Environment Canada Environnement Canada

CO_2/ CLIMATE REPORT

A Periodical Newsletter Devoted to the Review of Climate Change Research

2001 IN REVIEW
AN ASSESSMENT OF NEW RESEARCH DEVELOPMENTS RELEVANT TO THE SCIENCE OF CLIMATE CHANGE

Summer 2003 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 2001. 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[2-3]. Earlier issues of the *CO_2/Climate Report* can also be consulted for summaries of research papers published prior to 2001. Recent issues of these reports can be accessed on the MSC science assessment website at www.msc.ec.gc.ca/education/scienceofclimatechange.

In the interests of brevity and utility, the 2001 literature review is based on a selection of papers representative of the broad range of new contributions towards improved understanding of the science behind the climate change issue. Because of the conciseness of the review, readers should consult the relevant papers as referenced for further details on the various topics and results discussed. Undoubtedly, some important papers will have been missed in this review, either through oversight or lack of ready access to the relevant journals in which they appeared. Any related annoyance to the authors of such papers and inconvenience to the reader is unintended.

2.0 CHANGING ATMOSPHERIC COMPOSITION

2.1 Carbon Dioxide

During 2001, atmospheric concentrations of CO_2 reached 370 ppmv, an increase of 1.5 ppmv relative to the previous year. This increase is similar to average annual increments over the past decade. However, the magnitude of increase varies significantly from year to year. Although tropical ocean air-sea fluxes contribute to this variability, the predominant cause appears to be inter-annual fluctuations in growth and respiration of land ecosystems. One important factor in these variations may be the short-term cooling effect of major volcanic eruptions, which reduces terrestrial ecosystem respiration and thus enhances the net terrestrial carbon sink. Another is the effect of ENSO behaviour, which tends to cause the terrestrial biosphere to become a large source during El Niño events and a sink during La Niñas. A new global monitoring program, known as FLUXNET, is now being developed to provide an improved database to support related carbon research. FLUXNET involves comprehensive flux measurements at

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140 stations between latitudes 70°N and 30°S. It will also allow proper inter-comparison of existing regional monitoring networks[4-8].

Various inverse model studies, using such network measurements of spatial and temporal variances in atmospheric CO_2 concentrations to infer fluxes, simulate a net average carbon flux from all land ecosystems (including emissions from deforestation) of a about –0.2 GtC/year during the 1980s (that is, a small sink), increasing to –1.4 GtC/yr in the 1990s. Recent simulations with an advanced biogeochemical model estimate that the global net primary productivity (NPP) component of this net flux is now about 61 billion tonnes of carbon (GtC) per year, with 26% of this in the tropical forests. However, in much of the tropics, NPP is largely offset by higher respiration and emissions from deforestation. In contrast, lower respiration rates, land use change activities, fire prevention and additional nitrogen fertilization have resulted in large net carbon sinks in the extra-tropical regions of the Northern Hemisphere (particularly the US and Eurasia). Over Europe, for example, the sink could be as large as 2 GtC/year, while that for the US alone may on the order of 300 to 580 million tonnes of carbon (MtC) per year, with relatively little interannual variability. An estimated 50% of this sink occurs in forest ecosystems, much of it in the forest floors and soils. These components have often been overlooked in past carbon inventories. Experts note that these sinks in the temperate latitudes may not be sustainable over time[9-15].

Canadian studies indicate that boreal forest ecosystems tend to become a significant source of CO_2 immediately after disturbances due to fire or harvesting. However, they can revert back to a sink within 10 years following the disturbance[16].

The global flux of dissolved inorganic carbon into ground water, where it can remain for centuries to millennia, has been estimated at about 0.2 GtC/yr. Inland lakes may also sequester as much a 70 MtC/yr as organic carbon in sediments. This relatively small lake sink is likely to increase under warmer, wetter climates[17-18].

On the ocean side, changes in $d^{13}C$ ratios across the air-sea interface suggest net average ocean uptake of carbon during recent years of about –1.5 +/-0.9 GtC/yr. At least in the Southern Ocean, these changes in ^{13}C often differ from changes in total dissolved inorganic carbon. This difference is indicative of an anthropogenic CO_2 source. Simulations with several three dimensional ocean circulation models suggest a somewhat larger average ocean sink during the 1980s of -1.85 +/-0.35 GtC/yr, with a significant component in the Southern Ocean. However, another study using a 3D ocean model projects a much larger sink, increasing from 2.4 GtC in 1980 to 3.1 GtC in 1989 and 3.9 GtC in 1999. One of these ocean circulation models was also coupled to an ocean biogeochemistry model and forced with historical meteorological and remote sensing data to simulate year-to-year variations in ocean carbon sinks for the 1979 to 1997 period. Results indicate that 70% of the variance, which ranges from a low of 1.4 to a high of 2.2 GtC/yr, was caused by ENSO behaviour and dynamical processes in the equatorial Pacific. Ship data show similar evidence for the role of ENSO. For example, biological production in the tropical Pacific was observed to decrease by more than 25% below average during the 1997-98 El Niño, but to increase by 25% during the subsequent La Niña. A key factor in this variability is the change in the rate of upwelling of cold carbon and nutrient-rich deep waters. However, experts note that these ocean perturbations are significantly smaller than those occurring over land[6,20-25].

Three seasons of measurements in a northern Canadian boreal ecosystem near the northern treeline show a modest net annual carbon sink by its forest component of between 100 and 478 g/m^2. Soil respiration, which can be significantly influenced by response of root structure and activity to photosynthesis, is an important component of related carbon fluxes. Seasonal variations in this forest sink indicate a strong climate feedback due to timing of spring snowmelt and the length of growth seasons. Data from FLUXNET show similar C sink/climate feedbacks for temperate broadleaf forests, where net CO_2 exchange increased by almost $6g/m^2$ for each additional day in the growing season. In boreal fens, sinks are significantly weaker, and are primarily affected by variations in water tables. Other studies suggest that mosses may also be a significant component of the net boreal ecosystem productivity, contributing about 13% of NPP and reducing net forest floor respiration[5,26-28].

Most biogeochemical models assume a significant CO_2 fertilization effect on natural ecosystems, as well as delayed autotrophic and heterotrophic respiration rise with increasing temperature. However, these effects remain inadequately understood. Hence, there remains considerable uncertainty in ecosystem response to environmental change. For example, simulations with six different dynamic global vegetation models show a range of current global terrestrial sinks of 1.4 to 3.8 GtC/yr if only CO_2 fertilization effects are considered (i.e., climate is constant). This decreases to 0.6 and 3.0 GtC/yr if effects of recent changes in climate are also considered. When each model was forced with future changes in atmospheric CO_2 abundance and climate associated with the IS92a emissions scenario, this range increased by 2100 to 3.7 to 8.6 GtC/yr when CO_2 fertilization effects alone were considered, and 0.3 to 6.6 GtC/yr when climate change feedbacks were added. All models show saturation of CO_2 fertilization by 2030, and several already show declines in sinks by 2050. This implies that a rapid increase in atmospheric CO_2 and hence in climate warming appears likely to reduce the fraction of anthropogenic emissions removed through terrestrial sinks[29].

Recent experimental studies with various plant species (e.g. sweet gums and loblolly pines) exposed to enhanced CO_2 concentrations suggest the above ranges of uncertainty may be an underestimate. For example, CO_2 fertilization resulted in enhanced fecundity for loblolly pine, giving it a competitive advantage over other less responsive species. On the other hand, while both sweet gum and loblolly pine showed an initial increase in sinks in response to the fertilization effects, within a few years this increase was offset by increased oxidation from roots and/or surface litter. Furthermore, the enhanced growth under higher CO_2 may not be sustainable for many species. Studies may also be biased by failure to consider that natural ecosystems already have elevated CO_2 within the canopy under current atmospheric conditions. Hence, the terrestrial CO_2 fertilization effect may have been overestimated. Likewise, climate feedbacks may also be overestimated. For example, feedbacks involving soil nutrient supply and fast carbon turnover in ground litter of forests and grasslands may diminish over time due to acclimatization processes. Studies over even longer time periods are needed to determine how these system feedbacks respond over decadal timescales[30-39].

Simulations with ocean models suggest that the buffer factor caused by upper ocean carbonate chemistry tend to decrease atmospheric CO_2 uptake as its concentrations rise. This reduces the magnitude of the ocean sink, and enhances the rate of increase in atmospheric CO_2 concentrations. Furthermore, changes in ocean climate and increased ocean stratification may shift marine biological production northward but reduce marine export production. On the other hand, reduced ice cover in polar ocean would likely decrease surface stability in some regions, thus tending to enhance carbon uptake[40-41].

Paleo records suggest that oceans have an important role in very large changes in atmospheric CO_2 concentrations on millennial time scales. New high-resolution Antarctic ice core data, for example, indicate that the 76 ppmv increase in concentrations over 6000 years during the last deglaciation occurred in close correlation with changes in Antarctic temperatures. This is consistent with a large gas efflux from the Southern Ocean[42].

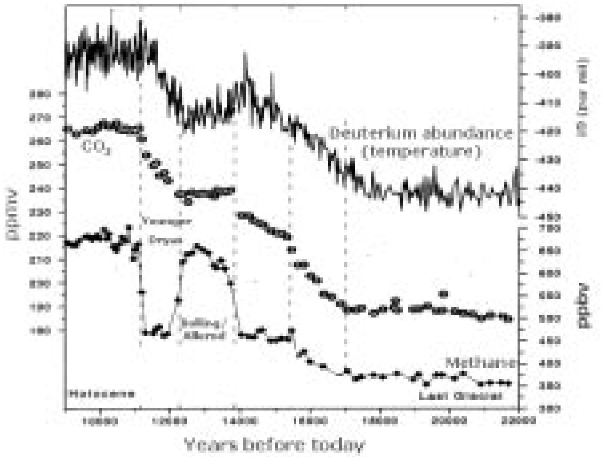

Figure 1. Greenland ice core data on trends in local temperature and in CO_2 and methane concentrations for the deglaciation period between the Last Glacial maximum and the onset of the Holocene. CO_2 and temperature variations show a strong correlation ($r = 0.85$), with no statistically significant time lag between changes in local temperature and CO_2 concentrations. The methane record shows evidence for a significant impact of regional climate fluctuations on concentrations. Adapted from Monnin et al., ref. #42).

