Much of the global surface warming has occurred over a small fraction of the Hemisphere, particularly the anticyclonic regions of Siberia and north-western North America. Some regions, such as the north Atlantic sector of the Arctic, have cooled. Proxy data sources, such as isotopic data extracted from ice cores, ocean coral, boreholes, pollen and algae assemblages in lake sediments can help reconstruct past temperature patterns for time periods prior to these observational records or in regions where such records are sparse. For example, temperature reconstructions from data collected at some 600 borehole sites from around the world suggest that observational records may have actually underestimated the extent of the land warming over the past 150 years and that the 20th century was the warmest in at least the past 500 years. Since 1982, satellite based measurements of sea surface temperatures indicate a more modest average ocean surface warming of 0.05°C warming per decade, although tropical SSTs increased by a much more dramatic 0.5°C/decade. In Southern Canada, surface temperatures warmed by between 0.5 and 1.5°C during the past century (with the greatest warming in the west, and in winter and spring), and the daily temperature range (DTR) decreased significantly. Such patterns are broadly consistent with that projected for greenhouse gas forcing, but also show significant discrepancies[196-203].

Within the atmosphere, radiosonde data provide the primary source of extended records. Recent improvements in the analyses of such data suggest a warming trend for the total troposphere of 0.10°C/decade since 1958 (decreasing to 0.07°C/decade when adjusted for ENSO effects). Both the lower troposphere and the surface temperatures warmed by an average 0.12°C/decade during that period. However, trends are sensitive to analysis methods, and can vary by as much as 0.1°C/decade (depending on which radiosonde stations are chosen for the analysis). Furthermore, analysis of the data is very sensitive to adjustments made to correct for systematic changes in instruments and observing practices[204-205].

A number of recent studies have also compared radiosonde records with observed surface data, satellite MSU data, and NCEP and ERA reanalysis results for the past two decades. Surface data measurements indicate a significant surface warming, amplified in north polar regions, over the period. One recent re-analysis of satellite microwave sounder data also suggest a significant mid-tropospheric warming at rates of 0.13°C/decade. Most studies of the satellite data, however, suggest much lower warming rates, or even slight cooling, for the lower troposphere since 1979, and an enhanced cooling in extratropical regions of the upper troposphere and in the lower stratosphere. The differences in trends between observed surface and lower atmospheric temperatures over the past 20 years are particularly prominent in the tropics and in data sparse regions, but disappear when comparing surface and radiosonde data for the longer period of the past four decades. While systematic and analytical errors inherent in each of the data records cause considerable uncertainties in the estimated trends and may thus explain some of the differences, experts agree that much of the recent difference is real. Temporary global scale changes in vertical structure of the atmosphere as well as in regional scale processes, perhaps related to such causes as ozone depletion, ENSO and NAO behaviour and volcanic eruptions, appear to be factors[206-217].

There is also evidence for significant climate changes in the high atmosphere, and within the oceans. The thermosphere, for example, has declined in density by 9.8% (i.e. cooled) over the past 2 decades, and is expected to decline more rapidly as the atmospheric greenhouse effect continues to be enhanced. Meanwhile, upper oceans waters between the surface and 3000 m depth have warmed by some 0.06°C over the past 50 years, representing a significant increase in heat content. About half of this added heat is in the upper 300 m[218-219].

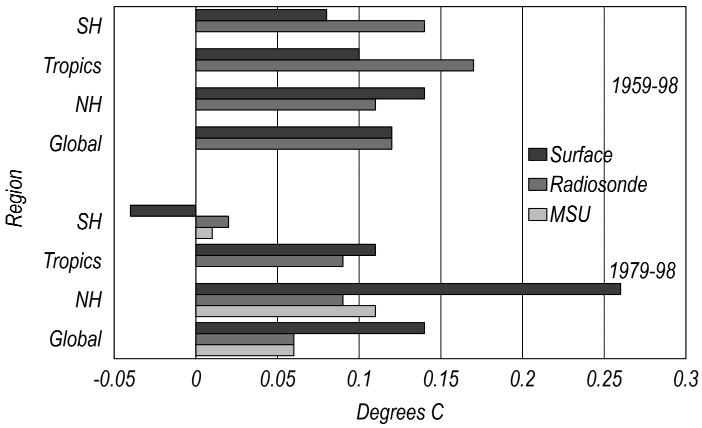

Figure 5. Comparison of temperature trends as derived from surface, radiosonde and satellite MSU instruments, for Southern Hemisphere, Northern Hemisphere, tropics and global regions. While the long term surface trends agree reasonably well with those in the lower atmospheric (850-300 mb) for the entire record, the surface appears to have warmed more slowly than the lower troposphere during the first two decades of the record, and more rapidly in the past two decades. Adapted from Angell (2000) [206].

