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2° is too much!

Evidence and Implications of Dangerous Climate Change in the Arctic

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UNDERSTANDING DANGEROUS CLIMATE CHANGE

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The UN Framework Convention on Climate Change, signed by nearly 200 countries (including the United States) after the Rio Earth Summit in 1992, sets the policy framework for international efforts to tackle the climate problem. Its guiding principle is to avoid “dangerous anthropogenic interference with the climate system.” The scientific community has pursued this goal by examining “dangerous climate change” from the perspective of catastrophic events (Hansen 2004), national sovereignty (Barnett & Adger 2003), and changes to ecosystems (O'Neill & Oppenheimer 2002). It remains, however, a crucial task for policymakers to agree on the level of warming that can be called dangerous.

In the Arctic, even a slight shift in temperature, pushing averages to above freezing, can bring about rapid and dramatic changes in an ecosystem that is defined by being frozen. Various threshold levels of global warming (1.5°, 2°, 3°, 4°C) have been used in studies of what constitutes dangerous climate change. And some governments and non-governmental organizations, including WWF, have supported restricting the global mean temperature increase to less than 2°C above pre-industrial levels. In order to understand some of the regional implications of dangerous climate change, we have assembled a series of papers in this report to examine the biophysical changes in the Arctic associated with a global temperature increase of 2°C above pre-industrial levels.

Evidence and Implications of Dangerous Climate Change

The rise in temperature will not be evenly distributed in time and space, even within the Arctic. Rather, global warming will vary substantially from one geographical area to another, as well as from season to season. In the first study of this report, Professor Mark New from Oxford University examines the extent of climate change in the Arctic, specifically temperature and precipitation changes, associated with a global mean temperature change of 2°C. His projections are based on four estimates of future emissions and incorporate results from six major global climate models used by the Intergovernmental Panel on Climate Change. They show that warming in the Arctic is two to three times greater than the global average.

Dr. Jed Kaplan, from the European Commission’s Joint Research Centre, demonstrates in the second paper that some tundra vegetation types will probably disappear in a 2°C global warming scenario. In the Arctic, temperature-sensitive plant species may be lost because they are unable to keep up with the changing climate by migrating quickly to suitable habitats.

Changes in sea ice will affect habitats in marine systems as well. In the report’s third paper, Dr. Josefino Comiso at NASA analyses satellite records in his study of the impact on Arctic sea ice of 2°C in global warming. Perennial sea ice is now melting at a rate of nearly 10% a decade. If current trends continue, polar bears and other species that require a stable ice platform for survival could become extinct by the end of the century.

Projected changes such as these present serious challenges to the health and food security of indigenous peoples and could result in the demise of some cultures. In the last paper of the report, Sheila Watt-Cloutier and advisers at the Inuit Circumpolar Conference discuss the policy responses needed to avoid a social and ecological catastrophe.

Local Dangers Have Global Consequences

It is important to realize that changes in the Arctic will not only affect people and species locally; they have global consequences as well. For example, biodiversity on a global scale may be threatened as local habitats of migratory species disappear. Arctic tundra is the main breeding habitat for more than 20 million geese and waders that winter in the mid-latitudes of Europe, Asia, and North America. Many of these species will be severely affected by the loss of tundra ecosystems projected for a rise in temperatures of 2°C. Figure 1 shows the current distributions and potential habitat loss for (a) waders and (b) geese. Species like the dunlin (*Calidris alpina*) and the spoon-billed sandpiper (*Eurynorhynchus pygmeus*) may loose up to 45% of their breeding habitat if global temperature

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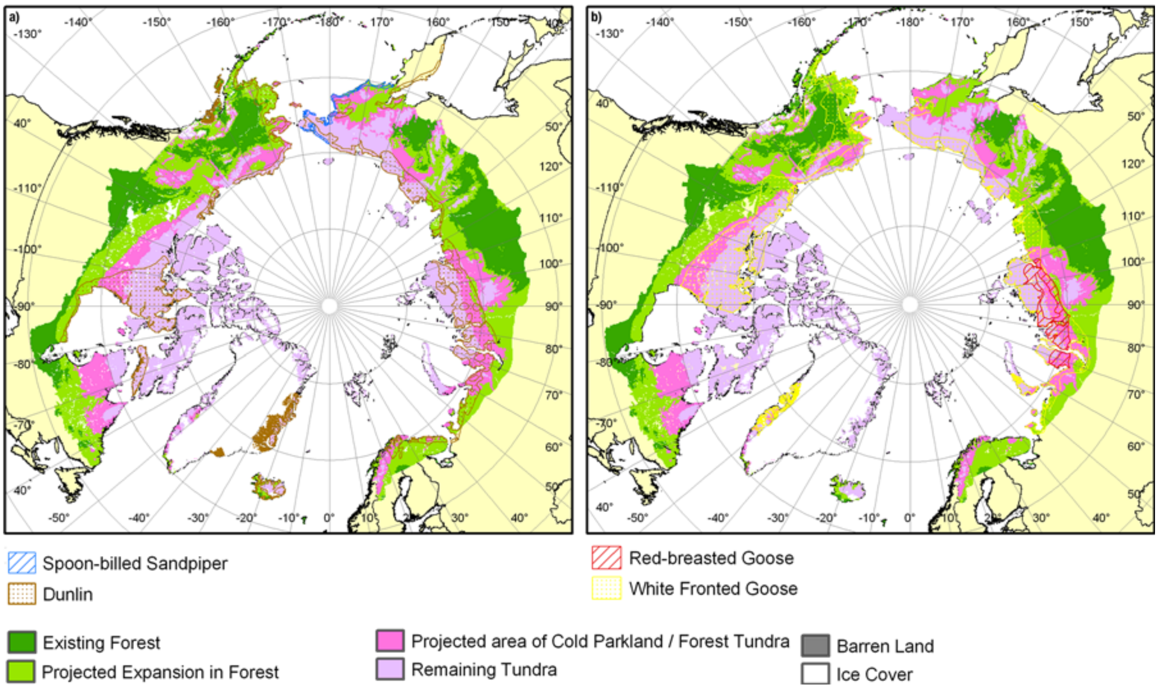

Figure 1. Current distributions and potential habitat loss for (a) waders and (b) geese. The vulnerabilities occur in the light green areas which illustrate the expansion of forests into taiga, and in the pink areas showing the disappearance of tundra. Analysis courtesy of Christoph Zöckler, UNEP/WCMC.

increases by 2°C; the red-breasted goose (*Branta ruficollis*) and the white-fronted goose (*Anser albifrons*) could lose up to 50%.

Changes in the Arctic can also intensify the warming effect across the planet and will contribute significantly to global sea level rise. Sea ice keeps the planet relatively cool by reflecting solar radiation back into space. Since seawater absorbs more heat from the sun than ice does, once the permanent sea ice begins melting the warming effect increases. On land, warming over Greenland will lead to substantial melting of the Greenland Ice Sheet, contributing to an increase in sea levels around the world. The tens of millions of people living in low-lying cities like Dhaka, Bangkok, Calcutta, Manila and the US states of Florida and Louisiana, are particularly susceptible to rising sea levels. Greenland contains enough potential meltwater to raise global sea level by about seven metres.

In the autumn of 2004, the eight countries with Arctic territories—Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States—released the most comprehensive study of regional climate to date: the four-year Arctic Climate Impact Assessment. More than 250 scientists and members of indigenous organizations from throughout the region also concluded that increased emissions of carbon dioxide and other greenhouse gases are causing temperatures in the Arctic to rise two to three times faster than the global average and are contributing to profound environmental changes (ACIA 2004). The findings prove dangerous climate change is well under way and serve as a wake-up call for the international community.

Solving the climate problem requires a shift away from fossil fuels in our energy system, efficient energy solutions, and the widespread adoption of renewable energy sources such as wind, biomass, geothermal, and solar electricity. The technologies and policies for putting these in place are achievable at low cost and carry additional benefits for human health and food and energy security. What is needed now is the political leadership to ensure that dangerous climate change is kept to a minimum. Rapid change in the Arctic, evidenced in this report, tells us there is no time to lose.