2.2 Other Greenhouse Gases

2.2.1 Methane

Atmospheric methane concentrations increased by only ~3 ppb/yr during most of the 1990s. This is significantly slower that that observed in previous decades. This may be due to the effects of warmer temperatures on atmospheric chemistry, which tend to increase OH concentrations, and thus enhances methane oxidation rates. Other studies suggest a dramatic decrease in Russian methane emissions may be moving the methane budget closer to a new equilibrium. However, there remains considerable inter-annual variability in the rate of increase. During the strong El Niño event in 1998, concentrations increased abruptly by 12.7 ppbv, likely due to increased emissions from wetlands and increased boreal wildfires. In 1999, increases returned to more moderate level, while concentrations actually decreased by almost 1 ppb during 2000. The latter is the first decrease recorded in almost three decades of data[8,43-44].

Most wetlands are both net sinks for carbon and sources for methane. These offsetting influences on radiative forcing appear to create a net 'CO_2 equivalent' sink in subtropical wetlands and a neutral effect in northern wetlands when using 100 yr integration values for their Global Warming Potentials (GWPs). Wetlands in both regions become a net sink if a 500-year GWP value is used. In regions such as Nova Scotia, these roles may change under a $2xCO_2$ type climate. That is because changes in temperature and water table depth may more than double methane emissions and significantly enhance CO_2 respiration relative to that of today[44-45].

During the last deglaciation, atmospheric concentrations of methane increased rapidly, in close correlation with both changes in temperature and CO_2 concentrations. However, there are also indications from Greenland continental shelf sediment cores of three pulses of light $d^{13}C$. These events may be linked to explosive release of methane from destabilized gas hydrates in the sea floor, triggered by decreased pressure as the Greenland ice sheet retreated from the continental shelf[42,46].

2.2.2 Nitrous Oxide

N_2O concentrations rose to 316 ppbv in 2001, an increase of 0.2% over the previous year. Improved ice core analysis indicate N_2O levels during the pre-industrial period of the current interglacial and the previous interglacial were about 266 ppbv and 269 ppbv, respectively, dropping to 190 ppbv during the intervening glacial period. The data also show two high concentration spikes during that the glacial period, but these appear to be linked to *in situ* production within the ice sheet[8,47].

2.2.3 Tropospheric Ozone

Ozone chemistry model studies indicate that pre-industrial concentrations of tropospheric ozone may have been much lower that past studies have suggested. This implies that the magnitude of ozone radiative forcing during the past century may have been underestimated. On the other hand, projections for future ozone increases may be exaggerated because of the inadequate inclusion of negative feedbacks between warmer climates and OH concentrations. These feedbacks could slow down the rate of increase in tropospheric ozone concentrations in some regions by more than 50%[44,48].

2.3 Aerosols

Various types of aerosols have been noted as important for their potential in changing global radiative fluxes. Improved inventories for sulphur emissions indicate global release from human activities in 1990 of about 72 million tonnes. About 80% of these come from coal and oil combustion. Sulphur emissions from Europe and North America are declining, but those for Asia are increasing significantly, resulting in relatively constant global emissions during recent decades. Local agricultural and industrial activities are an important cause for the rapid increase in pollution levels over south and southeast Asia regions (particularly during the winter monsoon), both adding large quantities of sulphur and soot to the air and reducing the air's oxidizing capacity. The effects of these emissions on regional methane and ozone concentrations differ significantly from that observed over Europe and North America. Satellite-based measurements of scattered solar radiances (an indicator of concentrations of fine aerosols) suggest biomass burning may be another very important human source of global aerosol emissions. The time-dependent effect of such changes in regional distribution of aerosol concentrations on global radiative flux patterns should be included in climate change attribution studies[49-51].

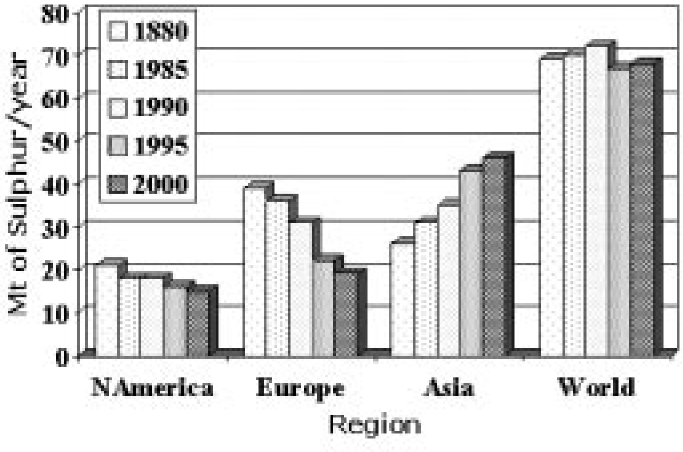

Figure 2. Global sulphur dioxide emissions from industrial activities, estimated in millions of tones (Mt) of sulphur per year, have remained relatively stable over the past two decades. However, the distribution of emissions has changed dramatically. Those over Asian regions have increased by 77%, while European and North American emissions have decreased by 51% and 29%, respectively. From Smith et al., ref #50).

3.0 RADIATIVE FORCING

3.1 Greenhouse Gases

While the growth rate of greenhouse gas forcing peaked at almost 5 W/m^2 ~1980, successful measures to reduce CFC emissions have resulted in a decline of this rate to current growth rates of ~3 W/m^2/century[52].

Analysis of three decades of satellite measurements of outgoing long-wave radiation show reduced outgoing radiation at the key absorption bands of various greenhouse gases. This provides the first direct evidence of an enhanced greenhouse effect[53].

Model simulations and observation both provide indications that water vapour content in the middle stratosphere has increased, likely as a result of input from a warming troposphere. Upper troposphere-lower stratospheric processes involving ozone chemistry may also be a contributor to this increase. This positive climate change feedback may have contributed almost one-quarter of the net increase in radiative forcing from well mixed greenhouse gases during the past two decades. The increase in stratospheric water vapour has also contributed to stratospheric cooling and hence ozone depletion[54-57].

Recent model studies using revised pre-industrial tropospheric ozone concentrations suggest ozone forcing may be in the order of 0.72-0.80 W/m^2, much higher than previous estimates. However, the relationships between changes in ozone concentrations and emissions of ozone precursors are dependent on a variety of spatial and temporal factors, and hence remain complex and difficult to aggregate at global levels. Although some studies have suggested that chemistry-transport models could be used to address these difficulties, thus allowing possible inclusion of such emissions under the Kyoto Protocol, others strongly disagree[47,58-59].

New estimates for radiative forcing from aircraft contrails that also consider the offsetting effect of these contrails on incoming solar radiation indicate a small net effect, on average, of about 0.01 W/m^2. This is much less than other studies have suggested[60].

3.2 Anthropogenic Aerosols

New estimates for current radiative forcing due to global anthropogenic emissions of sulphate aerosols, using detailed models, suggest a cooling effect of –0.3 to –0.5 W/m^2 for direct effects and –1.5 to –3 W/m^2 for indirect effects. The latter is caused almost equally by changes in cloud water droplet size and increased cloud liquid water content. General circulation model studies note that this effect is concentrated in the Northern Hemisphere and is amplified by sea ice feedbacks. Estimates based on several months of satellite data also support a close relationship between cloud optical thickness and aerosol concentration above a threshold level, but not for cloud liquid water path. These data project a net radiative forcing over oceans of between –0.7 and –1.7 W/m^2 for a 15 to 40% increase in aerosol concentrations[61-65].

Radiative forcing due to increased concentrations of black carbon is very dependent on its interaction and coagulation with other aerosols, but could globally exceed that of methane. The INDOEX experiment over south-southeast Asia also indicates that local air heating caused by black carbon can induce enhanced evaporation of cloud droplets and hence affect cloud behaviour. However, while this effect can be significant on a hemispheric scale, it is not likely enough to fully offset the dominant negative effects of aerosols on cloud lifetime and albedo. Much more work remains to be done to reduce related uncertainties by better assessing black carbon emission distribution around the world and improving the ability to model black carbon atmospheric chemistry[66-68].

Although the local influence of changing aerosol concentrations may be significant, the net global effects of all the changes in various tropospheric aerosols, including natural and anthropogenic sources, may be much smaller because many of the individual effects are offsetting, and the presence of clouds can mitigate their influence. One model study considering all direct effects suggests a net cooling over the past century of only about –0.12 W/m^2, much less than often assumed[69].

3.3 Natural Aerosols

Saharan dust storms, while episodic, can also create significant local radiative influences. Observations indicate that such events can reduce short-term net radiative fluxes over ocean surfaces by up to 10 W/m^2, and half as much over land[70].

3.4 Solar

Net changes in solar forcing over the past few centuries have been on the order of +0.5 to 0.7 W/m^2, but this long term forcing is expected to decrease slowly over the next few decades. Meanwhile, the 11-year sunspot cycle, which causes a decadal variability in solar forcing of +/-0.1 W/m^2, appears to cause a climate response consistent with a climate system sensitivity of between 0.3 to 0.8°C/W/m^2. Over the next few decades, this cycle is expected to be at its lowest in 2006 and 2016 and to peak ~2010[71-73].

Proxy indicators of solar activity over the past 11,000 years also provide evidence for a relatively weak 1500 year cycle as well as a 205 year de Vries cycle in solar irradiance. The 1500 year cycle may indirectly induce major changes in North Atlantic circulation that amplifies its effect on climate. At shorter century time scales, atmospheric NAO-AO feedbacks may be the more dominant amplifying feedback of solar forcing, particularly at the regional scale[74-77].

4.0 CLIMATE MODELLING

4.1 Climate Processes

4.1.1 Atmospheric processes

GCM simulations show that the strongest climate system feedback to forcings is water vapour, followed by clouds and surface albedo. Cloud feedbacks, however, involve differing processes that have opposite signs and hence are largely offsetting. As a result, net cloud feedback may actually be quite small[78].