5.2.2 Attributing Temperature Changes

Attributing the past century's trends in global temperatures and other climate variables to specific causes continues to be a challenge. Long term natural variability may be a contributing factor. The importance of such variability has recently been reenforced by south Pacific coral data, which suggest a large decadal-scale regional variability in SSTs similar to that previously reported for the north Pacific. However, such variability cannot readily explain the magnitude of recent trends, since many of these are unique within at least the past millennium. Hence, external forcings appear to have almost certainly been factors. This conclusion is supported by various statistical tests with model simulations, which suggest that as much as 80% of the multi-decadal variations and trends in the observations can be explained when human and natural forcings as well as long term internal natural variability are all included as factors in the simulations. In these simulations, the anthropogenic component is particularly strong in the warming of the past few decades, when natural forces push the climate towards a cooling. Furthermore, there is evidence for an acceleration of warming in recent years, consistent with an enhancement of anthropogenic forcing. Observed changes in the patterns of temperature change in recent decades in the intermediate waters of the southern Ocean, and of global ocean heat content, are also similar to that predicted by models simulating anthropogenic forcing. However, it is difficult to distinguish between the relative roles of greenhouse gases, aerosols and ozone depletion within the human signal. Furthermore, the net human signal was weaker and hence less obvious in earlier multi-decadal periods of the past century, and remains difficult to distinguish on decadal time scales against background noise of long-term natural variability within the climate system. For example, the observed rise in global temperatures between 1925 and 1944 may have been caused by the combined effects of rising greenhouse gas concentrations and unusually large natural anomalies within the atmosphere-ocean system, perhaps linked to a multi-decadal natural oscillation in North Atlantic Ocean climate. In contrast, the subsequent increase in tropical Pacific Ocean temperatures between 1945 and 1993 appears to be related primarily to changes in ocean circulation, rather than direct atmospheric radiative forcing[107,127,187,188,220-236].

Climate models suggest that direct effects of anthropogenic forcing may also cause changes in daily temperature range (DTR). However, the observed DTR changes over the past century can also be explained by changes in physiological behaviour of plants (and hence possibly an indirect effect of climate change) [87].

5.2.3 Hydrological Cycle

There is increasing evidence that water vapour concentrations are increasing in both the NH lower troposphere and lower stratosphere. The latter may be due to increased moisture flux from the upper troposphere in the autumn season. Over large oceans, the changes in tropospheric moisture content appear to be closely linked to changes in SSTs and lower tropospheric air temperatures (consistent with a moist adiabatic lapse rate). At the surface, relative humidity is rising over the USA, but decreasing over China (particularly in the northeast) [237-242].

Over Canada, annual precipitation increased by 5 to 35% over the past century, primarily due to increased frequency of intermediate to intense precipitation events. These increases are greatest in winter, resulting in a trend towards a greater percentage of precipitation as snow. Warmer climates, however, have resulted in less snow cover in spring. While these trends are broadly consistent with projected changes by models forced by human interferences in the climate system, some of the decadal changes appear to be linked to variations in the NAO and PNA[97,203,243-244].

Precipitation across the circumpolar arctic region has also increased substantially. These increases, together with altered melt conditions have in turn affected land ice sheet dynamics. For Greenland, studies using simple climate models suggest the ice sheet has been in near balance during most of the past century. However, since 1994, measurement data indicate that the net ice balance has remained near zero above 2000m altitude but declined below this level. This ice depletion is currently adding about 0.13 mm/year to global sea level rise (about 7% of that observed). The Columbia Glacier in southern Alaska has also experienced an accelerated flow rate and a 20% reduction in length since 1975. In Antarctica, increased surface melt water ponding has been an important factor in the break-up of ice shelves along the Antarctic Peninsula, with the Larsen C and the east Antarctic north coast most affected[145,245-248].

5.2.4 Extremes

Extremes in precipitation and in some temperature variables have become enhanced in many parts of the world in recent decades, and El Niño conditions have become more prevalent. Storms in the southern Hemisphere south of 30°S appear also to have become more frequent since 1958. However, there is no clear evidence for a global increase in storminess or more frequent drought. Furthermore, observed changes in extremes are highly variable in space and time, and often involve multiple climate variables that have not been well monitored or understood. Hail storms, for example, have increased in frequency in some regions of the US and decreased in others. Likewise, mean monthly wind speeds in the USA have increased in summer and autumn but decreased in the February and May. On a broad scale, some of these changes are consistent with climate model projections for a warmer climate. Such changes in climate extremes can cause major ecological change, and appear already to have stimulated corresponding shifts in the range of wild plants and animals[140,143,250-255].