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ARCTIC CLIMATE CHANGE WITH A 2°C GLOBAL WARMING

MARK NEW*

Abstract

Climate models used to predict the consequences of increased greenhouse gas (GHG) concentrations all exhibit a warming over the Arctic that is larger than the global mean warming. Results from six global climate models (GCMs), forced with four different GHG and aerosol emission scenarios indicate, that the earth will have warmed by 2°C relative to pre-industrial temperatures by between 2026 and 2060. These same GCMs predict, for a global warming of 2°C, an area-mean annual temperature increase over the Arctic (60-90°N) of between 3.2° and 6.6°C. Arctic warming is greatest in winter (4°-10°C) and least in summer (1.5°-3.5°C). The amount that Arctic climate has warmed by the time of a 2°C global warming appears to be independent of the rate of warming: simulations that warm globally by 2°C by the 2020s or 2030s do not necessarily produce a warming in the Arctic that is different from those that achieve a 2°C warming by the 2040s or 2050s. However, faster global warming is associated with greater rates of temperature change (up to 1.5°C/decade) over the Arctic. Area-mean precipitation increases in all seasons, leading to increased winter and early spring snow depth. More precipitation falls as rain rather than snow in summer. These changes will combine to change river basin hydrology. Spatial patterns of change in the Arctic are highly model-dependent. In general, warming is greatest in winter over the Arctic Ocean, especially where each model experiences large changes in sea ice. Warming over the North Atlantic and Greenland Sea is reduced or even reversed, most often due to reduced thermohaline circulation strength. The greatest warming in summer occurs over the continents. Differences in simulated climate changes between the models are larger over the Arctic than other comparably-sized regions of the globe. GCMs simulate different present-day and future sea ice, snow, clouds and ocean circulation. Complex interactions between these processes, along with relatively large natural variability over decades, lead to the wide range of simulated changes over the Arctic region.

1 Introduction

One of the most striking results from global climate model (GCM) simulations of the effect of increased levels of greenhouse gases (GHGs) on the Earth's climate is the latitudinal variation in the amount of warming. With some exceptions, the tropics warm most slowly, followed by the mid-latitudes, while polar regions have the largest rates of warming (IPCC 2001b; Holland & Bitz 2003; Flato 2004; Hu et al. 2004). Within this general pattern, the Arctic experiences the greatest warming, with most GCMs showing temperature changes at least twice the global mean temperature change for a doubling of CO_2 concentrations in the atmosphere over pre-industrial levels (Holland & Bitz 2003). Records of temperature change over the 20th century show similar Arctic temperature "amplification" relative to the global mean change, at least for the latter third of the century (Jones et al. 1999; Serreze et al. 2000; Johannessen et al. 2004), though the location of greatest warming differs between GCMs and observations[1], and is not unanimously attributed to a high-latitude amplification of a GHG signal (e.g., Przybylak 2000; Polyakov et al. 2002; Polyakov et al. 2003). Any amplified warming has potentially major ecological and socio-economic implications for Arctic areas (for example Chapter 16, IPCC 2001a; Kaplan et al. 2003).

The goal of the United Nations Framework Convention on Climate Change is to stabilise the concentration of greenhouse gases in the atmosphere at a level that would prevent "dangerous anthropogenic interference with the climate system". Agreement on the level of warming that can be

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[1] Greatest warming in GCMs is generally over the Arctic Ocean, while the largest warming in the observed record is over Northern Eurasia.

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called dangerous remains a crucial task for policymakers. Further, a stabilization at a given global mean temperature change does not mean that the same changes will be experienced in different regions, as the spatial patterns of climate change will be very different to the global mean changes (IPCC 2001b, Figures 9.10 and 9.11). The aim of this paper is to document the extent of climate change (specifically temperature and precipitation changes) in the Arctic predicted by GCMs for a global mean temperature change of 2°C, considered by some organizations, including WWF, to be the critical level beyond which dangerous climate change occurs. The northern polar amplification of temperature change means that for a global change of 2°C, much larger regional changes in the Arctic are possible. The paper starts with a review of the mechanisms causing Arctic climate change amplification in GCMs. This is followed by sections that address the question of when a global 2°C temperature change might occur, and what changes in climate might be expected in the Arctic. Changes in sea ice are not assessed, except with reference to mechanisms causing Arctic temperature change amplification, as sea ice changes are addressed in detail in a companion paper (Cosimo 2004).

2 Amplification of Arctic climate change

As noted above, GCMs used to simulate the effect of GHGs on climate through the 20th and 21st centuries show a marked amplification of temperature changes at high northern latitudes. Simulated temperature increases at southern high latitudes are on average less than half those at corresponding northern latitudes (see for example, Figure 9.8, IPCC 2001b). Two of the main reasons for these differences relate to snow and ice feedback effects, and ocean circulation/stratification.

Snow and ice have high albedo (reflectivity), so areas with snow and/or ice cover reflect a large proportion of incoming solar radiation, resulting in cooler surface temperatures than ice/snow-free surfaces. Any reduction in the amount of snow/ice cover in a region will produce an additional warming as more solar radiation is absorbed at the ground or by the ocean. In Antarctica, a large proportion of ice and snow occurs as permanent ice sheets grounded on continental Antarctica. The great thickness of these ice sheets, along with temperatures many tens of degrees below freezing for much of the year, means that GCMs simulate relatively small changes in the overall area of ice/snow over the next 100 years[2]. In the ocean areas surrounding Antarctica, any amplification of warming due to reduced sea ice extent is partially offset by enhanced heat uptake by the Southern Ocean. It should be noted that the heat uptake by the Southern Ocean represents a transient response to warming at the ocean surface, but because of the long timescale at which the ocean responds to atmospheric warming, this effect is likely to continue well beyond the end of the 21st century (the timescale that is the focus of this study). Over longer timescales, at least one model has shown a greater sea-ice albedo-warming feedback over the margins of Antarctica than the Arctic, as the model reaches equilibration after a doubling of CO_2 (Hall 2004). This may be because the lower cloud cover in Antarctica means that surface albedo changes have a more direct effect on the radiation budget (the effects of clouds are discussed in more detail below).

In contrast, northern high latitude geography is characterised by land in sub-polar areas and the Arctic Ocean at polar latitudes (>70N). Apart from Greenland, there is little permanent grounded-ice, and land areas are subject to strong seasonality in snow cover. Thus any warming can potentially reduce the seasonal extent of snow/ice, reducing albedo, and forming a positive feedback. Similarly, in the Arctic basin, sea ice is sensitive to warming, and reductions in mean sea ice extent produce a similar positive feedback on polar temperatures (Holland & Bitz 2003; Johannessen et al. 2004).

The extent of Arctic amplification varies considerably between different climate models. For example a study of 15 different models from the CMIP2[3] project, all forced with a gradual 1% increase in

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[2] GCMs do not simulate much change in West AntArctic Ice Sheet (WAIS), which has been identified as the least stable part of the greater AntArctic ice cover. The WAIS comprises approximately 14% of total AntArctic ice cover (USGS, 1999), so its loss, while a relatively low probability event over the next 100 years (Oppenheimer, 1998), could affect local climate considerably through changes in albedo, the influence of fresh water influxes on Southern Ocean circulation, and exposure of near-shore water to the atmosphere..

[3] CMIP2: second Coupled Model Intercomparison Project (http://www-pcmdi.llnl.gov/cmip).

CO_2, documented a temperature amplification at the North Pole of 1.5°-4.5°C times the global mean change in temperature at time of CO_2 doubling (Holland & Bitz 2003). Further, the extent of Arctic amplification was mostly uncorrelated with the range of the global temperature responses: large amplification occurred in models with both large and small global temperature change at the time of CO_2 doubling, and vice versa. These differences in Arctic climate change are strongly correlated to the reduction of sea ice (Flato 2004), but different representations of snow on land, cloudiness and ocean heat transport have also been suggested to play a role (Holland & Bitz 2003; Hu et al. 2004). Of potential importance for the size of the temperature amplification is sea ice thickness in a GCM's current (or control) climate. In about half of the CMIP2 models, thinner initial sea ice leads to greater amplification (Holland & Bitz 2003), probably because thinner sea ice is easier to melt.

Changes in snow cover tend to be less important in overall Arctic warming (Holland & Bitz 2003), but can have important regional effects over continental areas. The effect of snow cover is complicated by the interactions of increasing precipitation (which, if acting alone, would also mean more snowfall) and warming (which leads to faster melting of snow and makes a larger part of the precipitation to fall in liquid form), and there are generally no consistent results between different models.

Cloud affects polar energy budgets in two ways. Low-altitude cloud acts to reduce incoming solar radiation from the surface, reducing the impact of surface albedo changes (e.g., Ingram et al. 1989), while higher-altitude cloud cover increases downward long-wave radiation, amplifying warming, especially in winter. Over the Arctic, present day total cloud radiative forcing of surface temperature has a strong seasonality, being positive (i.e. a warming contribution) in winter and negative in summer (Curry et al. 1996; Walsh & Chapman 1998). Over the whole year, the net forcing for cloud is slightly positive (Curry et al. 1996). Changes in cloud cover, thickness and type in the Arctic may therefore produce seasonally different effects. Further, the radiative effect of clouds varies as a function of surface albedo (Curry et al. 1996), so the ice-albedo changes and cloud radiative feedbacks are closely interlinked. Despite this, Holland and Bitz (2003) suggest that, in the majority of GCMs for which cloud cover data were available in the CMIP2 study, ice-albedo changes dominate any negative low-elevation cloud feedbacks, while increases in higher altitude cloud cover produces an additional (but small) positive feedback.