While human emissions can have a significant direct influence on the chemical composition of the atmosphere, the indirect effects of climate change can also create important atmospheric chemistry feedbacks. A study with the Hamburg GCM, for example, suggests that atmospheric temperature and humidity changes will have major feedbacks on the abundance of NO_X and ozone in the atmosphere. Ozone tends to decrease in the troposphere and increase in the stratosphere, relative to an atmosphere without climate change. These changes can exceed those due to direct emissions. Warmer climates are also projected to increase tropospheric-stratospheric air mass exchange. This will accelerate the rate at which CFCs enter the stratosphere and are destroyed, thus reducing their atmospheric lifetime and advancing the ozone layer recovery time[79-80].

4.1.2 Land processes

Both observational data and models indicate that seasonal variability in Northern Hemisphere snow cover is strongly correlated with atmospheric circulation anomalies in mid-latitudes[81].

Various land surface parameterization schemes have been developed by modelling groups to represent atmosphere-vegetation-land interactions in GCMs. The Canadian scheme (CLASS) was tested against observations and other models under the phase 2 of the Atmospheric Model Intercomparison Project (AMIP2) for its ability to accurately simulate surface hydrological processes in three major Russian river basins. It performed well for a number of aspects of basin hydrology but underestimated runoff and overestimated soil moisture levels. When the same model was tested over Canadian boreal hardwoods for simulation of physiological processes, it successfully explained 80% of observed CO_2 fluctuations and simulated gross primary productivity well. It also confirmed that many of the related variables are very sensitive to variations in climate. Similar tests of the IBIS biospheric model over the Canadian boreal forests, which generally show good results, indicate that inclusion of a thick organic soil layer is important in properly simulating soil moisture fluxes linked to thaw processes in northern landscapes[82-84].

Vegetation-climate interactions also cause large local and potentially global feedbacks. For example, simulations with a global vegetation-climate model suggest large regional climate feedbacks at the north and south margins of the boreal forest ecotones due to albedo effects of changes in vegetation types.

Other studies involving impacts of land cover change provide similar conclusions, particularly for mid-to-high latitudes where seasonal snow cover amplifies such feedbacks. Deforestation over Europe during the last few millennia also appears to have resulted in a dryer, warmer spring season and a wetter, cooler summer in the Mediterranean. In contrast, the effect of tropical deforestation on CO_2 release appears to have a greater affect on climate than related albedo change. These feedbacks may also be very sensitive to the rate of climate change. For example, ecosystems that respond slowly to climate change are more likely to eventually change from sinks to sources of atmospheric CO_2 if climate change is rapid than if it is slow. Thus effort to reduce rates of global warming may reap double dividends[29,85-87].

Tropical vegetation changes can also have large impacts on local hydrological processes, although concurrent large scale circulation changes can complicate the predictability of such climate-vegetation feedbacks. This is illustrated in a study of Amazon rainforest response to deforestation over the past few decades. In that study, where anticipated trends towards mesoscale drying due to local hydrological cycle response to land clearing was more than offset by increased regional precipitation induced by concurrent changes in global circulation patterns. Removal of all forests could reduce regional rainfall in the Amazon by more than 300 mm/year and about half as much over SE Asia. The reduced evapotranspiration adds to local effects of any global temperature changes in climate, and thus contributes to large-scale circulation changes. These, in turn, extend the climate impacts well beyond the deforested regions. Such impacts appear to persist under warmer climates and can thus significantly modify model simulations of climate change due to greenhouse gas forcing. They should therefore be included in future climate projections[88-91].

Most vegetation models now also include a significant CO_2 fertilization feedback effect. However, new evidence suggests that this effect may be exaggerated, since at least some ecosystems appear to quickly recycle much of the enhanced carbon uptake back to the atmosphere[32].

4.1.3 Ocean Processes

Salinity redistribution and non-linear response of ocean state are two possible mechanisms by which oceans may help maintain the heat transport mechanisms required to sustain a reduced north-south temperature gradient under warmer climates[92].

Coupled climate model simulations indicate that the global climate may naturally oscillate between two quasi-stationary ocean states on very long time scales of 13,000 years. Transitions between these two states can occur rapidly as a result of catastrophic changes in overturning in the Southern Ocean. Such changes in Southern Ocean deep water formation have occurred during the past millennium, and can lead to large changes in global ocean circulation and opposing see-saw effects on hemispheric circulation. Sea ice formation and melting processes alter the salinity and hence turn-over of sub-ice waters and as well account for much of the fresh water flux into the oceans. These processes appear to be critical in maintaining stable states between the multi-millennial climate transitions. They also contribute to climate variability on shorter time scales. In the North Atlantic, for example, where sea ice processes contribute about 75% of freshwater influx, variations in sea ice flux and melting are also primary factors in the interannual and decadal-scale variability of the ocean thermohaline circulation system. Model studies indicate that errors as small as +/-7% in estimation of ice concentrations can affect simulations of regional climates by more than 6°C. Hence, accurate parameterization of sea ice characteristics and behaviour (including dynamics, thickness and albedo variations) are important in effective model simulations of control climates and sensitivity to change, particularly at the regional scale. Paleo studies can help provide the data needed to improve the parameterization of these ice variables[93-98].

4.2 Model Development/Validation

Advancements in coupled climate models include such features as improved land surface, sea ice and middle and upper atmospheric components, as well as integrated atmospheric chemistry. Some, including the NCAR Community Climate System Model, can maintain stable control climates without flux adjustments. These improvements can make large differences in the regional characteristics of climate simulations, as illustrated by comparison of the HadCM2 and HadCM3 simulations. Large differences between these two simulations appear to be caused by the introduction of a new land surface scheme and changes in the physical representation of atmospheric processes (especially boundary layer physics and cloud behaviour) [99-101].

Inclusion of sea ice dynamics in the HadCM2 coupled model improved control run ice distribution and reduced model sensitivity to a doubling of CO_2 by 15%. Studies into dynamic-thermodynamic sea ice behaviour also show improved simulation of Arctic climates when using Lagrangian rather than Eulerian formulation of ice thickness distribution[102-103].

An intercomparison between observations and control climate simulations by 15 coupled climate models indicate that the current generation of coupled models reproduce major features of the climate system quite well, although to varying degrees. No single model appears to be superior to the others in all aspects of climate simulation, and flux adjusted models generally (but not always) do better than non-flux adjusted ones. Most models still underestimate the downward flux of long wave radiation, estimated at 344 W/m^2 (globally average. This underestimate is generally greater in cold, dry climates than in more tropical regions (thus creating an anomalous meridional gradient in the flux) and appears to be due to radiation codes that inadequately deal with downward IR flux in a cloud-free atmosphere. Most models also use inaccurate Antarctic topography, which appears to cause systematic biases in model simulations of surface mass balance in the region[104-106].

Recent simulations of climates of the past century with version 2 of the Canadian coupled climate model (using improved ocean mixing) shows reduced asymmetry in hemispheric warming rates relative to most other model studies. This is closer to that observed and suggests both hemispheres have been warming at similar rates[107].

Multi-millennial control climate simulations with the GFDL coupled climate model generated an abrupt, multi-decade cooling episode similar to that inferred from paleoclimate records. This naturally occurring event was triggered by a shutdown of ocean convection in the North Atlantic induced by wind-driven transport of buoyant waters into the region. Simulations of the last glacial maximum climate using 17 different climate models (mostly GCMs) generally show good agreement with paleo records for most regions of Eurasia, although south-west Europe was generally too warm and too wet, while western Siberia was too cold, particularly in summer. Similar global simulations using the HadCM3 coupled model, which also agreed well with paleo data for many regions, showed a transient intensification in the thermohaline circulation during the glacial period that caused an anomalous warming of the North Atlantic not identifiable in the paleo records. This may be because of inadequate temporal resolution in the paleo data[108-110].

4.3 Model Results

Recent climate model simulations continue to provide a range of projections for future rates of global warming. Ensemble simulations with the non-flux adjusted NCAR coupled climate model, for example, projects a warming of 1.9°C by 2100 (significantly lower than most other simulations), accompanied by a decrease in daily temperature range and a modest 3% increase in average global precipitation. However, large increases in precipitation are projected over northern Hemisphere mid-latitudes and some other areas. If CO_2 concentrations were stabilized at 550 ppmv, this would be reduced to 1.4°C by 2100. The German ECHAM model simulates a fast climate system response of about 1.4°C after ~60 years (transient response at time of CO_2 doubling) and 3.8°C after 120 years (~4x CO_2). Equilibrium responses were 2.6°C and 4.8°C for 2x CO_2 and 4x CO_2 respectively. This lag between CO_2 increase and full climate response also means that past forcings have already committed the climate system to an additional 1°C warming to the 0.6°C warming already realized. While the lag is currently about 20 years, it will increase as the magnitude of the forcings rises. As climates approach new equilibriums, asymmetries in the hemispheric transient response to the forcing disappear. However, most climate model studies have not yet considered the possible positive feedback of reduced terrestrial and ocean carbon uptake due to warmer climates, which could enhance global temperatures increases by some 15%[52,100,111-116].

Model simulations also suggest a 20-30% decrease in the intensity of the thermohaline circulation system during the next century. The somewhat more modest reduction relative to earlier studies appears to be due to the offsetting influences of increased buoyancy caused by warmer surface waters and reduced buoyancy due to salinity effects. Most studies suggest that the slowdown of the North Atlantic Deep Water formation part of the system will gradually recover once the climate has reached equilibrium. However, the region of subsidence in the Southern Ocean may shut down completely under a CO_2 tripling and not recover within the subsequent millennium. The Southern Ocean response is complicated by sea ice feedbacks. These may initially moderate surface warming in the region but then cause an accelerated warming and sea ice retreat beyond 2100 if, as some models suggest, circulation changes enhance the transport of warm tropical waters into the region[111,112,114,117-120].

Warmer climates are also expected to change the frequency of various types of recurrent weather patterns and to generally suppress atmospheric circulation. This may decrease the rates of atmospheric transport processes, mixing and inter-hemispheric exchange and cause a change in the frequency of recurrent circulation regimes. Stronger zonal mean winds in the low latitude upper atmosphere and weaker regional easterlies also significantly enhance atmospheric angular momentum, slightly lengthening each day[121-123].