While tropical storm records across all oceans since 1966 do not display a global scale trend, they do show a surprising linkage with NAO patterns and hence high latitude climates. This appears to be at least partially due to the influence of the NAO on low-latitude trade wind behaviour and thus the frequency of intense hurricanes. Intense hurricane frequencies were high in mid century and during the past decade, and low in the intervening period. While economic losses in the USA due to hurricanes and other extremes have increased dramatically, most of this increase appears to be related to demographic factors rather than increased intensity of the climate events that cause them. However, there is evidence of a linkage between American flood damage and an upward trend, at the national level, in the frequency of wet days and two-day heavy precipitation events[256-260].

The multi-decadal oscillations in the polar and North Atlantic atmospheric pressure patterns, such as those related to the NAO and the Arctic Oscillation, and hence in regional climates and sea levels, appear to be linked to complex feedbacks between these oscillations, related shifts in wind patterns, and changes in the Atlantic thermohaline circulation system. The intensity of the latter has declined over the past decade, largely due to current low sinking rates of Labrador Sea Waters. Similar atmosphere-ocean variability linkages exist over other oceans. The changes in the central North Pacific pressure patterns, for example, appear to be linked to the multi-decadal variations in Pacific current intensities, El Niño- La Nina behaviour, and regional climates. There may also be connections between Pacific Ocean variations and long term fluctuations in western Indian Ocean climates. Some argue that the ultimate driver for many of these changes may be the Southern Oscillation. Tropical Pacific coral records indicate that such oscillatory behaviour may change over time as background climates change. However, the relationships between background climate state and long term climate variability is poorly

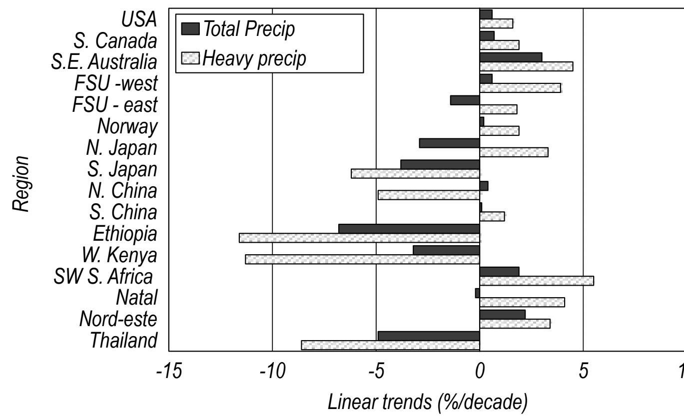

Figure 6. Trends in total precipitation and frequency of heavy precipitation events for various regions around the world. In most regions, changes in frequency of heavy precipitation had the same sign as, but large amplitude than changes in total precipitation. Adapted from Easterling et al. (2000)[251].

understood because of the complexity of feedbacks involved, Climate models will need to be able to reproduce both the changes in background climate states as well as the linked fluctuations if regional and temporal changes in climate are to be projected with any confidence[196,224,259-265].

In the Arctic Ocean, sea ice cover has decreased by 14% in extent and 40% in thickness over the past few decades. While much of this decrease may be linked to NAO and AO changes, these factors appear inadequate to fully explain the magnitude of the change observed. In contrast, trends in sea ice conditions around Antarctica since 1987, while variable from region to region, show greater areal extent, but with increased open water within the pack. This is consistent with longer ice seasons and increased drift towards lower latitudes, driven by atmospheric circulation changes[268-274].

Analysis of a selection of lakes across the Northern Hemisphere suggest that ice seasons have on average shortened by some 12 days over the past century, both because of delayed freeze-up and earlier break-up. However, lakes in some areas, such as the Russian Arctic, have seen little change in timing of break-up (despite earlier onset of spring melt) and earlier onset of freezing, extending the ice season[275-276].

5.2.5 Biological trends

There is continuing evidence that various terrestrial biological species are responding, in a non-linear manner, to the changes in their climatic environment. In Alaska, for example, there has been a decline in growth rate and hence carbon uptake of white spruce ecosystems over the past 90 years, apparently due to drought stress. This growth rate decline has more than offset any positive effects of longer growing seasons. Meanwhile, two centuries of anthropogenic disturbances in much of the North American boreal forests have contributed to a widespread transition from coniferous to deciduous landscapes, affecting a variety of climate variables. In Europe, a network of phenological garden observations indicate that growing seasons have lengthened by 11 days since 1951, many butterfly species have expanded their range northward and are appearing earlier, and the population of the Norwegian dipper has increased. In the tropics, the populations of many amphibian species have decreased or collapsed[277-281].