Poleward ocean heat transport can play a direct and indirect role in Arctic temperature change. Alterations in the strength and/or location of heat transport will directly affect the amount of warming, and also indirectly affect the ice-albedo feedback by influencing the nature of sea ice retreat (Holland & Bitz 2003). Compared to their control climates, most current GCMs show a reduction in northward ocean heat transport in the North Atlantic (<65°N), which is correlated with a reduced rate warming in this sector (see Section 5). At higher latitudes (>65°N), most GCMs show increased poleward ocean heat transport. Reasons for this increase are unclear, given the reduced heat transport further south, but it does suggest a role for atmospheric heat transport south of 65°N. Increased heat transport north of 65°N is correlated with a decrease in ice thickness and ice extent, and may be an amplifying factor in these sea ice changes (Holland & Bitz 2003).

3 Data and Methods

3.1 Data

Monthly data from six coupled ocean-atmosphere GCMs, each driven by several forcing scenarios, were downloaded from the IPCC Data Distribution Centre[4] (see Table 1). These models exhibit a range of sensitivity to greenhouse gas forcing. The transient climate response (TCR) for each model is listed in Table 1, and ranges from 1.4°C to 3.1°C. TCR is defined by the IPCC (2001b, Figure 9.1) as the temperature change at the year of CO_2 doubling, when the climate model is forced by a 1% annual compound increase in CO_2 from pre-industrial concentrations (as in the CMIP experiments), and is a measure of the GCM's sensitivity to CO_2 forcing (and by inference total GHG forcing). The models

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[4] http://IPCC-ddc.cru.uea.ac.uk

represent a subset of range of models reported by the IPCC (2001b), but span nearly the full range of TCR of the larger IPCC group of models. Scenarios used to force these models were:

- the IS92a greenhouse gas only (IS92aGG);
- IS92a greenhouse gas plus aerosols (IS92aGS);
- SRES A2; and
- SRES B2.

Table 1. GCM-scenario combinations used in this study, and the Transient Climate Response (TCR) of each model.

		Scenarios			
Model	TCR (°C)	IS92aGG	IS92aGS	SRES A2	SRES B2
HadCM3[a]	2.0		✓	✓	✓
ECHAM4[b]	1.4	✓	✓	✓	✓
CCSRNIES[c]	1.8/3.1[g]	✓	✓	✓	✓
CGCM1[d]	1.96	✓	✓	—	—
CGCM2[d]	No data	—	—	✓	✓
GFDLR30[e]	1.96	—	—	✓	✓
CSIROMk2[f]	2.0	✓	✓	✓	✓

[a]Gordon *et al.* (2000) [b]Roeckner *et al.* (1996) [c]Nozawa1 *et al.* (2001) [d]Flato and Boer (2001) [e]Delworth *et al.* (2002) [f]Hennessy (1998) [g]CCSRNIES used different versions of their model for IS92 and SRES simulations, with different TCRs. TCR values from IPCC (2001b).

This combination of models and scenarios permits a range of emissions scenarios and model responses to be assessed. In particular, it enables an evaluation of the sensitivity of Arctic climate change to relatively high and low emission scenarios (and hence relatively fast and slow rates of global climate change). Estimates of future CO_2 concentrations and total radiative forcing arising from these emissions scenarios are illustrated in Figure 1. The scenarios used span nearly the full range of radiative forcing in the SRES marker scenarios at the time of global mean temperature change of 2°C (2030s-2050s, see Section 4.1, below). Although other SRES scenarios were available for some models, the above are available across nearly all models, enabling a consistent analysis. Note that only SRES scenarios were available for the GFDLR30 model, while different versions of the CGCM and CCSRNIES models were used for the IS92 and SRES scenarios. Control run[5] simulations were also available for each model; these are necessary to calculate the warming in each model relative to the model's pre-industrial climate.

3.2 Time of 2°C global temperature change (Y2C)

For each model, control-run surface temperature data were used to calculate a "pre-industrial" mean temperature climatology, and these were spatially averaged to calculate a global mean pre-industrial surface temperature. For each climate change simulation, the global temperature fields were spatially averaged to calculate time-series of global mean annual temperature, which were then differenced from the "pre-industrial" global mean temperature. The resulting global mean temperature-anomaly series were then smoothed with a 21-year moving average, and the date at which the 21-year mean global temperature anomaly exceeded 2°C was taken as the time of 2°C global temperature change. The ECHAM4 IS92aGS simulation only ran to 2049, and did not reach a 2°C global temperature change by the end of the simulation; consequently this run was excluded from much of the further analysis.

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[5] A control run is a long (many hundreds of years) simulation where the CO_2 levels are specified at pre-industrial levels. Data from a control run are then used to determine the GCM's unforced climate, which serves as a reference against which simulations with enhanced levels of GHGs and aerosols can be assessed.

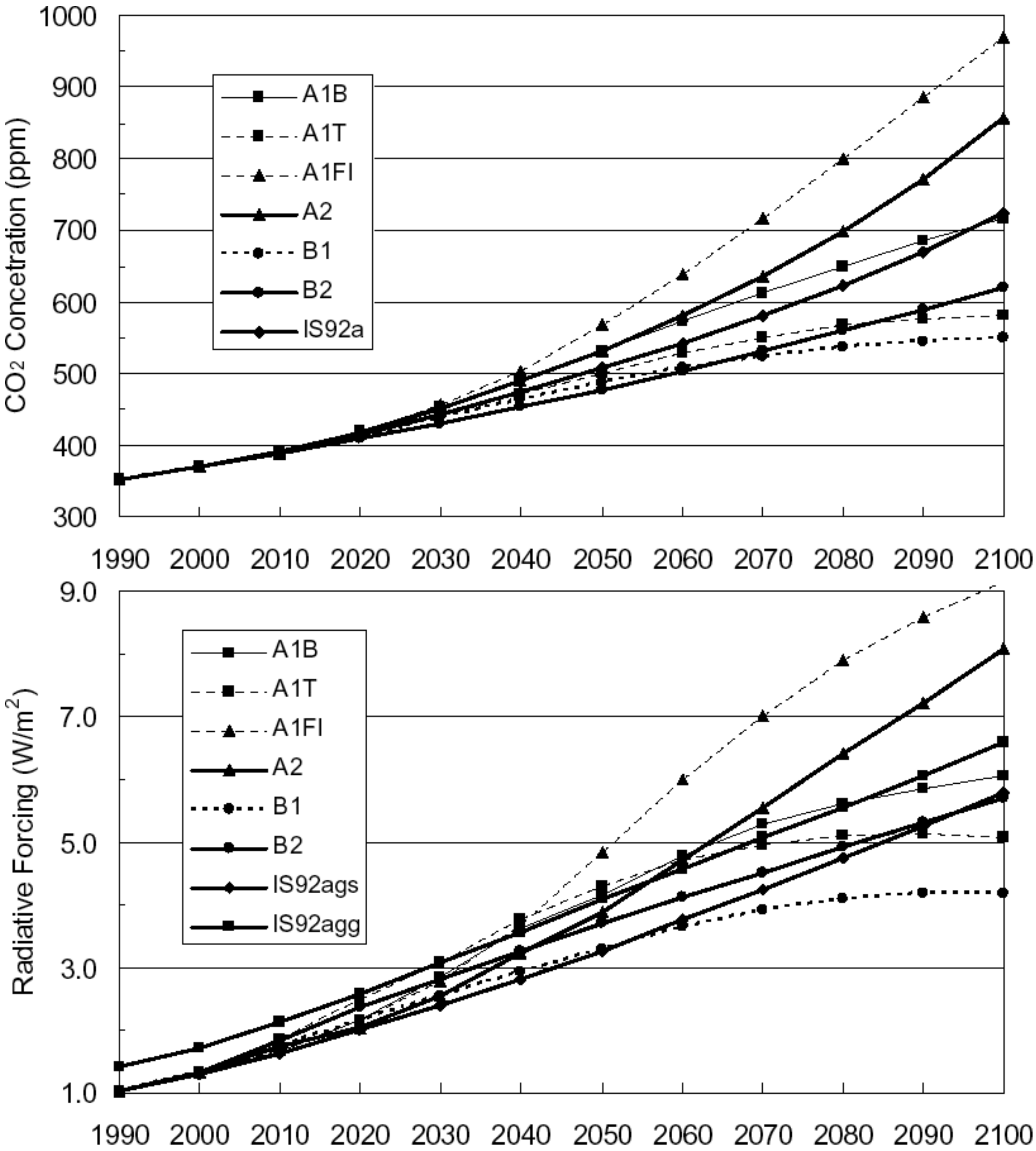

Figure 1. Estimated concentrations of CO_2 and globally averaged increase in radiative forcing from all greenhouse gases and aerosols (relative to pre-industrial levels) arising from various IPCC emissions scenarios. Scenarios used in this study are in bold. Data from Appendix II of IPCC (2001b).