Much of the change in tropospheric temperatures may be manifested as changes in behaviour of circulation patterns such as the North Atlantic/Arctic Oscillations (NAO/AO) and Antarctic Oscillation (AAO). The non-linear processes involved appear to include stratospheric planetary wave feedbacks, and may have already contributed to AO changes during recent decades. Reduced sea ice in the Southern Ocean will also cause regional changes in pressure patterns that could increase regional winds and cyclonic activity, but decrease winds and storm activity at mid-Southern Hemisphere latitudes. However, NCAR PCM model simulations suggest that such sea ice reductions may still be quite small at the time of CO_2 doubling. One study suggests an increase in interdecadal climate variability in tropical regions (including more intense ENSO cycles due to stronger La Niña events), but decreased variability at high latitude. The reverse is projected at interannual time scales[124-129].

Over Europe, warmer climate simulations with an RCM suggest increased precipitation in northern Europe and a decrease in the south. However, the intensity of rainfall is projected to increase in most of the region[130].

Ocean thermal expansion has likely increased the rate of sea level rise during the past century. Under the IS92a forcing scenario, this factor alone could add another 20 to 37 cm of rise by 2100. This projected rise has large regional variance, with some regions predicted to rise by twice this rate, others very little[131].

The range of uncertainty in model projections continues to be large, despite major improvements in understanding of the climate system. This underscores the often- underestimated complexity of the climate system. Some improvement in the consistency between models on many sub-continental features of future climate change seems to be apparent, but some caution that this may also arise because of systematic errors in parameterizations common to all models. A number of studies have considered how the continuing uncertainty in model projections might be better quantified through the use of probability statistics. Proponents of such studies argue that probability statistics could help reduce the misuse of model results through preferential selection of future climate scenarios for policy reasons. One such attempt to quantify probabilities suggests a median probability of a 2.5°C global average surface warming by 2100, with a 95% probability interval of 0.9 to 4.8°C. Another projects a 90% probability range of 1.7 to 4.9°C, with a median projection for warming rates over the next century closer to 3°C. However, others argue that such probability statistics are inappropriate and misleading, since they cannot be applied to the social sciences inherent in future emission projections[132-141].

5.0 TRENDS

5.1 Pre-industrial Climates

5.1.1 Glacial-Interglacial climates

There continues to be debate about the role of CO_2 as an agent of climate change on very long time scales of millions of years. On such scales, other slow-changing factors such as continental drift, solar forcing and ice sheet dynamics can dominate the forcing for extended periods of time. Discrepancies in CO_2-climate correlations have been noted for the mid-Mesozoic period of ~150 to 180 Mybp, and for the warm periods ~54-60 Mybp and 14-18 Mybp. However, recent studies suggest that CO_2 and climate are well correlated for at least the past 300 million years, with CO_2 forcing able to explain at least a third of climate variability over the past 10 million years. Furthermore, CO_2-climate discrepancies may be artifacts of poor preservation and resolution of sediment cores and hence not real[142-148].

For the past 400 kyrs, updated Vostok ice core records show a strong correlation coefficient of 0.84 to 0.89 between CO_2 concentrations and Antarctic air temperatures. There is also evidence for coincident changes in these records at the onset of each of the past four deglaciations. Temperature and ice volume changes in the Northern Hemisphere followed several thousand years later. Ocean sediment cores show similar evidence. This suggests that the large glacial-interglacial climate shifts were likely triggered by external solar forcing, but that this relatively weak forcing was significantly amplified by ocean and vegetation feedbacks and related changes in atmospheric CO_2 concentrations. Climate feedbacks appear to be important in the subsequent ice sheet decay processes[149-154].

There are indications that the last interglacial (the Eemian) may also be a good proxy for studying the current interglacial. New evidence indicates that, during the intervening glacial period, tropical oceans were much colder during the Last Glacial Maximum (more than 3-4°C colder than today) than suggested in past paleoclimate studies. While high latitudes remained cold throughout the glacial period, temperatures in the sub-tropical South Atlantic Ocean appear to have warmed between 25 and 41 kybp, consistent with solar forcing present at the time. Hence, the processes controlling these global and regional changes in climate appear to be complex. Furthermore, the role of the tropics in global scale climate processes may previously have been underestimated, and that for the North Atlantic overestimated[155-159].

Careful time calibration of the Greenland and Antarctic ice cores indicate that abrupt millennial scale shifts in climate at the two poles often appear to occur in opposite phases. The transitions over Greenland tend to be more rapid (as much as 10°C within a few decades) than over Antarctica, suggesting there may be a see-saw pattern of change between the hemispheres that is linked to ice discharge-surface Atlantic water processes in the North and slower deep ocean processes in the south. However, there is also evidence that the see-saw pattern does not always occur. For example, the Antarctic Cold Reversal between 14 and 11.5 kybp, which interrupted the deglaciation process that began ~18kybp, was coincident with the Greenland Bolling Allerod cooling over Greenland. Hence, different mechanisms may be involved during cold to warm transitions from those for warm to cold transitions[159-163].

Tropical coral records also suggest ENSO behaviour over the past century may have been more intense than at any time during the past 130 ky. This may be because of dampening of ENSO behaviour by cool oceans during the glacial period and changes in precessional solar forcing during the Holocene[164-165].

5.2.2 Holocene climates

The ocean thermohaline circulation system appears to be somewhat like a hysteresis loop that has been wide and hence stable during the warm Holocene but narrow and easily reversed during deglaciation and the preceding colder glacial periods. For example, during the early Holocene, fluctuations in the southern margin of the shrinking Laurentian ice sheet may have caused episodic rerouting of continental meltwater runoff from a southward flow into the Mississippi Basin to an north and eastward flow into the North Atlantic and back again. The related effect on the thermohaline circulation may have been a key contributing factor to large climate oscillations during this period. Alternatively, some of these abrupt anomalies, such as the Younger Dryas event, could also be caused by an ENSO-like response to orbital forcing[166-169].

While Pacific bowhead whales began to frequent most of the Canadian Arctic during the early Holocene, they were largely absent in the western Arctic during mid-Holocene. This suggests a regional cooling in the western relative to the eastern Arctic, a pattern opposite to that of today. In southern British Columbia, the early Holocene was warm and moist, becoming more arid and variable in mid Holocene. By comparison, a similar warm early Holocene in the Yukon was followed by colder climates in recent millennia. In western Quebec, a doubling of forest fire frequency during the past 2000 years suggests that a moist mid-Holocene period has changed to a drier climate. Thus, if future climate becomes more like that of the mid-Holocene, fire frequencies in eastern Canadian boreal forests may decline[170-173].

Proxy data from Central America and the Middle East suggest that both regions repeatedly experienced major, prolonged periods of drought, in phase with a 208 year cycle in solar irradiance. One of these events is believed to have contributed to the collapse of the Mayan culture in Central America some 1100 to 1200 years[174-176].

5.1.3 Past Millennium

Improved millennial scale proxy records for the Northern Hemisphere indicate that significant warming occured in some regions during the so-called Medieval Warm Period (MWP), but that there is no evidence of a hemispheric-scale warm period at that time. When compared with observational records, results confirm that temperatures in recent decades are about 0.2°C warmer than that for the MWP, and that the rate of warming during the 20th century was the strongest of the millennium. However, while recent ENSO behavior is unique in at least the past 200 years, the positive NAO behaviour of the past few decades has occurred before[177-181].

Sea salt records from Baffin Island ice cores suggest reduced ice cover in the Baffin Bay region ~1900 but a return to heavier ice conditions in recent decades. This is consistent with evidence for recent cooling in the region. Meanwhile, borehole studies for mid-latitude regions of the Northern Hemisphere, which agree well with observed data for the past century, suggest a warming of 1°C during the past several centuries. Despite possible biases due to land change effects and other local factors, such borehole results generally agree with those from other types of proxy and observational data, and are collectively indicative of a large scale warming during the 20th century[182-185].

In western Canada, the single driest year of the past four centuries occurred in 1937. However, prolonged droughts in the region appear to be clustered in multi-decadal cycles and were more prevalent in previous centuries[186].

5.2 Past Century

5.2.1 Temperature

One method of reducing biases due to urban heat island effects is to identify and remove climate stations in densely populated areas, using satellite-based light data. Inadequate global data coverage during early periods of the historical temperature records may also have biased trends, although model studies suggest this bias may have resulted in underestimated warming during the past century. Biases due to changing observation methods may also have been a factor in apparent differences in trends of measured night-time air temperatures over the eastern Pacific since 1979 relative to SSTs (with SSTs increasing more rapidly). Alternatively, this difference may also be a result of changing lapse rates, ENSO effects and volcanic influences, and hence real[187-189].

Improved analyses of global trends suggest a surface warming since 1861 of 0.61 +/-0.16°C, with slightly greater warming in the Northern Hemisphere than the Southern Hemisphere. When data are adjusted to remove ENSO and volcanic influences, the residual trends show a much stronger warming in recent decades (0.25°C/decade) than in either the unadjusted data or in previous decades of the record. SSTs in recent decades have warmed by between 0.09 and 0.14°C/decade. There is no evidence that the recent warming is greater in areas with decreasing humidity and hence caused by desertification. Borehole data and other proxies also indicate large regional trends of similar or larger magnitude. In interior western Canada, for example, they suggest a surface warming of 1.6°C since 1895[183,184,185,190-193].

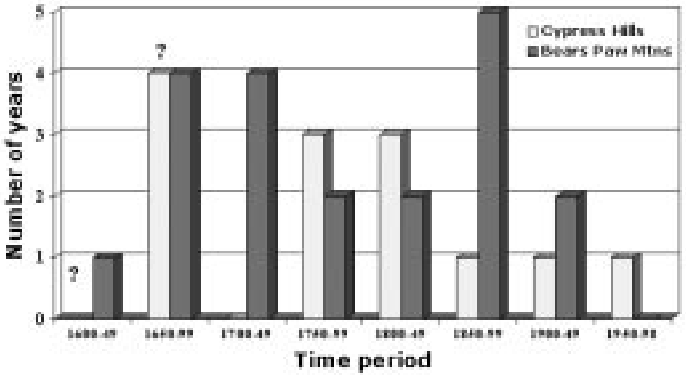

Figure 3. Estimates of frequencies of moderate to severe drought years (July Palmer Drought Severity Index of less than –3) for Cypress Hills (SE Alberta) and Bears Paw Mountains (SW Saskatchewan), based on tree ring analyses. These indicate that the number of such drought years in these locations during the past century were low relative to preceding centuries. The record for Cypress Hills begins in 1682, and hence numbers for the first two periods indicated are incomplete. Adapted from Sauchyn and Skinner, reference #186.