Ocean habitats and species distribution are also changing. Changes in multi-species indicators in the North Pacific, for example, demonstrate a good correlation with regional oscillations in atmospheric and ocean circulation, together with a major regime shift in regional climate in 1977 and again in 1989. In the North Sea, decline in cod populations may be linked to regional increases in ocean temperatures. In tropical oceans, the 1998 ENSO event caused extensive damage to coral reefs, which appear to die if exposed to extended periods of high temperatures. Although there are indications that some coral species can adapt and recover from such damage quite quickly, it appears unlikely that such adaptive capacity will be able to deal with future projected rates of warming[282-285].

6.0 Impacts

Full understanding of the ecological and social impacts of CO_2 increases and climate change must include consideration of the interactive effects of the physical and chemical responses of natural systems, the concurrent impacts and stresses of changing social behavior on those systems, and the vulnerability of social systems to change. This requires collaboration between physical and social scientists, and the integration of physical and social scenarios within coupled models to replicate the dynamic feedbacks between these systems. Such research must also seek ways to downscale the output of model projections to the scale at which they are most relevant to the affected systems. Multiple downscaling approaches that use different types of regional climate models, weather data generators and other techniques, each with their own advantages and liabilities, may provide the best method for addressing this challenge[286-288].

6.1 CO_2 Fertilization Effects

Observed and projected changes in atmospheric CO_2 concentrations represent a change in plant diet not seen in over 500,000 years, and may be second in importance only to land use change in shaping future ecosystem behaviour. Observations indicate that, within multi-species ecosystems, the responses of successional and other ecological processes to enhanced CO_2 concentrations vary by species and light availability. Over time this varied response will affect ecological processes, composition, and ultimately species diversity within ecosystems. Most species exhibit enhanced photosynthesis and reduced nitrogen concentrations (and thus food quality) under higher CO_2 concentrations. Enhanced biomass accumulation and soil carbon storage are often observed. For example, mixed grasslands along CO_2 concentration gradients near natural CO_2 springs in New Zealand indicate increased carbon and nitrogen storage in soils under enhanced CO_2 conditions. However, the sustainability of such biomass accumulation and its contribution to enhanced ecosystem carbon storage is uncertain. The response is also sensitive to other environmental factors. In an arid ecosystem, for example, perennial shrubs were observed to double growth under a 50% increase in CO_2 concentrations during a high rainfall season, but showed no enhanced growth in a dry year. Studies to reduce these uncertainties need to better observe the feedback processes involved and to develop fully coupled models that address the complex, non-linear feedbacks of real ecosystems[289-292].

Biological response to the direct effects of enhanced CO_2 also affects local radiation budgets and decreases ecosystem evapotranspiration, although the effects are variable from region to region. Hence, contrary to commonly held views, this effect can cause a net increase in aridity. In Amazonia, for example, model studies suggest that the direct effects of doubled CO_2, together with similar effects of regional deforestation, could increase regional temperatures by about 3.5°C and decrease local precipitation by 0.4 mm/day. When the effects of global climate change are also added, similar studies suggest a likely increase, on average, in water supply and soil moisture in most mid to high latitude regions, but decreases in tropical regions[91,293].

6.2 Water resources

Over one-half of the world's population now lives in water stressed areas. Experts suggest that this situation will be significantly exacerbated by future increase in water demand and by the effect of land use change, water management programs and other human activities on runoff and water supply characteristics. In some regions, climate change will add significantly to these stresses, and to related degradation of water quality. Within the Great Lakes basin, for example, the modeled response of water levels and runoff characteristics (while sensitive to the climate scenario used) suggests a significant reduction in water resources. New York City could also see a major reduction in its water supply system. Similar concerns emerge from hydrological responses to climate change in the Columbia River Basin, with risks of increased conflict between water resource users due to reduced low summertime streamflows. Likewise, in Greece, projections are for significant decreases in runoff, with related implications for drought risks. In China, increased water shortages in up to 10% of the country by 2030 could cause major economic losses. Improved water resource management programs are needed to address both the impacts of long term variability/climate change and the concurrent changes in demographic factors. Furthermore, particularly because of the uncertainty in regional climate change projections, they should focus on local ecological and human tolerance to extreme thresholds, rather than on changes in annual median conditions[294-305].

6.3 Extreme Weather

The risks of climate surprises, such as weather extremes, are influenced by a number of factors that make them difficult to predict. Some, in fact, are inherently unpredictable, since they may have never been experienced before by living generations. Furthermore, many weather surprises, such as those related to ENSO behaviour, are dependent on subtle small-scale changes in temperature gradients and hence their response to climate change are as yet difficult to predict with existing tools. Others, however, can be predicted more easily, or can be studied using historical data, climate models and other analytical tools. Studies suggest, for example, that changes in ocean thermodynamic conditions in response to global warming may push dominant tracks of tropical cyclones in the Southern Hemisphere further poleward. The challenge to the research community is to provide information with respect to linkages between extreme weather and climate change to decision makers and others in a balanced manner[306-309].