3.3 Arctic climate change at time of 2°C global temperature change

All Arctic temperature and precipitation changes were expressed relative to the pre-industrial mean climate for the model run in question. For each model, the thirty-one year mean monthly climate[6] centred on the time of 2°C global temperature change was calculated and differenced from the control-run mean field. In the first instance, only near-surface temperature and total precipitation changes were analysed.

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[6] A thirty-year mean is the "standard" time period used in many climate change studies, by the World Meteorological Organisation, and by the IPCC Data Distribution Centre. For the Arctic, where there can be natural variability on 10-20 year time scales, any thirty-year mean calculated at the time of a 2°C global warming will likely contain a proportion of decadal-scale natural variability, as one might expect in the real world in the next century.

The resultant change fields were summarised for all model simulations, using the common 0.5 degree grid, by calculating the mean and standard deviation of all models on a grid-point by grid-point basis; these statistics were calculated for monthly, seasonal and annual fields.

Changes in area-mean temperature and precipitation in the Arctic (here defined as latitudes > 60°N) were calculated from these fields using area-weighted averaging. Rates of climate change at the time of 2°C warming were also estimated, by calculating the linear trend in temperature for the 41-year period centered on the year of 2°C global warming. These rates were determined for both area-mean temperature and for GCM grid-box temperatures.

4 Results

4.1 Time of 2°C Global Temperature Change

The time at which the simulated global mean temperature exceeds the control run global mean by 2°C ranges from between 2026 and 2060 (Figure 2). The inter-model spread for a single scenario (e.g. B2) is nearly as large as the total spread; however, there is a tendency for the scenarios with greater accumulated radiative forcing (IS92aGG, A2) to exhibit a greater rate of warming, and an earlier Y2C.

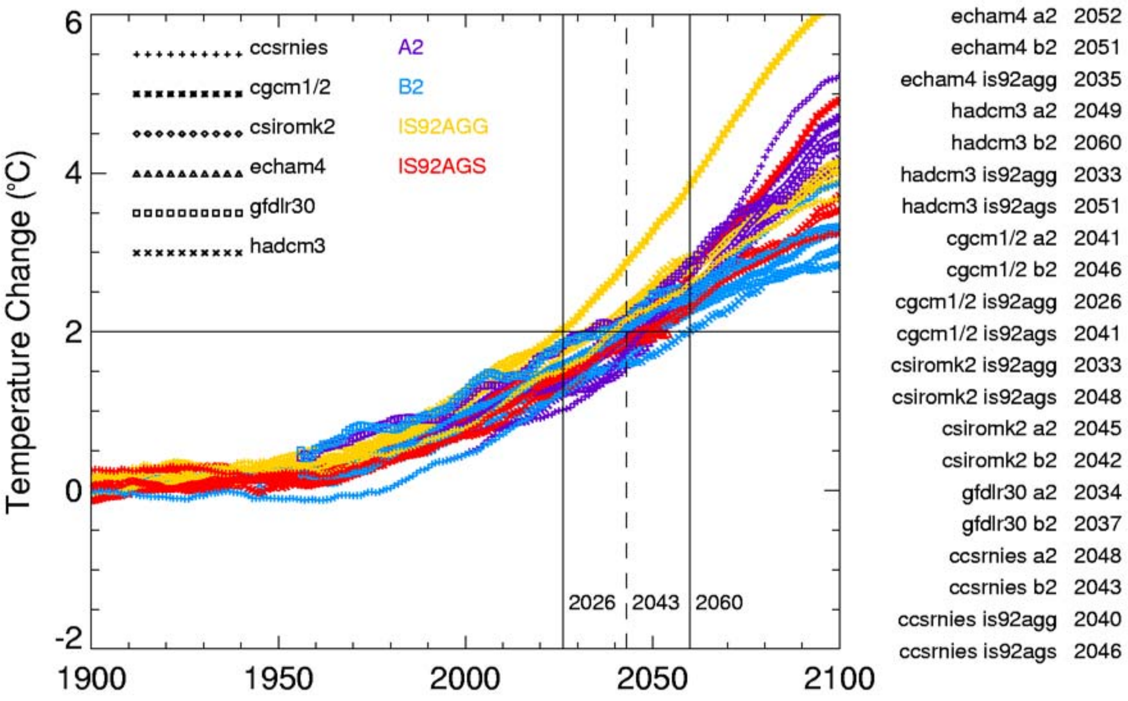

Figure 2. Global mean annual temperature anomalies relative to control climatology, smoothed with a 21-year moving average. Vertical lines indicate the range in time at which the 21-year global mean temperature anomaly exceeds +2°C. Figures on the right show the time at which the 21-year mean global temperature anomaly exceeds +2°C for each GCM-scenario combination.

4.2 Arctic-wide Climate Change at Y2C

The co-evolution of global and Arctic (defined as latitudes greater than 60N) area-mean temperature is shown in Figure 3. Each series is smoothed with a 21-year mean to remove shorter-term variability. Most models show a similar response, with Arctic temperature change ranging between 3.2°C and 4.5°C at the time of a 2°C global warming. The CCSRNIES model shows a stronger response, with a change of up to 6.6°C. In all models, Arctic temperature change over time is approximately a linear function of global temperature change. This would suggest that, for the amounts of global warming simulated by these models over the next 100 years, the nature of the feedbacks causing Arctic amplification in a specific model remain the same. As noted previously, the dominant feedback causing the temperature amplification in the CMIP simulations of these models is related to sea ice (Holland & Bitz 2003). If warming proceeds until a model has little remaining sea ice, the ice-albedo feedback would necessarily reduce, and the linearity reported here may break down.

The similar slopes for the relationships between global and Arctic temperature change suggest that the relative size of Arctic temperature amplification does not depend strongly on the rate of global warming, at least for rates of warming arising from the forcing scenarios evaluated here. Some models show greater amplification when forced by lower emissions scenarios, while others show more amplification under higher emission scenarios. Differences in the amplification are, if anything, more dependent on differences between the models themselves (Table 2). For any model, scenarios with faster (slower) global warming also show faster (slower) Arctic warming, but the Arctic amplification is similar for fast and slow warming scenarios. Thus, in each model, the temperature change in the Arctic when the global temperature change reaches 2°C will be similar regardless of when this global change occurs. There may be additional lags in the Arctic climate system (e.g. changes to permafrost) that will only become apparent later, but over the timescales considered here, the snow/ice albedo feedback shows the strongest relationship to temperature change (Holland & Bitz 2003; Flato 2004), and is likely to be dominant.

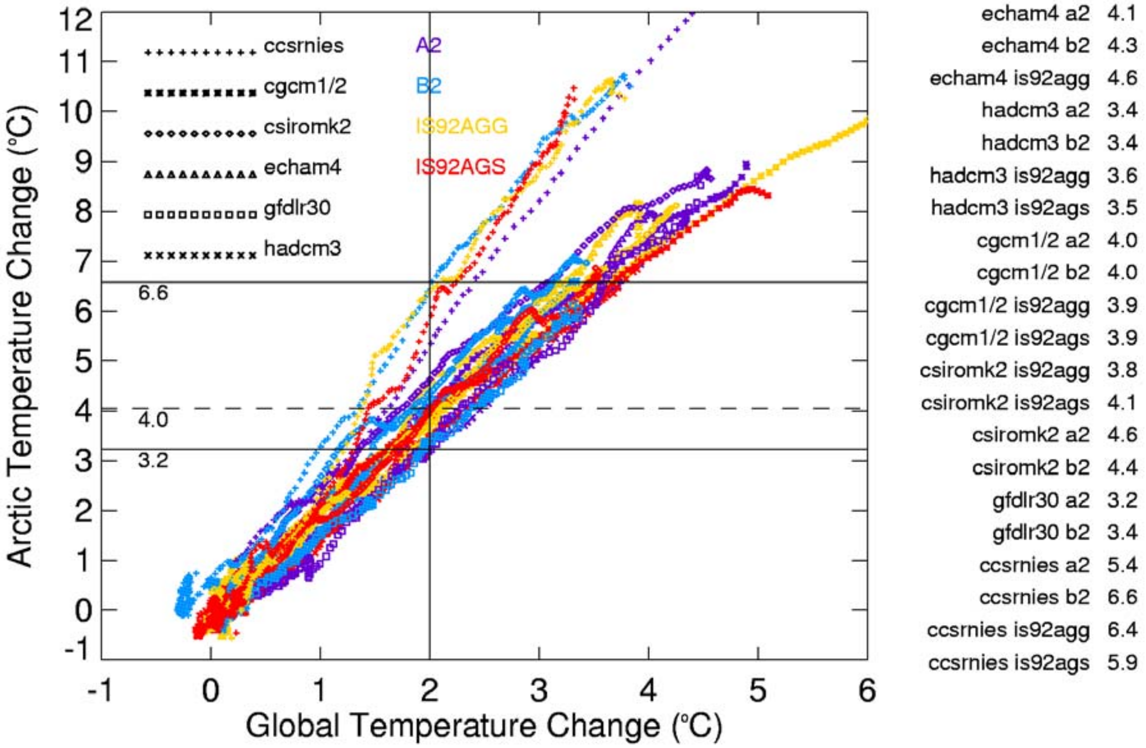

Figure 3. Co-evolution of global and Arctic annual temperature anomalies, smoothed with a 21-year (31-year for the Arctic) moving average. Horizontal lines show the range (solid) of and median (dashed) temperature changes predicted for the Arctic when the global temperature anomaly reaches 2°C. Figures to right list the 31-year mean annual Arctic temperature change at the time of 2°C global warming for each model.