Observed heat content of the upper 3 km of the world's oceans has risen about 10 times as fast over the past 50 years as that for either the atmosphere or cryosphere. There is evidence that intermediate waters in the Atlantic Ocean have been warming since at least 1920[194-195].

Canadian data, including those for biosphere reserves, show significant century-scale trends across southern Canada towards more frequent warm days in winter and spring, increased growing degree days, frost free days and cooling degree days, and decreased heating degree days. In recent years, these trends have reversed in eastern Canada. Oscillatory factors such as NAO have contributed to considerable variability in these trends. Similar trends towards fewer cold days, together with declining short term temperature variability, is apparent across the US and England. In many respect, these changes suggest a current trend towards more benign climates[196-199].

In Antarctica, a dramatic warming in the Peninsula region (likely unprecedented in the past 500 years) has been partially offset by cooling in other regions, resulting in a warming across all climate stations of about 1.2°C since the 1930s. The cause for the regional differences in trends is not well understood, but could be due to changes in ocean currents, atmospheric circulation patterns and/or the modified effects of global warming caused by ice-atmosphere feedbacks[200].

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5.2.2 Attribution of temperature change

Long-term climate simulations demonstrate that significant temperature and precipitation anomalies can occur entirely due to natural variability, thus making the detection of influences of various types of radiative forcing more difficult. Furthermore, despite the lack of evidence for significant solar forcing in recent decades, the combination of solar and volcanic forcing has been a significant factor in changes in climate over the past century. Various model simulations and statistical studies now provide good evidence to indicate that the anthropogenic signal in recent decades can be detected with high confidence. Within this signal, it is still difficult to separate the greenhouse gas forcing signal from that of other human factors because of the partial masking by aerosol effects and ozone depletion. Both greenhouse gas forcing only and the combined greenhouse-aerosol forcings can explain the spatial and temporal patterns of change of the past 50 years, although the strongest anthropogenic signal is for the latter. About half of the increased warming due to rising greenhouse gas concentrations during the past two decades may have been offset by cooling effects of ozone depletion. Other indicators relating to land-ocean temperature contrasts, meridional gradients, ocean heat content, and magnitude of seasonal cycles also generally show changes during the past 40 years that are unlikely to occur due to natural variability but are consistent with anthropogenic forcing simulations. However, there are some regional trends, like that for Atlantic Ocean intermediate water temperatures, that are likely natural in origin. Furthermore, while sampling error in observed data appears to be a relative small factor in these attribution studies, there are indications that attribution results are sensitive to the attribution techniques used[194,195,201-213].

The albedo effect of land use change is another aspect of human influence on climate that may, over centuries, have been significant. This effect can vary with geographical locations. Some studies suggest that much of the cooling between 1000 and 1900 AD may have been due to such land use change in more temperate regions. Others indicate that land use change during the past century, much of it in the tropics, may have caused warming of comparable magnitude and similar spatial patterns to that of greenhouse gases. Hence, the possible role of land use in climate change further complicates the attribution of the human role in past climate change. Experts argue that this factor should therefore be included as a forcing in related model experiments[214-216].

5.2.3 Hydrological

In contrast to temperature, precipitation can vary abruptly in space and time and hence related trends are more difficult to measure accurately. In Canada, for example, analyses suggest that the observing network is inadequate for proper representation of precipitation distributions in areas north of 60°N, as well as in large areas of southern Canada. The available data indicate that total precipitation has been increasing across Canada, with much of the increase due to more frequent moderate and light precipitation events. The fraction of spring precipitation falling as heavy events has increased in eastern Canada, and that for winter also increased in the north. For southern Canada, heavy winter snow fall events increased until a few decades ago, but have subsequently become less frequent. Rivers across Canada have generally experienced a decline in streamflow variables over the past 50 years, perhaps due to increased evaporation. However, flows increased in early spring, consistent with earlier snow melt. Likewise, river freeze-up and break-up are both occurring earlier in the season. Along the B.C. coast, recent river flow data show increases throughout the year through most of the north, but decreases in the southern interior of B.C. in fall and winter. In the Great Lakes, the annual cycle of lake water levels appears to have advanced by about one month. In Lake Ontario, its amplitude has increased by 23%. Factors affecting trends and variability of these levels include flow regulation and land use change, warmer climate and related impacts on snow melt and runoff patterns, and ENSO behaviour[217-223].

Precipitation across the U.S. has generally increased in recent decades, particularly in heavy events. This has contributed to increased high streamflow events in the east. In the west, where snow melt runoff is a larger factor in extreme streamflows, reduced snow cover has mitigated the impact of heavier precipitation on high flows[224].

On a global scale, precipitation networks only represent the 25-30% of the earth surface covered by land. Global coverage by satellite has only been available since 1979. Hence good global records of precipitation patterns are not available for longer time periods. Despite these limitations, available data for global land areas suggest an annual average increase in precipitation since 1900 of about 9 mm, with most land areas experiencing increased persistence of wet spells. Variability in several regions in Africa and South America, particularly in semi-arid and arid regions like the Sahel, are significantly influenced by atmospheric and oceanic oscillations like ENSO, NAO and AO. However, it is unclear whether the longer term trends are due to long term natural variability or to local or global human interference with the climate system[225-227].

Stratospheric water vapour concentrations appear to have increased since 1954 at a rate of about 1% per year. This may be due to in situ methane destruction and/or advection of water from the troposphere. Within the Northern Hemisphere troposphere, most of the North American and Asian regions have experienced an increase in precipitable water and specific humidity below 500 mb since 1973. A longer record of 850 mb specific humidity dating back to 1958 suggests that most of the increase was in more recent decades. Chinese data also show an increase in surface atmospheric moisture content since 1951, particularly at night and in winter[228-230].

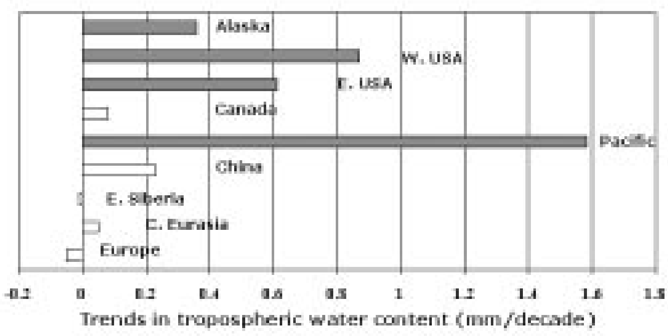

Figure 4. Regionally averaged annual trends in precipitable water content of the troposphere below 500 mb, between 1973 and 1995. Adapted from Ross and Elliott, reference #229. Shaded bars represent statistically significant trends.

5.2.4 Atmospheric and Ocean Circulation

Multi-proxy reconstructions of the North Atlantic Oscillation suggest increased variability over recent centuries. Furthermore, they provide evidence that much of the upward trend in global air temperatures in recent decades is linked to increasingly positive values of the NAO index, and indirectly to changes in the overlying stratospheric vortex and underlying sea surface temperatures. A continued rise in SSTs due to global warming may cause this positive anomaly to continue. However, there are also indications that such positive NAO anomalies, while unusual within the past century, have occurred several times within the last 600 years. Another factor in long term climate variability in the Atlantic region (including U.S. precipitation patterns) is the behavior of the Atlantic Multidecadal Oscillation (AMO), which has a periodicity of 65 to 80 years[128,231-234].

In the Pacific Ocean, the current intensity of ENSO activity may be higher than for most of the past 130,000 years. The Pacific Decadal Oscillation, which has been active in the region for at least the past 200 years, also has an ENSO-like pattern that appears to have strengthened during the past century. The causes for these trends are not well understood. There are also indications that these Pacific variations are linked to variations in the Atlantic Ocean that can occur years to decades later. Mechanisms for such linkages include Southern Hemisphere wave trains and changes in the atmospheric flux of fresh water from the Pacific to the Atlantic Ocean[165,235-237].

In recent decades, the height of the tropical tropopause has also increased at the rate of about 20m/decade, coincident with decreases in temperature, pressure and saturation volume mixing rate. Meanwhile, sea level pressures have decreased over western Canada in winter and spring and increased in summer and fall seasons. These trends, which amplify poleward, are consistent with a weaker winter/spring Arctic High and with milder winters[238-239].

5.2.5 Extreme Weather

An annual extreme weather loss index developed for the U.S. indicates no long term trend since 1950, but high loss periods in the early 1950s, early 1970s and early 1990s. Thunderstorm damage has also increased significantly over the past 50 years, although societal factors may have been a major contributor. Although average thunderstorm rainfall increased significantly across most of the U.S., 35% of stations assessed showed decreased activity during the last 20 years[240-243].

Since 1995, hurricane activity in the Atlantic Ocean has doubled relative to the preceding 24 years, with a five-fold increase in the Caribbean region. This may be due to the combined effect of reduced vertical wind shear and higher sea surface temperatures. This shift is consistent with past relationships with multi-decadal oscillations in the North Atlantic temperatures, and may indicate the onset of enhanced hurricane activity in the region for the next few decades. It is not clear as to whether global warming has been a factor. Hurricane land fall events along the US coast also appear to have a significant inverse relationship with ENSO behaviour, primarily due to the effect of wind shear. Changing NAO conditions, however, may also influence this hurricane-ENSO relationship, since hurricanes appear to travel further south during weak NAO periods and further north (and thus more likely to hit the US east coast) during high NAO conditions. However, the accuracy of early records used to establish this NAO-hurricane linkage is questionable[244-248].