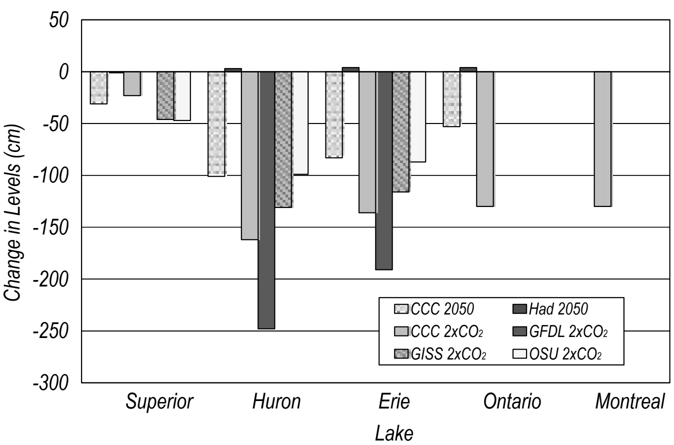

Figure 7. Projected changes in Great Lakes and Montreal (St. Lawrence) water levels under various climate change scenarios. The CCC 2050 and Had 2050 are both transient scenario projections for 2050, while the remainder of the scenarios are for equilibrium doubled CO_2 response (relevant for several decades after actually doubling, or between about 2070 and 2100). Adapted from Mortsch et al. (2000) [299].

6.4 Natural Ecosystems

Many plant species will be able to adapt to the projected rates of climate change, but many others will not. Invasive species with high dispersal capacity will adapt most quickly, often resulting in increased dominance of landscapes by fast growing weedy species. Other, in contrast, may become extinct. Rates of habit loss and extinction are likely to be most marked in higher latitudes and montane regions and where species are isolated, impeded in migration by large water bodies, or stressed by other human influences[310].

Within the Arctic, warmer climates will stimulate the emergence of new plant communities (over century time scales) and enhanced biomass accumulation, primarily as shrub species. However, permafrost and tundra vegetation are significantly influenced by local controls and will respond to changing climates through poorly understood non-linear and discontinuous processes. Hence such response is as yet difficult to predict[311-312].

The sensitivity of forest ecosystems to climate change depends on their phenology, with boreal forests most sensitive to changes in temperature and frequency of severe frost events, temperate forest primarily to changes in temperature, and low latitude coniferous forests to changes in moisture. In Canadian boreal forests, effects of changes in temperature and frost frequency also affect risks and patterns of outbreaks of insects and wildfire, which play a major role in forest response. In mid-eastern USA, oak and pine species are likely to increase their presence at the expense of maple, beech and birch species. However, more extreme precipitation and wind events may also increase disturbances. Furthermore, changes in temperature and precipitation, in addition to their direct effect on plant physiology, can also produce widely varying effects on the biogeochemical cycling processes within forest ecosystems. These can induce extremely complex indirect responses which are often overlooked in impact studies[313-316].

The vulnerability of wetlands to changes in climate depends on the location of the wetland within the hydrologic landscape, with those dependent on precipitation as the primary source of water supply being the most sensitive. Impacts could range from altered community structure to changes in ecological functions, and from disappearance to enhancement. In boreal regions, changes in runoff behaviour will also alter the influx of organic carbon into lakes and hence indirectly affect lake ecosystems by changing the penetration of damaging UV light radiation[317-319].

Warmer climates are expected to significantly alter the distribution and behaviour of insect, animal and bird species around the world. For example, most butterfly species in Britain are expected to advance their first appearance each year by several days for each degree of warming, and the population of Norway's national bird (the dipper) is expected to increase substantially. Other species, such as northern Europe mammals and tropical amphibian populations, may decline significantly, and species interaction may also be altered. However, experts indicate that these responses of species must also consider the complex interactions between changing habitats, breeding patterns, predators and food supplies, few of which have been adequately represented in response studies[279-281,320].

Meanwhile, chemical response to enhanced CO_2 concentration within tropical ocean waters may cause a significant decrease in calcification rates in coral communities[321].