Far more significant is the rate of temperature change in the Arctic at the time of 2°C global warming (Table 2). For the models with broadly similar Arctic temperature amplification (i.e. all models except CCSRNIES), differing climate sensitivities and forcing produce rates of change in area-average Arctic temperature that range from 0.45°-0.75°C/decade. Although the CCSRNIES model has the largest amplification of Arctic temperature change, and therefore produces the fastest rates of Arctic temperature change, the rates it does produce are alarming – between 0.92 and 1.55 °C/decade. The highest rate of 1.55°C/decade is interesting, as it is partly due to a regional warming in the Arctic that is much faster than the longer-term rate (Figure 3). Although the cause of this period of above average warming is unclear (it could be an abrupt change caused by overall warming or, more likely, natural variability superimposed on the underlying global warming signal), it does suggest that over decadal timescales, there can be extreme rates of regional warming. Periods of more rapid Arctic temperature change are evident from a number of different model runs at various times (Figure 3).

Table 2. The mean Arctic temperature amplification, and the rate of temperature change, at the time of a global mean warming of 2°C for each model-scenario combination. The rate of change is calculated over a 41-year period centred on the time of 2°C global warming.

Model	Scenario	Arctic Amplification (°C/°C)	Arctic Rate of Change (°C/decade)
echam4	a2	1.9	0.74
echam4	b2	2.0	0.52
echam4	is92agg	2.1	0.58
hadcm3	a2a	1.8	0.69
hadcm3	b2a	1.9	0.48
hadcm3	is92agg	1.9	0.59
hadcm3	is92ags	2.0	0.62
cgcm2	a2	1.9	0.68
cgcm2	b2	1.9	0.42
cgcm1	is92agg	1.7	0.72
cgcm1	is92ags	1.7	0.63
csiromk2	is92agg	2.1	0.60
csiromk2	is92ags	2.1	0.58
csiromk2	a2	2.0	0.73
csiromk2	b2	1.9	0.50
gfdlr30	a2	2.0	0.60
gfdlr30	b2	1.9	0.45
ccsrnies	a2	2.8	1.55
ccsrnies	b2	3.0	1.09
ccsrnies	is92agg	3.0	0.95
ccsrnies	is92ags	3.4	0.92

Changes in seasonal mean temperature are largest in winter and autumn and lowest in summer (Figure 4). The median change in temperature in the winter is 6.2°C, approximately one and a half times the annual change in the Arctic and three times the global mean change. The reduced warming in summer is fairly well understood (IPCC 1995). Where sea ice remains, most additional atmospheric heat is consumed by surface melting, and where sea ice is removed, the thermal inertia of the ocean mixed layer suppresses air temperature increases near the surface. The marked seasonality in the amount and rate of change has important implications for the impacts of climate change in the Arctic. Natural processes and

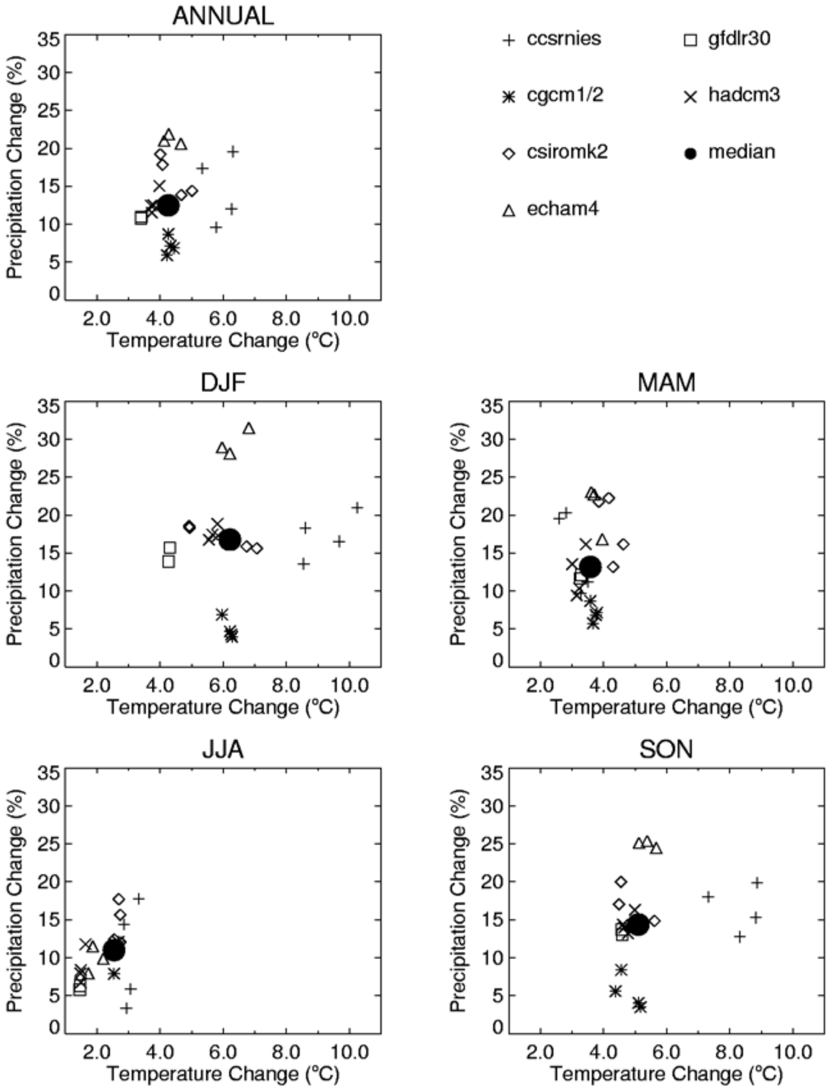

Figure 4. Seasonal changes in mean temperature and precipitation in the Arctic at the time of a global 2°C warming.

human activities that are dependent on winter temperature are likely to be more severely affected (see companion papers).

Area-average precipitation change is always positive, but varies considerably from model to model. Annual precipitation change varies from +5% to +22%, with a median change of +12%. Changes in precipitation in each season have roughly similar ranges, with maximum changes of just over +30% in DJF and +18% in JJA (Figure 4). There is a slight hint of a correlation between rainfall and temperature change, as noted at the global scale by Allen and Ingram (2002) and for the Arctic by Raisanen (2001b), but the relationship for the models studied here is weak and not statistically significant. Raisanen's (2001b) analysis of 19 CMIP2 models showed a much stronger relationship between temperature and precipitation change in the Arctic. This is partly because his study included more models, some of which had a greater range of predicted temperature and precipitation changes, strengthening the weak relationship seen with the models used here, but also because this study includes results from four simulations with each model. Inspection of Figure 4 shows that between-model variations in precipitation change can be quire large (e.g. from 10% to 20% for HadCM3), which adds considerable noise to the temperature-precipitation relationship.

5 Regional Patterns of Change

5.1 Temperature

The median pattern of temperature change in the Arctic at the time of 2°C global warming simulated by each GCM is illustrated in Figure 5 and summarized for all GCMs in Figure 6. These figures illustrate areas of agreement and disagreement between model results. While there are significant inter-model differences, both in the amount of warming and its distribution, there are a number of similarities worthy of mention. The largest warming in annual temperature is generally located in the central Arctic Ocean. This warming is primarily due to large positive anomalies in winter. In summer, the Arctic Ocean generally warms less than the surrounding land areas. The other common pattern is a lower warming or even a cooling in the North Atlantic. This pattern is most pronounced in HadCM3, but is present in all models, and is often related to the weakening of the Atlantic thermohaline circulation. Local anomalous areas of cooling or high warming in individual models are probably related to changes in the sea ice characteristics relative to the control simulation. There is no relationship between the Arctic-wide average rate of warming and the spatial patterns of warming; patterns appear to be dominated by responses specific to the model.