Analyses of Northern Hemisphere extra tropical cyclone activity suggest links to NAO and PNA behaviour. Over the past half-century, there has been an increase in intensity in the western Pacific and the Atlantic, and in frequency over the western Pacific and the Arctic. Other areas have seen decreases in intensity (eastern Pacific and over north America) and/or frequency (over the subpolar Pacific and over the Atlantic Gulf Stream). Over the North Pacific (between 25 and 40N), a steady increase in both the frequency and intensity of winter cyclones has affected extreme surface wind intensity and extreme wave heights in the region. These regional changes are attributed to increasing upper tropospheric winds and vertical wind shear in the central Pacific, and ultimately may be linked to rises in western tropical Pacific SSTs[249-250].

Changes in vertical wind shear during ENSO cycles also appear to affect tornado behaviour in the southern Prairies, causing more frequent events during El Niño periods and less frequent during La Niña[251].

Development of a seasonally adjusted extremes index may be a useful tool to help users to assess risk of losses. However, some caution that use of relative changes is not a good indicator of the frequency of crossing critical absolute thresholds of climate variables, and that care must be taken in interpreting the significance of such an index[252-253].

5.2.6 Cryosphere and sea level

Various satellite sensors show evidence of significant changes in the Antarctic ice sheet, including accelerated flow and thinning of the Pine Island Glacier (which provides the largest discharge for the West Antarctic Ice Sheet) and thinning of part of the ice sheet that feeds it, and the rapid break-up of ice shelves along the Antarctic Peninsula. The latter appears to be linked to recent warm conditions in the region. Canadian RadarSat data have been particularly useful in detecting early cracks in coastal ice shelves, which presage the formation of huge icebergs[254-255].

Surface elevation measurements of the Greenland ice sheet by aircraft and satellite sensors indicate significant thinning on the north-western side of the ice sheet since the early 1950s. Regional differences in sea level rise, if linked to gravitational adjustments caused by changes in Greenland ice mass, are also consistent with a substantial loss of ice over the past century[256-257].

Tide gauges along the Eurasian coastline suggest a regional mean sea level rise since 1950 of about 1.8 mm/yr, increasing to 5.8 mm/yr since 1980. Much of these variations can be explained by changes in Arctic Ocean circulation and atmospheric pressure patterns, which may in turn be linked to global climate change. Globally, key tidal gauges suggest ocean levels have risen by 1.4 mm/yr over the past 40 years. However, model studies project that sea level rise due to thermal expansion alone during the period should be only about 0.5 mm/yr. One plausible explanation for this difference is that the paucity of tidal gauges in many regions of the world's oceans may be resulting in significant error in the measured data. Recent satellite altimeter data, for example, appear to be much closer to that simulated by models. Changes in ocean circulation and atmospheric pressure patterns may also have a significant influence on regional tide gauge data[258-260].

Both warmer temperatures and changing winter snow cover appear to be important factors in observed trends for enhanced permafrost decay in many regions of the Arctic. During the unusually warm conditions of 1998, for example, thaw penetration was much deeper than normal in the Mackenzie Delta because of a more intense and longer thaw season. At Alert, on the other hand, deeper winter snow cover may have been more important[217,261].

Ice cover in the Nordic Sea has declined by about 33% over the past 135 years. NAO appears to be an important influence on the variability of the ice cover, although intensified winter circulation at high latitudes, perhaps induced by global warming, has also been a factor in recent decades. This is consistent with other indicators of change in the Arctic Ocean. For example, submarine data suggest a rapid thinning of ice in the western Arctic Ocean in the late 1980s, and between Fram Strait and the North Pole since the mid 1970s. Some of these changes in thickness may have been due to altered ice composition to more (and thinner) first year ice, induced by a shift in ocean circulation. This rapid decline may be linked to a loss of the near surface cold halocline layer in the Arctic Ocean, which normally reduces ocean heat fluxes to the surface. This cold layer appears to be partially recovering as the Arctic Oscillation weakens[262-265].

Consistent with other evidence of earlier break-up of lake and river ice in many regions of the world, records of the timing of the fall through the ice of a tripod erected each year on the Tenana River in Alaska indicates that this event has advanced 5.5 days since 1915, primarily due to direct melting[266].

During the past 4 decades, snow cover extent over the Northern Hemisphere has been decreasing by an average 2% per decade. In parts of northern Asia, the duration of the snow season has increased by about 4 days per decade since 1937, primarily due to earlier snow fall. However, this trend also appears to have reversed in recent decades[267-268].

5.2.7 Ecological and socio-economic trends

A large and global range of recent phenological changes have been reported, including earlier leaf unfolding, earlier blooming, delayed leaf senescence, advances in timing of insect life cycles and in the dates for first calling of various frog species, decline in western toad populations and changed distribution of butterfly and cricket species. In western Canada, for example, blooming of trembling aspen has advanced by 26 days since 1900, while the onset of spring has advanced by about 8 days in Europe (since 1969) and by six days in North America (since 1959). However, most studies fail to take into account the slow drift in the vernal equinox (tied to actual time of spring) relative to calendar dates, which could result in overestimates of advancement of spring by up to 10%[269-271].

Some aspects of these changes can be advantageous to species (e.g., longer growing seasons), but important species interactions can be disrupted if they respond at different rates, putting some species at risk. In Britain, for example, the distribution of about three-quarters of 46 butterfly species studied decreased over the past 30 years. Although factors involved in species response can be very complex, the net loss of species due to rapid changes in climate could be staggering. Risks may be higher in tropical regions, where the range of each species tends to be narrower[270,272-278].

A global scale assessment of changing land ecology indicate that, over the past century, African deserts have increased in size by 585,000 km^2 while tundra regions have decreased by 707,000 km^2. Over the past three decades, onset of spring across Europe has advanced by about a week, and the growing season has increased by 5 days. During the past two decades, the NDVI vegetation growth index, based on satellite observations, has increased by an average of 12% over most of Eurasia, and a more modest 8% over North America. However, there has been a decrease over some regions, such as parts of Alaska and over Canada's boreal forests. This may be due to dry conditions in these regions. Much of Alaska has seen a substantial increase in woody plant abundance during the past half-century, affecting summer albedo and winter snow cover. However, in the lowlands of central Alaska there has been a significant decline in birch forests and fens over the past half-century. This appears to be linked to permafrost decay caused by earlier warm periods, and appears likely to continue under future warming scenarios[279-283].

High sensitivity of lake biology to DOC content and other factors make sediments from small oligotrophic lakes and wetlands good indicators of long term environmental change, particularly for local hydrology. Improved monitoring of such indicators in areas such as the Prairie wetlands would significantly enhance the ability to effectively address the many policy issues with respect to related ecological response to change[284-285]

6.0 IMPACTS

Projections of future climates simulated by global climate models are as yet of relatively low resolution and have significant uncertainties, particularly with respect to regional scale changes in climate. Yet most impacts of climate change will be felt at the regional scale. Various methods are used to address this downscaling challenge. Some use the dynamical approach of nesting a high-resolution regional climate model within a GCM to downscale the GCM projections to a more detailed regional scale. Others use a reductionist approach where, for example, basin hydrology is assumed to be the sum of its subcomponents, or statistical relationships that relate large scale features of the climate system that can be simulated by GCMs to small scale climate characteristics important to impacts studies. All methods have limitations, and hence results of impact studies like those reported below must still be used with caution[286].

6.1 Natural Ecosystems

Paleo records of species response to past climate change indicate that adaptation occurs through both migration and genetic evolution. Observed rates of migration for many plant species are typically in the range of 20 to 40 km per century, with some being as slow as 1 km/century and others as fast as 100 to 150 km/century. The latter tend to be weedier species. The typical migration rates are an order of magnitude slower than the 300 to 500 km shift in climate regimes expected during the next century, and would apply to about one-third of species in Canada's ecosystems. Genetic evolution (where the plant adapts without migrating) may also be one to two orders of magnitude slower than projected changes in climate in future decades. Hence, adaptive evolution is not likely to significantly improve the chance of species survival under rapid climate change, particularly when migration of these species is constrained by natural barriers or human land use patterns[287-289].

These and other studies indicate that the response of species to climate change is often complex, indirect and dependent on the combination of concurrent stress factors. For example, bird species that migrate long distances (like the pied flycatchers or blue tits) have a greater challenge in adapting to climate change if the rates of ecological change in breeding areas differ from those in over-wintering areas, and/or if rates of response of bird populations differ from that of their food supply. These factors may have already contributed to the decline in some migratory species in western Europe. Species of butterflies and crickets in northern regions appear to be more adaptable to climate change than those in the tropics, where species tolerance ranges tend to be narrower. In Oregon forests, western toad populations appear to be declining due to the complex interaction of climate-induced low water levels and increased exposure of the toad eggs to solar UV radiation. In Canada, experts suggest that, in addition to climate change and enhanced solar UV radiation effects, aquatic species will be further stressed by acidification, eutrophication, altered biogeochemical processes and human alteration of hydrological flow. For rainbow trout, much better winter conditions in warmer climates may be more than offset by a marked decrease in growth during the warmest periods of summer. In the high Arctic, break-up of coastal ice shelves, 90% of which have already disintegrated over the past century, are resulting in the loss of melt water lakes on the ice surfaces that support unique microbial life that is part of the region's food web[271,273-277,290-295].

Failure to adequately address complex feedbacks in climate change impacts on global forest ecosystems suggests that past assessments may have significantly underestimated uncertainties. While most experts agree that above ground biomass will likely increase in northern forests, and soil carbon decrease, there appears to be little agreement on the rate at which forests can migrate, or on the response of tropical forests[296].

One of those complex feedbacks is the role of foraging herbivores in forests, which may benefit some species relative to others and could differ from one region to the next. Another is the role of soil frost season which, despite warmer winter temperatures and shorter frost seasons, can actually become more widespread in areas where less snow cover increases soil exposure to sub-zero temperatures[297-299].