6.5 Agriculture

New studies suggest that, within the eastern USA, moderate changes in climate, particularly if accompanied by increased precipitation, will likely increase crop production. Although a more dramatic increase in temperature without corresponding increases in precipitation would cause mostly negative impacts, these may also be at least partially offset by direct CO_2 fertilization effects. Experiments with rice production in India show similar offsetting effects of rises in temperature (which decrease yield) and in precipitation and direct CO_2 effects (which increase production). These studies do not take into account either changes in climate variability or land use change. Furthermore, they also do not consider the influence of climate change on the distribution or intensity of outbreaks of various plant diseases. Such impacts are as yet difficult to assess on a global basis. Hence, given the importance of variability and the large uncertainty in model projections of future climate at such regional scales, it remains difficult to assess with confidence the aggregate impacts on agricultural ecosystems, or to prescribe appropriate adaptation strategies (e.g., irrigation). A better approach may be to identify critical tolerance thresholds and assess the model-projected risks of exceeding such thresholds[322-327].

6.6 Social Infrastructure and Health

Global economic impacts of climate change may be modest over the next century, but will vary significantly from country to country and region to region. Studies for the eastern US coastline also indicate that there will be winners and losers within each country or region. While warmer, wetter climates, for example, could benefit inland ecosystems, coastal ecosystems and structures would be threatened by rising sea levels, reduced wetlands and increased coastal erosion and flooding during storm surges. Demographic processes that enhance population densities in such vulnerable areas, and the lack of social infrastructures for dealing with disasters in poor countries further add to risks of danger[302,328-330].

Heat waves in land regions around the world can be expected to become more frequent and intense. In the Czech Republic, for example, the frequency of tropical days may increase as much as five-fold. Canadian studies suggest that the elderly and the poor will be particularly vulnerable to related heat stress, the latter because of inadequate disposable income to achieve appropriate relief. While there also continues to be concern about the effect of warmer climates on the spread of temperature sensitive diseases such as malaria, recent studies suggest that concurrent changes in other climate variables, particularly precipitation and humidity, could moderate such changes. Furthermore, such studies have inadequately addressed the role of health infrastructures in determining risks. Meanwhile, the combined effects of ozone depleting substances and climate change on the stratospheric ozone layer is likely to significantly increase average UV exposure within one to two decades, particularly in the Southern Hemisphere and the Arctic, then to cause a decline in subsequent decades[331-336].

7.0 Policy

7.1 Science-Policy Debate

Some scientists argue that there is no proof that climate change is already happening. Others note that the use of computer models into the scientific research process has added a new type of uncertainty that is not yet well understood by scientists, that the science itself is too uncertain to act now, and that the risks of climate change are substantially exaggerated. Furthermore, they suggest, action to reduce greenhouse gas emissions will only modestly reduce the expected rate of warming by 2100, and hence must be justified for reasons other than the dangers of climate change, such as energy conservation and clean air. Despite these skeptical voices, most experts accept the risks of climate change as a serious problem that requires action now. They note that the unrealistic demands for proof of climate change reflect a significant misunderstanding of uncertainty and risk management, and argue that scientific uncertainty is at least as likely to underestimate as overestimate the risks. Hence, such uncertainty should be an incentive for greater action, rather than less. They also note that the science community (including the IPCC), in collaboration with philosophers of science and social scientists, will need to communicate the different types of scientific uncertainties involved in terms more comprehensible and relevant to non-scientists[337-345].

Several investigators have recently reiterated the argument that the Global Warming Potential concept currently in use to compare the climate forcing effects of emissions of different greenhouse gases is seriously flawed. However, others note that these flaws are well understood, and that a tool of this type is essential to the greenhouse gas inter-comparisons needed to develop efficient and effective national action portfolios for reducing the risks of climate change under the FCCC and the Kyoto Protocol[346-351].

Recent studies have noted that benefit-cost analyses, which are often used to assess need for action, are seriously flawed by value-laden assumptions that are often biased towards minimized need for response. Costs of impacts, for example, are often based on physical consequences of climate change, without considering social dimensions, and hence do not reflect social realities. Furthermore, such analyses also fail to consider the potential for large costs caused by surprises, such as abrupt reductions in the Atlantic Ocean thermohaline circulation system and related impacts on Europe. Hence they may not be appropriate tools for guiding decisions on policy response, including those with respect to trade-offs between mitigation and adaptation. Rather, such decisions might better consider physical thresholds beyond which significant harm is done to ecosystems or society, and be based on tools that can properly factor in social contexts. They should be focused on minimizing harm to the most vulnerable countries, moving towards common per capita emissions and spreading the cost of adaptation. To develop the skills and knowledge to deal with this issue may need a generation of students in academia who focus increased attention to understanding both the physical aspects of climate science and impacts and the social aspects of climate policy and land and climate ethics[352-356].