Rates of change also show significant spatial variability. Areas with larger temperature anomalies tend to be associated with greater rates of change (as expected). Annual average temperature changes at rates of approximately 1°C and 0.5°C per decade over the Arctic Ocean and surrounding continental areas respectively. In winter, where the sea ice feedback produces large changes in temperature over the Arctic Ocean, average rates of temperature change are similarly elevated, ranging from about 1.5 °C per decade at the ocean margins to 2.7 °C per decade in the interior of the ocean. In summer, rates of warming are lowest over the Arctic Ocean and range between 0.25° and 0.5°C per decade of polar land areas. The range in warming rates varies considerably in areas with the largest rates of change, so these median estimates of the average rate of change have large confidence bounds.

5.2 Precipitation

The broad patterns of precipitation change are similar between models (Figure 7), although the absolute amounts of change are quite varied, and depend to some extent on the amount of rainfall in the control simulations (“wetter” models tend to have larger absolute changes in precipitation). All models simulate a general increased precipitation over most of the Arctic; HadCM3, GFDLR30 and CSIROMk2 show reduced rainfall over the North Atlantic and/or Greenland seas that correlate with areas with the smallest or negative temperature changes. There is some tendency for the largest absolute precipitation changes to be over land areas, but the loci of these maxima vary between models to the extent that there is very little commonality. The greater changes over land is at least in part due to the due to the fact that GCM precipitation is larger over sub-Arctic continents (at ~50-70°N) than over the Arctic Ocean. Model simulations generally show the largest *relative* (per cent) increase in precipitation over the Arctic Ocean (cf. Raisanen 2001a).

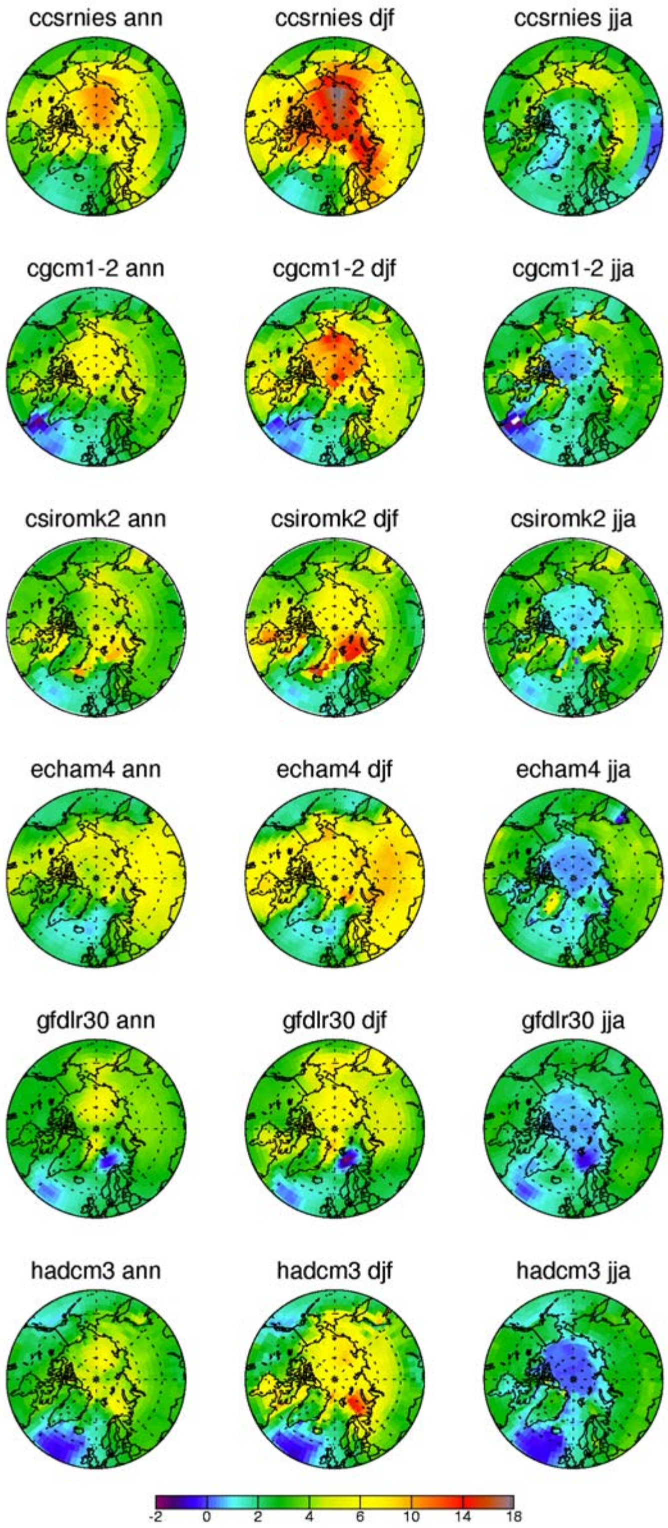

Figure 5. Median annual, winter and summer temperature changes (°C), relative to control (pre-industrial) climatology, at the time of a global warming of 2°C, calculated from the range changes simulated by each GCM forced by the four (three for ECHAM4 & two for GFDLR30) emissions scenarios. Note that the map domain extends from 50°N.

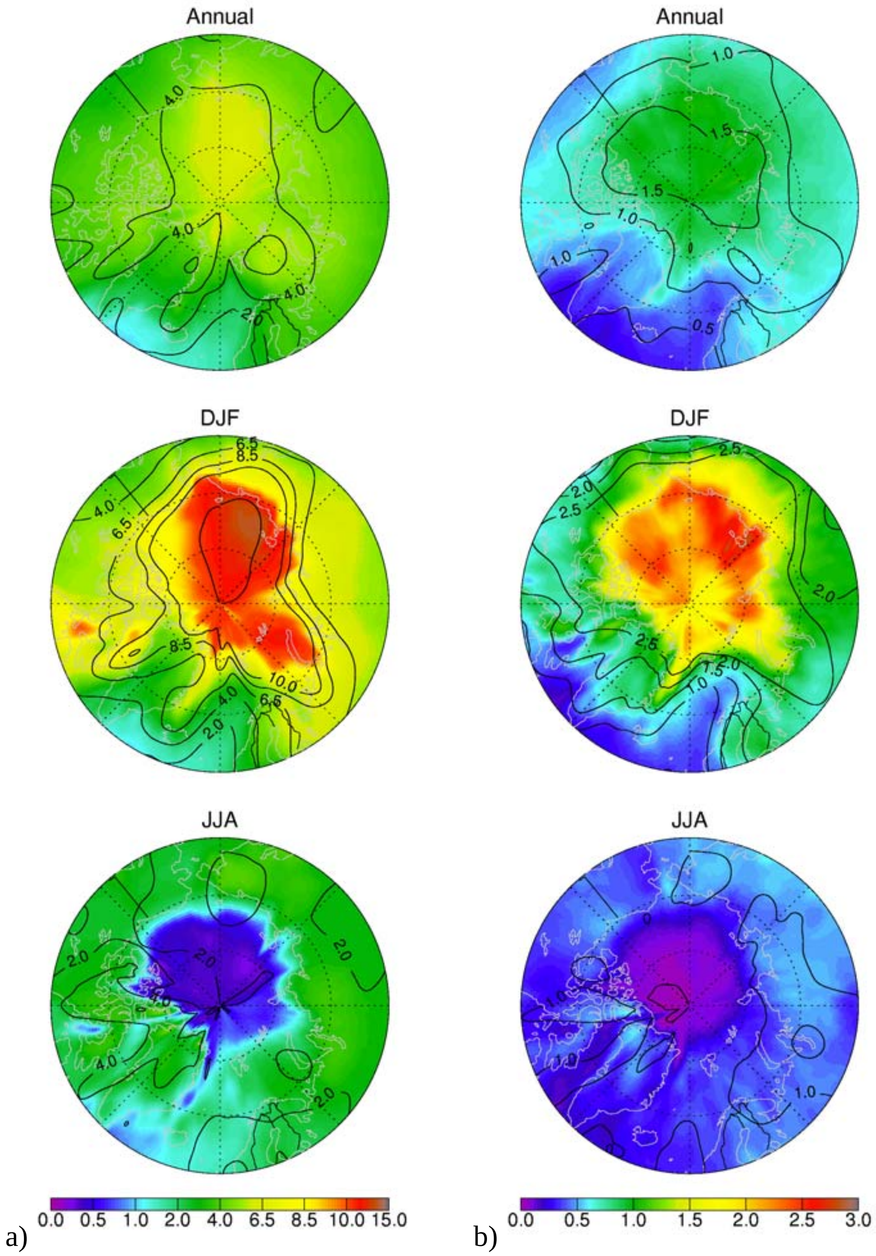

Figure 6. Summary of annual and seasonal temperature changes over the Arctic at the time of 2°C global warming, as simulated by the GCMs used in this study. a) Median (colours) and range (lines) of mean temperature change, in °C. b) Median (colours) and range (lines) of the rate of temperature change, in °C per decade. Note that the map domain extends from 50 °N.