Another complex factor that complicates projections of climate change impacts on natural ecosystems is the concurrent effects of rising CO_2 concentrations. Most dynamic vegetation models, using results from laboratory experiments, assume that the CO_2 fertilization effect will help mitigate some of the negative effects of climate change. For example, such studies for Oregon forests suggest that this effect alone could increase average growth rates for all forest types by 50%. However, experimental field studies suggest that the response of natural, multi-species ecosystems may be much more complex, and may involve intricate soil nitrogen feedbacks that also affect decomposition rates. The assumed fertilization effects may also not be sustainable, at least for some species, and may be at least partially offset by other environmental stresses. Furthermore, CO_2 fertilization appears likely to change the species composition of ecosystems, favouring some over others. Ecosystems with large species diversity will fare better than those with poorer diversity. This suggests that the trend towards declining global biodiversity will reduce the biosphere's adaptive capacity[34,38,300-302].

For Canada, integrated studies involving a number of these factors suggest that, for the western boreal forest, productivity could increase by up to 40% by 2080, while other areas, particularly in southern Canadian ecozones, could see drought-induced reductions of up to 50%. Both fire severity and insect damage in these regions are expected to increase significantly, resulting in a gradual transition to a younger forest and, consequently, altered habitat for wildlife. While fire risks may increase in western and central Canada, they are likely to decrease in northern and eastern Canada, where precipitation is projected to increase significantly. This geographical pattern of fire response, similar but amplified to that for the somewhat warmer climate of 6000 years ago, would result in a significant reduction in the net carbon pool of Canadian forests. Forest fire risks are also expected to increase in Australian forests, primarily because of the effect of heat waves on the number of days with very high and extreme fire danger[303-305].

Future climate scenarios suggest increasing aridity in the sand dune areas of the southern Canadian Prairies by 2080. This is projected to induce a general shift towards less woody species, more open grassland with increased abundance of C4 species, and enhanced dune activity. Proactive management of these ecosystems can help mitigate some of these changes306.

Recent stresses on global coral reefs, including climate shifts, over-fishing, disease and pollution, have contributed to a 27% loss of coral, with another 20% loss projected for the next 20 years. The intense 1997-98 ENSO event alone resulted in a 90% loss of coral in the Indian Ocean. Such coral losses, if permanent, have large economic and social impacts, since coral ecosystems contribute an estimated $400 billion to the world's economy each year, and are an essential part of the livelihood of 500 million people[307].

6.2 Hydrology

Climate change will affect runoff, available water resources and ground water recharge in many regions. Recent studies project that the mean annual discharge of about two thirds of major global river basins will decrease under a warmer climate, with many of these basins in tropical and mid-latitude regions. Some basins, largely in higher latitude regions, are projected to experience an increase in mean annual flow. The seasonality of river flow is likely to change significantly in those systems currently affected by snow cover. However, model projections of impacts of warmer climates on total precipitation remain inconsistent and uncertain for many regions of the world. Furthermore, related effects on water resources, floods and severe droughts are likely to be modified by soil degradation due to desertification and mismanagement and other stresses. Studies suggest this may be of particular concern to dry and wet regions in Africa. In Canada, like many other regions, additional stresses include altered water flow and storage, pollution, habitat destruction and overexploitation, enhanced UV exposure and acidification. Ground water, like that for the Edwards Aquifer region in Texas, will also be affected.

Globally, some 1 billion people already lack clean drinking water, and 3 billion lack basic sanitation services. Global population growth and the projected changes in distribution of water resources will significantly exacerbate this problem in the decades to come. This will not only impact on human health and regional economic productivity, but may also endanger many aquatic plant and animal species. Researchers argue that water resource planners need to improve management structures and be more pro-active in applying research results like those noted above to management policies. Various adaptive measures need to be selected and implemented on the basis of both effectiveness and political realities, including job creation potential and other social implications. For example, in the Great Lakes Basin, water conservation, contingency plans for living with reduced supply, conflict resolution mechanisms, changing land

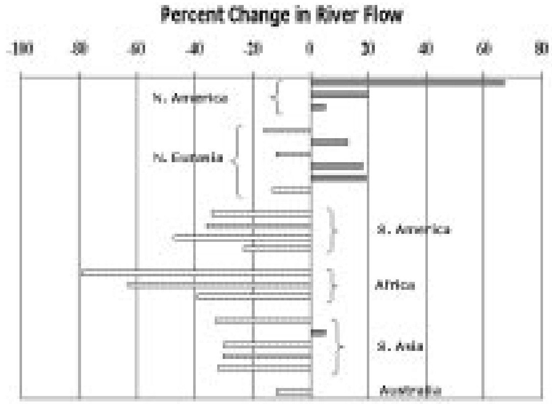

Figure 5. Estimates of change in annual flow in 23 major river basins under warmer climates, based on Canadian coupled climate model simulations for 2070-2100 when forced with the IS92a emission scenario. Results suggest significant increases for some of the mid- to high-latitude river basins, but large decreases for most low latitude rivers. Adapted from Arora and Boer, ref. #308.

use practices, and better management of marine shipping channels are all appropriate responses that should be promoted. In contrast, measures such as developing more storage capacity, tax write-offs, subsidies, and increased pumping capacities may all be counter-productive[293,308-315].

6.3 Agriculture

By 2050, the Canadian Prairies are expected to experience warmer but more arid growing seasons, adversely affecting the production of spring-seeded small grain crops, and possible shifting favourable cropping conditions northward. Migration and/or population expansion of plant pests are also likely to adversely affect agricultural productivity and profitability, although the related impacts will vary with crop type and the type of change in weather. By 2090, the net added costs for pesticide use in global agricultural production could be on the order of $200 million/year[316-317].

Adaptive measures can help mitigate such adverse effects of climate change on agriculture. However, because of the importance of soil characteristics and hydrology in understanding these impacts, particularly in areas with poor water holding capacity, the effectiveness of such measures is best understood when using high spatial resolution models[318-319].

6.4 Sea Level Rise

Past studies may have overestimated some aspects of land ice contribution to future rates of sea level rise. For example, recent studies suggest that enhanced snow accumulations on the Greenland ice sheet under warmer but more humid polar climates may significantly offset enhanced melting over the next 70 years. Likewise, proper allowance for reduced area of temperate glaciers as they shrink somewhat moderates the projected rate at which they melt and disappear in the decades to come. On the other hand, the added risk of concurrent changes in coastal storms could add as much as 20% to total losses related to sea level rise[320-322].

6.5 Extreme Weather

ENSO behavior may become increasingly unstable as it responds to changing ocean dynamics induced by warmer climates. Simulations with an advanced coupled hurricane-ocean model project a 3 to 10% increase in maximum hurricane wind speeds in all tropical ocean basins in response to a warming in ocean surface temperatures of 2-3°C. In the Southern Hemisphere, tropical cyclone activity is expected to move poleward, and decrease in the southern Pacific[323-325].

Studies suggest that, under warmer climates, global regions where precipitation increases will also experience more frequent high precipitation extremes, while those with decreased precipitation will experience more frequent low extremes. In central Alberta, the magnitude of the 100 year return period extreme flood event under a $2xCO_2$ type climate could increase 35% or more. Historical records show that floods have also been the most significant type of natural disaster within the Toronto-Niagara region. Researchers note that current water management infrastructure may be inadequate to deal with future risks, and that analyses will be needed to help identify and understand vulnerabilities and prepare appropriate adaptation measures to prepare for the enhanced risks of weather disasters posed by climate change[116,326-328].

6.6 Socio-economic systems

By 2080, about 3.5 billion additional people around the world may experience water shortages, 300 million more could be affected by the spread of malaria, 100 million by hunger and another hundred million by coastal floods. Meanwhile, potential increases in the frequency of ENSO events could increase related global agricultural damages by $300-400 million, increasing to $1 billion if ENSOs also become more intense. However, researchers caution that the health risks posed by mosquito, water and food-borne diseases, such as malaria and cryptospridiosis, are sensitive to a variety of environmental, social and demographic factors, including international travel. Many of these factors are not well understood and need to be studied, and better tools are now becoming available to do so. Adaptation could partially, but not entirely offset these potential health risks and losses. Net health impacts on developed countries will likely be small providing such countries maintain their investments in public health care, water treatment and drinking water regulations[329-334].

Risks of land instability due to permafrost decay circles the Arctic Ocean, and includes some large settlements and major resource extraction infrastructures. Proper monitoring and prediction of decay can allow appropriate adaptation strategies to be implemented. Meanwhile, melting of mountain top glaciers, which for decades have accumulated toxics advected onto their surfaces from industrial regions, are already becoming a significant source of downstream freshwater contamination. For example, between 50 and 97% of POPs and PCBS in Bow Lake, in the Canadian Rockies, have originated from upstream melting glaciers[335-336].

Climate change will alter atmospheric chemistry, change and slow down circulation patterns, delay the recovery of the stratospheric ozone layer and influence the type of air borne allergens present. Hence, it will have significant impacts on the formation, concentration and dispersal of air pollution and on the intensity of UV radiation, which both affect human health. These health impacts may be greater than previously thought, and better understanding of these linkages is needed to help develop appropriate adaptive measures[55,57,121,337-338].

Measures to reduce fossil fuel emissions could have multiple benefits by reducing local air pollution and the risks associated with climate change. Extreme and prolonged heat stress will be an important concern, particularly for those segments of the population that are very young, elderly, poor or ill. Behavioral change can help reduce related mortality and morbidity, and milder winters will have some offsetting health benefits. However, because of the complex social and economic infrastructure of megacities, such as Mexico City and New York City, developing adaptive strategies in these locations is of critical importance. However, this is also a challenge, since such strategies must involve the cooperation of the many different political jurisdictions affected. They will require flexibility, long term planning and education[338-342].

For indigenous people, like the Inuit of the Canadian Arctic, the impacts of climate change threaten not only their physical well-being but their cultural survival. Hence, their survival may depend on both the application of traditional knowledge as well as that of modern science. Integration of traditional knowledge with that from modern science will help to both build capacities of these communities to conduct their own research and ensure adaptive responses best suited to their circumstances and their survival[343].