Not surprisingly, the general public continues to demonstrate a poor understanding of the science of climate change. Although there is an increased acceptance that the world is getting warmer and wetter and that future climate change poses a serious risk, there is still a reluctance to act or to accept high cost solutions to address this risk. Yet public interests and opinion are important factors in developing a response strategy. In order to give societies the options for future climates from which to choose, scientists and policy makers must therefore collaborate not only with each other but seek public input in responding to several key questions. In addition, assessments of options for action need to consider the co-benefits each can provide for other social concerns, which range from local air quality issues to global problems such as desertification The first question to be addressed deals with the thresholds or conditions at which climate change becomes "dangerous". While some suggest this occurs at temperature increases greater than 2°C, or at CO_2 concentrations of 550 ppmv, not all agree. The second is whether these danger thresholds can be successfully avoided through emission reductions. Some Integrated Assessment Model (IAM) studies, for example, suggest that the probability of success in keeping climate change below 2°C warming over the next century and at a rate of less than 0.15°C/decade is at best 25%. Finally, decision makers need to decide what would need to be done to cope if danger cannot be avoided. IAMs and other policy tools, such as climate impact response functions, can help provide consistent frameworks for addressing these questions[287,357-363].

The IPCC has a key role in promoting such science-policy collaboration. However, in its efforts to avoid commenting on matters involving policy substance, it may also have been overzealous in avoiding the discussion of policy process. Given that other bodies under the FCCC process also do not have a policy development function, IPCC may need to address this void. Revisions in the IPCC process in developing its Third Assessment report, intended to respond to criticisms of its past process and improve its academic rigor, could help to do so[342,364-367].

7.2 Mitigating Greenhouse Gas Emissions

The prime focus of climate change mitigation efforts continues to be the reduction of greenhouse gas emissions from industrial processes. The most effective near term strategy may be the reduction of emissions of non- CO_2 gases, particularly tropospheric ozone pre-cursors, and sooty aerosols. Such near term strategies are relatively simple to implement and have many co-benefits with respect to air quality and economic efficiencies. However, considerable efforts to reduce CO_2 emissions through, for example, improved energy efficiency, would still be needed to achieve any significant net reductions. Furthermore, while these strategies buy us time, a global shift to carbon free energies will ultimately be needed to meet the objectives of the FCCC. Such shifts will need to seek alternatives that are non-land intensive if they are to be viable on a large scale[368-371].

In addition to the energy sector, the agricultural sector is also a major contributor to greenhouse gas emissions, particularly when food-processing emissions are included. Furthermore, deforestation activities in the tropics during the 1980s may also have released 2.4 GtC/year (some 50% higher than IPCC estimates). Sinks due to regrowth of Amazonian forests may be partially offsetting these emissions, but new mega developments in the region in the late 1990s may have further enhanced these emissions. Other recently reported emission sources include conversion of tropical wetlands to cultivated lands (which increases N_2O emissions) and peat harvesting in temperate bogs (which decreases methane emissions but significantly increases CO_2 release). Different methods of managing these land change and use activities can enhance or reduce such emissions[372-378].

Enhanced forest management programs, including forest conservation, large afforestation projects, prompt reforestation after harvesting, nitrogen fertilization and use of harvested wood to replace fossil fuel combustion could both reduce the emission of carbon dioxide due to deforestation and sequester large amounts of carbon over time due to incremental growth elsewhere (more than 100 MtC/year in Canada alone). Likewise, farm management practices such as minimum tillage can both reduce emissions related to fossil fuel use and sequester large amounts of additional carbon in agricultural soils. In Canada, for example, such activities could change the net soil carbon flux from an average source of 39 kgC/ha in 1990 to a sink of 11 kgC/ha by 2010. Despite many other benefits such programs can provide, market driven economic incentives may be needed to achieve some of these conservation and sequestration activities. However, such sequestered carbon stores, or 'sinks', take long time periods to accumulate and must be protected from subsequent combustion or removal, while reduced fossil fuel emission credits are immediate and permanent. In addition, conversion of agricultural lands to forests could significantly increase surface albedo, particularly in areas with seasonal snow cover, and hence more than offset any reduction in climate forcing provided by the CO_2 sequestered by these forests. Furthermore, measuring the amount of carbon sequestered by the above activities will be difficult, particularly for soil carbon, and will require much more research into tools that combine the use of modeling and measurements. Additionally, the development of simple but effective accounting rules to avoid inappropriate credits towards emission reduction commitments will be a challenge[93,346,379-385].

Other technological solutions for reducing greenhouse gas emissions include the removal of CO_2 from industrial smokestacks and its sequestration in land or ocean reservoirs. In the latter case, the scrubbed CO_2 can either be directly piped into the deep ocean or be allowed to chemically react with sea water and limestone to create a bicarbonate solution that can precipitate into the ocean. Alternatively, some have proposed strategies for geoengineering the earth's radiation balance by artificially reducing net solar absorption in the climate system. However, these alternatives are as yet considered very risky, particularly given the uncertainties about atmospheric radiative processes and their feedbacks[386-389].