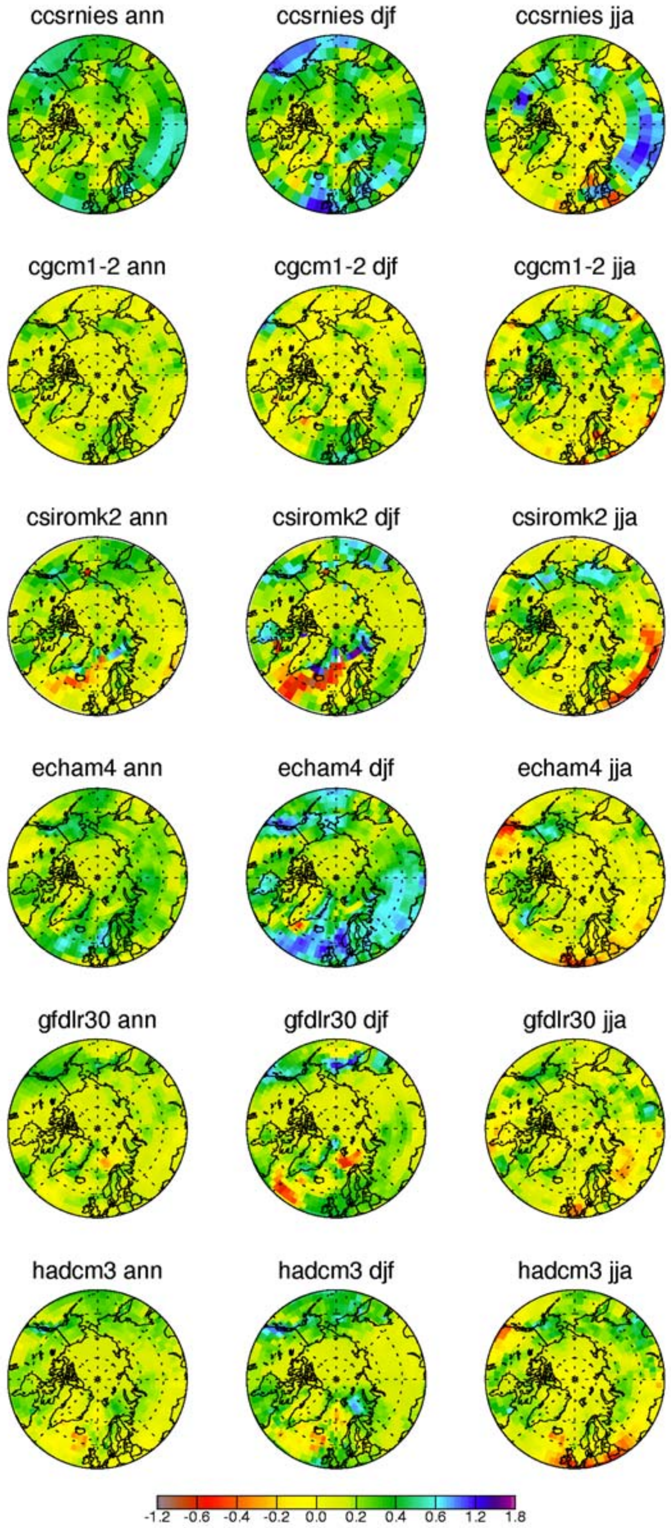

Figure 7. Median annual, winter and summer precipitation changes (in mm), relative to control (pre-industrial) climatology, at the time of a global warming of 2°C, calculated from the range changes simulated by each GCM forced by the four (three for ECHAM4 & two for GFDLR30) emissions scenarios. Note that the map domain extends from 50°N.

6 Conclusions

This paper has had two main objectives: (1) to provide an estimate of the time span within which global mean temperature might increase to 2°C above its pre-industrial level, and (2) to describe the possible changes in Arctic climate that will accompany a 2°C global temperature increase. As this involves projections into the future – with its associated uncertainties about emissions of GHGs and aerosols and their associated atmospheric concentrations – the study makes use of results from coupled ocean-atmosphere GCMs forced with four emission/concentration scenarios. Differences between GCMs and between forcing scenarios result in a range of dates at which global mean temperature anomaly is predicted to reach +2°C: between 2026 and 2060, with a median date of 2043.

The geography of the Arctic (land-sea distribution) and snow/ice albedo feedbacks, along with minor changes in cloud and ocean heat transport, lead to an amplified regional warming over the Arctic that ranges from between 3.2° and 6.6°C for a global change of +2°C. In each of the GCMs that were evaluated, the amplification is similar for fast and slow warming scenarios: changes in the Arctic will be comparable regardless of when a global change of +2°C occurs. However, a faster global warming will necessarily produce more rapid warming in the Arctic. The Arctic temperature change amplification means that these rates of warming are likely to be between 0.45° to 0.75°C/decade, and possibly even as large as 1.55°C/decade. These results are derived from transient simulations of climate change driven by progressive forcing of climate by GHGs and aerosols through the 20th and 21st century, and therefore represent a climate system that has not reached equilibrium. It is important to realize that the ultimate climate changes in the Arctic should global temperature change be stabilized near +2°C may be quite different, particularly as the oceans equilibrate with the atmosphere and interact with sea ice. However, there are too few long-duration GCM simulations to equilibrium after stabilization (e.g. Mitchell et al. 2000; Dai et al. 2001) to address this rigorously.

Warming over the Arctic is largest in winter (4°-10°C, median of 6°C) and least in summer (1.5°-3.5°C, median of 2.6°C). These area-averaged changes mask important regional patterns of change. Winter warming is largest in the Arctic Ocean, and varies from model to model according to model-specific changes in sea ice, while summer warming is largest over land. Thus, the contrast between winter and summer is smaller over land than over the Arctic Ocean. Most models show relatively little warming or even localized cooling over the North Atlantic and Greenland Sea, which is related to reduced strength and/or reorganisation of the North Atlantic thermohaline circulation.

All models show increases in Arctic-wide precipitation. Patterns of change vary considerably between models, with some localized decreases in precipitation. These increases in precipitation will, however, be accompanied by changes in the character of precipitation. Although information on the proportion of precipitation that falls as snow was not available for these GCMs, the increased warming implies that a higher fraction of summer precipitation will fall as rain. One study that used a similar set of 21st century climate simulations over the Arctic, Meleshko *et al.* (2004), showed that March snowmass increased, in line with greater winter precipitation, and that May snowmass decreased due to increased rates of melting and reduced solid precipitation in spring. These changes have the potential to alter the hydrological regimes of river basins in the Arctic, with earlier spring snowmelt and more direct run-off earlier in the summer.

Evaluations of GCM sea ice distributions in control simulations (e.g., Hu et al. 2004) have shown that all models have difficulty replicating the observed distributions and thicknesses, and that the magnitude of the snow/ice-albedo feedback effect (and hence regional temperature change) can be sensitive to the distribution and thickness of ice in a model’s control climatology. Similarly, GCMs vary widely in their ability to replicate the average behaviour and variability of mechanisms influencing Arctic climate (such as the North Atlantic Oscillation and the Atlantic thermohaline circulation). This is reflected in the wide range of predicted climate changes for the Arctic between the GCMs studied here. Where there is a consensus between GCMs one can be more confident in the robustness of the results of this analysis. For example, all GCMs exhibit greater warming in the Arctic than the global mean warming, so we can be confident in this result. However, the size of Arctic warming relative to global warming varies widely between models and we have little or no basis on which to judge whether one model is "better" than others. Therefore, calculation of a "mean Arctic temperature change" across all models has little meaning; rather, the range in predicted changes provides us with some bounds on the likely temperature changes, but also an indication of the rather large uncertainties in the current generation of GCM simulations of Arctic climate change.

A further source of uncertainty in this study arises from the analysis of only a single realization of each GCM-scenario combination. Single simulations make it difficult to quantify the relative contributions of natural variability and GHG forcing in the change in the Arctic at a time of 2°C global warming. Indeed, it is possible that multiple simulations with the same GCM may produce differences as large as the differences between the models studied here. More robust results could be achieved through analysis of ensembles of simulations, but this was not possible with data available from the IPCC Data Distribution Centre. However, by analysing the results for four difference GHG scenarios, and comparing between simulations at the time when the global temperature anomaly reaches 2°C, some idea of the relative importance of within and between-model differences can be gained. In general, differences between models are greater than difference within models, suggesting that the range of temperature and precipitation changes is mostly related to GCM choice rather than within-model variability. However, within-model variability does play a secondary role in the variability of results presented here. This is in agreement with the results of Raisanen (2001b), who estimated for the CMIP models that internal model "noise" accounted for only 10% (temperature) and 30% (precipitation) of the between-model variation in climate change at the time CO_2 doubling.