7.0 POLICY RESPONSE

7.1 Science-Policy Dialogue

The volume of scientific literature published in science journals has been doubling every 11 years, with costs for related research now estimated at about $3 billion annually. The magnitude of this effort reflects both the complexity of the science and the perception that this is one of the most pressing issues now facing global society. However, effective integration of such complex but uncertain science into decision-making is challenging. While most experts agree on the significance of evidence of recent global warming and the related role of humans, there are those who still argue that this evidence is lacking. There are also concerns that the process for anonymous peer review, while useful in detecting errors in papers, may not be as effective in improving the quality of research output as often assumed. Several researchers have noted that normal scientific methods, involving adversarial debates within disciplines, can in fact be a barrier to effectively communicating complex, multi-disciplinary science. This is of particular concern when sound scientific advice is needed to deal with issues that have large potential impacts on the public and therefore have some urgency for decision makers, and when the uncertainties involved are beyond the ability of normal scientific methods to deal with. They note the need for post-normal scientific processes that focus on regular multi-disciplinary assessments that are circulated for extended reviews by both peers and stakeholders. The IPCC is such a post-normal science process. Likewise, science assessment bodies reporting directly to legislative assemblies could help transform complex information into accessible knowledge. Other approaches include integrated assessment modeling (IAM) and direct dialogue between scientists and affected citizens, using scenarios of plausible regional impacts of climate change. While IAMs help to present the science in an integrated, logical manner, they are still rudimentary and also have difficulty dealing with issues of uncertainty. Such post-normal science processes also present a challenge to the authority of normal science, and can lead to divisiveness within the scientific community[344-354].

There are some who still continue to argue that solar forcing has been, is and will continue to be the dominant cause of climate change, in contradiction of the IPCC conclusions. Some lobbyists also continue to argue that the IPCC process was biased by interference from policymakers. However, the U.S. NAS and academies of science from 17 other countries have, in separate communiqués, expressed their confidence in the IPCC process and results. Others have noted that complaints about ‘interference’ by stakeholders in assessment processes are also at odds with American Administration requests that interested parties should be involved during assessment processes. Furthermore, by using bogus experts, lobbyists discredit the concept of scientific debate and legitimate dissent[355-359].

Several studies have noted the need to better quantify the uncertainties in future climate change projections to assist policy makers and reduce abuse of model simulations for political reasons. While some research groups have tried to assign such probabilities to future scenarios, others caution that it may be impossible to properly assign probabilities to various future scenarios because of the human element involved in the emission scenario component of the uncertainties. Rather, it may be more practical to estimate risks of exceeding critical danger thresholds using Bayesian methods. Furthermore, decision makers need to be fully aware of the full range of possible outcomes and should seek flexible policies that help make decisions less sensitive to scientific and demographic uncertainties[136,139,140,360-361].

While science experts, in general, indicate that the risks of climate change justify mitigative action on climate change, despite remaining uncertainties in the science, a survey of American high school students indicate they are not as convinced. This lower confidence in the science could be due to a number of factors, including student lack of understanding of the science and the policy processes, and inadequate knowledge of teachers. Some educators argue for a unified and adequately funded public education program that will both improve awareness of the climate change issue and serve as a very useful teaching model for understanding the science of complex systems, the application of the precautionary principle, and methods of problem solving and conflict resolution. Another possibility for educating the public could be a huge Monte Carlo experiment in which idle time on a million personal computers is used to run a vast number of alternative coupled climate model scenarios, thus concurrently narrowing uncertainties about future climate change[362-366].

Communicating the science of climate change to the public through media is especially challenging because of the need to link information to emotions of the audience. There is need for more research into the psychological barriers to personal action, and into cultural or belief factors that influence personal and moral responsibilities[367-368].

Although scientific knowledge is an important basis for action on climate change, traditional knowledge from indigenous peoples can add an important contribution by providing an independent set of observations and perspectives on how people and climate interact. Such knowledge can be an important source of climate history and local scale expertise in adaptation, can help formulate research questions and hypotheses and can foster collaborative relationships between northern indigenous communities and research scientists[343,369-370].

International experts have noted that, contrary to arguments raised by opponents, the Kyoto Protocol is an effective start to mitigative action, is flexible and progressive, already engages developing countries, can generate many technological opportunities and therefore need not be costly, and can succeed without American participation. They also agree that, while the Kyoto Protocol only includes binding commitments in the first reporting period for developed countries, there must also be curtailment of emissions from other countries within a few decades if UNFCCC objectives of stabilizing atmospheric greenhouse gas concentrations are to be met. Representatives of the American science community have likewise urged that, despite the American government decision not to ratify the Protocol, Americans also need to pursue a domestic emissions mitigation program and a related strong science research program[371-377].

7.2 Mitigation and Adaptation

The use of the Global Warming Potential (GWP) index as a measure for comparing radiative impacts of different species of greenhouse gases is now well accepted in the policy community. However, there are some serious limitations to such use of GWPs, particular because of the sensitivity of the index values to the time horizon considered. Alternatives suggested include an economically driven, flexible index that focuses on danger thresholds of climate change. This approach would give more value to reduction of gases with short life times if the need for reducing rate of global warming is urgent (i.e. near critical thresholds), and places more emphasis on long-lived gases if the concern is long-term[378].

To-date, the policy debates on greenhouse gas emission reductions has focused on associated economic costs, but have largely ignored other environmental co-benefits. These include substantial drop in death rates, improved work productivity and reduced health care costs associated with improved local air quality. Estimates for four major global urban centres suggest that these benefits can be very large. Likewise, a similar study for electricity production costs in Italy indicated a net benefit for compliance with Kyoto targets if such co-benefits were included in the analysis. Others argue that there are many actions that can be taken to reduce greenhouse gas emissions that do not have to be costly, and that the international success in reducing CFCs emissions to limit stratospheric ozone depletion illustrates that such initiatives can be undertaken without large punitive consequences. Improved agricultural management methods, such as better methods of nitrogen fertilizer application, can also help to both reduce greenhouse gas emissions and enhance productivity and efficiency[53,339,338,379-380].

Measures to enhance terrestrial carbon sinks can provide an effective offset to greenhouse gas emissions in the short-term, although they do not avoid the need for major concurrent reductions in greenhouse gas emissions. For example, in China, enhanced afforestation practices during recent decades have changed the regional forests from a significant source of 22 MtC/year prior to 1980 to a sink of 21 MtC/year since then. Likewise, studies in eastern North American hardwood forests indicate that improved management can enhance carbon uptake in these forests. Changing agricultural practices in North America are already sequestering large amounts of carbon into soils. A global program to restore two-thirds of carbon lost from global agricultural soils during centuries of past cultivation could remove an additional 40 to 80 GtC from the atmosphere over the next century. Restoring desertified lands would further add to this sink. Measures to develop these sinks under the Kyoto Protocol would also encourage improved land management practices and generate other benefits[380-385].

However, these terrestrial sinks are, in many respects, temporary. Hence, including them as credits under the Kyoto Protocol would effectively transfer the burden of mitigative responsibility to future generations. Furthermore, if natural sinks occurring within countries are allowed as credits, some countries would be permitted to meet their Kyoto objectives without undertaking any real action to reduce the risks of climate change. Hence, conditions for legitimate use of sinks as credits should include that they: be incremental to business as usual rates of carbon storage; be measurable; and be maintained for an extended period of time. Developing effective methods for measuring such sinks will be difficult, and may necessitate restricting the types of human measures allowed as credits. Carbon flux monitoring initiatives such as CarboEurope and the North American Carbon Program may be important in providing the scientific basis for such carbon sink verification[386-395].

Carbon sinks through iron fertilization of ocean surface waters are also being investigated by several countries as an alternative for sequestering atmospheric carbon into the deep oceans. However, some experts caution that such projects have known negative environmental consequences that far outweigh the benefits and hence should not be considered under the Kyoto Protocol[396].

Direct injection of liquid CO_2 into the deep ocean, particularly in regions of subsidence, as a means of long-term carbon sequestration also has possibilities. However, such injection is as yet very costly and may cause significant regional environmental harm because of the increase in water acidity in the vicinity of injection. Another suggested alternative is direct injection of crop residues into the deep ocean, which could sequester 250 MtC/year[397-400].

In addition to the impact on carbon storage, land use change can also affect the hydrological and surface radiative properties of the earth. Land area used for croplands and pasture has increased by more than a factor of five over the past 300 years, and in many regions, these changes have significantly change surface albedos and hence the absorption of incoming solar energy. Studies for tropical Africa suggest replacing trees with savanna can also dramatically alter regional rainfall patterns and atmospheric circulation. The past effect of these vegetation changes on climate may not have been adequately addressed in past research studies and hence in the IPCC assessment. Any measures to develop carbon sinks by replacing these agricultural lands once again with forests should also consider the consequent impact on surface properties, which could more than negate any radiative forcing benefit of consequent reductions in CO_2 concentrations[401-404].

While carbon sequestration projects are the most commonly proposed options for mitigating climate change through geo-engineering, other options include the direct manipulation of radiative flux through the use of aerosols. Experts caution that all such geo-engineering solutions may be difficult to govern and enforce because they involve the global commons. Furthermore, they may involve adverse side effects that are as yet not well understood[405].

Archaelogical studies provide evidence of at least four cultural collapses during the late Holocene that can be linked to a failure of past societies to adapt to change in climate. These include that of the Akkadian culture in Mesopotania (~4200 years ago), the Peruvian Mochica culture (~1500 years ago), the Yucatan Maya culture (~1200 years ago) and the Tiwanaku culture of Bolivia-Peru (~1000 years ago). While some of these were also stressed by other factors, all failed to adapt to the onset of extended periods of drought. These examples illustrate the vulnerability of complex societies to significant changes in climate[406].

Mitigation efforts could substantially reduce the number of people at risk of danger due to future climate change. However, significant risks are already unavoidable. While it is unclear whether more recent changes in precipitation, such as the decreases in the dry tropical regions of the African Sahel, are human induced or natural, they provide important examples of these risks. Hence, to help avoid a fate similar to that of the above ancient cultures, adaptation is considered an essential element of human response. Since climate models perform very poorly in simulations of future changes in precipitation in many regions, such as that for Africa, the challenge of understanding and coping with such change is formidable. Some argue that improved adaptation to existing climate variability would be an appropriate strategy that would also reduce vulnerability to future change, regardless of the direction it takes[225,312,333].

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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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