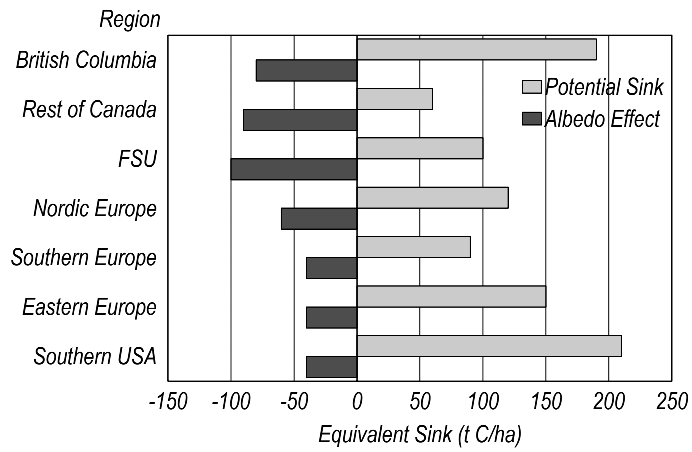

Figure 8. The reduced surface albedo due to conversion of land from arable soils to forest cover (expressed as equivalent tonnes of C sinks/ha) can significantly reduce the effectiveness of carbon sinks generated through afforestation in offsetting fossil fuel emissions. Comparisons are based on carbon accumulated in forests during a full rotation. From Betts (2000) [93].

7.3 Adaptation

Climate change will occur within a changing socio-economic world, and will alter the frequency with which certain critical thresholds that affect the risks of natural disasters are crossed. Hence assessment and adaptation strategies should use multiple-scenario, risk-based procedures that focus on the transient nature of both physical and socio-economic change and likelihood of problems associated with such thresholds. They also need to consider who needs to adapt, and how. Such procedures should be based on a sequential decision-making framework that has the flexibility to deal with uncertainty and with both near-term and long term concerns. If effective, they can, in turn, increase the thresholds at which changes in climate become intolerable. Possible conflicts between various adaptation programs and strategies, and between stakeholders, need to be addressed by cross-linking, optimization and joint adaptation, where applicable. This approach should both improve the effectiveness and minimize the costs of such adaptive strategies. However, as illustrated by the difficulty in cooperative management of ocean fish stocks, for some impacts this may be a challenge that will require major institutional changes[390-398].

Monitoring of long term changes in climate and other physical and socio-economic stresses on public health are needed to help assess the changing risks and to optimize adaptation programs. One such monitoring activity is Canada's EMAN program, which primarily addresses ecological well-being. The insurance industry statistics also serve indirectly as a proxy for monitoring changes in risks due to natural hazards. These statistics show a rapid rise in natural disaster losses in recent decades, although demographic changes are a significant factor. Researchers warn that, if such losses are to be reduced, new disaster mitigation programs are needed that provide better warning, greater flexibility, reduced infrastructure vulnerability and increased personal accountability for actions. Such adaptation programs must also consider the concurrent health effects of poor air quality and increased UV exposure, and seek to create multiple co-benefits and address economic and social inequities that impede effective adaptation in the long term. Many risk management programs (like, for example, those for water management activities in the Great Lakes Basin) already focus on dealing with climate variability, but now need to be adjusted to plan for long term climate change, including the possibility of rapid shifts in climate and more intense or frequent extremes[335,399-405].

Although the agricultural sectors in industrialized economies like that of Canada have an extensive range of technological tools and adaptive skills to deal with both environmental and socio-economic changes in the short term, these can actually reduce adaptability and hence increase economic vulnerability to long term change. Difficulty in distinguishing between natural variability and long-term change is an important factor, and no single analysis technique appears to properly capture such vulnerability[406-408].

In less industrialized countries, such adaptive tools and skills are inadequate to deal with current climate variability, let alone climate change. Furthermore, climate change will not only affect poor economies more than wealthier ones and enhance the inequitable distribution of food and other resources within and between countries, but will have greatest impact on the physical and social well-being of poorest citizens of all countries. Hence adaptive tools for agriculture in developed countries that focus on physical and market-based problems may be largely irrelevant to the much large political and social problems in the developing world. Rather, such tools should focus on social vulnerability to change associated with inequitable distribution of resources, on the poor, and on the related interruption of the displacement, division and environmental degradation cycle caused by poverty[394,409-412].

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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; Chemosphere-Global Change Science = CGCS; GRL = Geophysical Research Letters; JGR = Journal of Geophysical Research; JAWRA = Journal of the American Water Resources Association; MASGC = Mitigation and Adaptation Strategies for Global Change.

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