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CLIMATE CHANGE AND ARCTIC VEGETATION

JED O. KAPLAN*

Abstract

High-latitude vegetation plays a significant role in the lives of humans and animals, as well as in the global energy balance and carbon budget. These ecosystems are probably among the most strongly affected by climate change over the next century. Changes in key climatic gradients; especially growing-season warmth, soil moisture, and snow cover are likely to substantially alter the composition, structure, and function of Arctic ecosystems in the future. To investigate the potential impact of future climate change on Arctic vegetation, I performed a study using state-of-the-art remote sensing data and vegetation modelling. A unified circumpolar classification recognizing five types of tundra and six forest biomes was used to develop a map of observed Arctic vegetation and to simulate the vegetation of the Arctic at present and future global warming scenarios. The geographical distributions of vegetation types in the present-day Arctic, including the position of the forest limit and the distributions of the tundra types, were predicted from climatology using the biogeochemistry-biogeography model BIOME4. Projection of the effect of the 2°C global warming projected to occur between 2026 and 2060, based on an ensemble of transient ocean-atmosphere GCM simulations, suggests a potential for greater changes in terrestrial Arctic ecosystems during the 21st century than have occurred between the mid-Holocene and the present. Forest extent increases in the Arctic in the order of $3x10^6$ km^2 or 55% with a corresponding 42% reduction in tundra area. Tundra types generally also shift north, with the largest reductions in the prostrate dwarf-shrub tundra, where nearly 60% of habitat is lost. Modelled shifts in the potential northern limit of trees reach up to 400km from the present treeline, which may be limited by dispersion rates. Simulated physiological effects of the CO_2 increase (to ca. 475 ppm) at high latitudes were small compared with the effects of the change in climate. The change in Arctic vegetation, to a landscape of taller tundra types and forest biomes, would have a significant biophysical feedback to the climate system, particularly through changes in surface roughness and albedo. These effects could further amplify warming, especially in continental regions. On the other hand, the increase in forest area of the Arctic could sequester ca 600 Pg of additional carbon, but this effect is unlikely to be important over the next century.

1 Introduction

The natural vegetation of the Arctic is a keystone in the culture of its indigenous peoples and is essential to the survival of flagship animal species. The Arctic has a unique and rich flora and fauna that includes many endemics. High-latitude ecosystems also play a significant role in the global energy balance and carbon budget through the strong seasonality in surface albedo, carbon storage in widespread, often frozen organic soils, methane emissions from tundra wetlands, and the presence of millions of lakes and ponds. Future global climate changes are expected to have a strong signal in the Arctic and it is likely that terrestrial vegetation patterns will change significantly. In turn, changing patterns of Arctic vegetation will almost certainly affect future climate through biophysical and biogeochemical feedbacks to the atmosphere-ocean system: increases in tree and shrub cover would reduce total and seasonal albedo, warmer temperatures might increase carbon sequestration, and changes in the hydrological cycle due to melting permafrost could effect large changes in wetland area and methane emissions (Oechel et al. 1993; Foley et al. 1994; Bonan et al. 1995; Chapin et al. 1995a; Christensen 1999; Chapin et al. 2000). Animals, and humans, would almost certainly also be affected by these vegetation changes.

Most recent global modelling experiments and analyses of palaeodata treat Arctic ecosystems simplistically, where Arctic vegetation is commonly lumped into a single biome, “tundra.” This situation exists despite large variations in the physical and biogeochemical characteristics of Arctic ecosystems, including surface albedo, roughness, conductance to water vapour, carbon storage and turnover, and nutrient-use patterns. In order to overcome some of the limitations of current treatments of tundra vegetation types, recent work has taken a comprehensive approach to describing and

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modelling terrestrial ecosystems of the northern high latitudes (Walker et al. 2002; CAVM-Team 2003; Kaplan et al. 2003). Globally consistent vegetation classification and mapping using remote sensing data as a base has resulted in new, detailed maps of the vegetation of the Arctic for the present day. Meanwhile, comprehensive analysis of palaeo-vegetation data sets produced vegetation maps of the Arctic at key periods in the past (Bigelow et al. 2003). Using both these data sources, vegetation models have been developed to more accurately depict the structure and functioning of Arctic ecosystems on a global scale. Comparisons of model results to both present-day vegetation and palaeodata have demonstrated that the modelling approach is robust and justified. New experiments using this modelling technique have the goal of drawing conclusions about the sensitivity of Arctic ecosystems to climate change that are more strongly scientifically justified than statements based solely on contemporary observations or site-scale modelling (Kaplan et al. 2003).

Recent work has highlighted the importance of the land cover of the Arctic in the climate system. Over the late Quaternary, with the warm and cool cycles of the Ice Ages, Arctic vegetation changed dramatically. The vegetation feedback to the atmosphere, through widespread changes in surface albedo, is seen as a necessary component in the inception of glacial periods, where shifts in vegetation cover from forest to tundra are required to produce the build-up of persistent summertime snow cover in key parts of the Arctic (de Noblet et al. 1996; Pollard & Thompson 1997; Meissner et al. 2003).

During full glacial conditions, up to three quarters of the Arctic land mass was covered by ice sheets. Lower sea levels, however, exposed important areas to Arctic vegetation, most notably the Beringia land bridge between Eurasia and North America. Tundra vegetation was considerably more extensive than today and forests were confined to areas thousands of kilometres from the Arctic region. Glacial Arctic vegetation was characterized by sparse vegetation, few trees, and a prevalence of graminoid and forb tundra, a vegetation type representative of very cold and dry climate conditions without a widespread modern analogue. Reconstructions of vegetation far to the south of the Arctic proper show non-forest (tundra or grassland) extending far into southern Europe and Russia at the Last Glacial Maximum (LGM ca 21,000 yr BP). Palaeo-environmental data show that low- and high-shrub tundra was greatly reduced in extent at the LGM compared to today, being largely confined to the Beringian land bridge, while graminoid and forb tundra was very much more widespread (Bigelow et al. 2003). Graminoid and forb tundra occupies only restricted areas today, on dry and sunny micro-sites throughout the continental Arctic.

After the last Ice Age, rapid deglaciation was followed by the colonization of the Arctic by tundra shrubs and trees, and the gradual disappearance of widespread graminoid and forb tundra. Forests reached their northernmost extent in some regions 10-12,000 years after the LGM, during the period of maximum high-latitude summertime and annual solar radiation caused by variations in the Earth’s orbital cycle. But the Laurentide ice sheet, although substantially reduced from its LGM size, was still sufficiently large to have a major downwind cooling effect during the early Holocene. Northern Europe and eastern North America, therefore, experienced a thermal maximum several thousand years after the insolation maximum. The Arctic reached a maximum in vegetated area by 6 ka, after which a gradual decline in summertime insolation has caused a small southward retreat of the northern forest limit on the order of a few hundred kilometres (Kaplan et al. 2003).

Over the past 50 years, the cover of shrubs and small trees in the Arctic has generally increased (Silapaswan et al. 2001; Sturm et al. 2001b). Future climate changes are expected to be rapid, and possibly outside of the range of climate changes experienced during the early Holocene (Cubasch et al. 2001). Using large-scale vegetation modelling, we can gain some insight into possible future changes in Arctic vegetation cover, and draw inferences on potential interaction with the climate system and ecosystem habitat changes.

This report presents a new composite map of vegetation in the present-day Arctic and a set of unique, high-resolution model simulations of Arctic vegetation under a series of future climate scenarios. The observed map is based on recently available remote-sensing products and the global vegetation model has been specifically designed and tested for the Arctic. A simulation of present-day vegetation is compared to the observed map, and through four future scenarios based on GCM ensembles that represent a spatially heterogeneous mean global warming of 2°C, I make an assessment of the sensitivity of Arctic vegetation to anthropogenic change in atmospheric CO_2 concentrations and climate. The work is exploratory and makes use of several different general circulation models, representing a wide range of future climate scenarios. Nevertheless, I am able to draw some pr eliminary conclusions about the sensitivity of high-latitude ecosystems to climate change.

2 Methods

2.1 Classification of tundra vegetation types

Most previous classifications of tundra vegetation types have been based on species assemblages and tailored to specific regions. Application of these schemes outside the region for which they were designed can be problematic because key species are absent or display wide phenotypic plasticity (e.g. *Salix spp.*). Widely used but loosely defined terms such as “high Arctic,” “sub-Arctic,” and “polar desert” have geographical connotations that cause confusion, especially when applied to radically different environmental conditions in the past, when plant communities with no modern analogue occurred or latitudinal gradients were not apparent because of the present of ice sheets, for example. To avoid these problems, I combined a new, standardized circum-Arctic classification scheme for tundra at the biome level (CAVM-Team 2003; Kaplan et al. 2003) with existing global vegetation classifications used by modellers (Kaplan 2001) and remote sensing (JRC 2003). Each biome is defined in terms of physical structure and dominant life forms and is floristically distinguishable, both in modern vegetation and in pollen-based reconstructions of palaeo-vegetation. Each biome occupies a unique and definable climate space. The global scheme used here distinguishes 28 global biomes, of which five are tundra biomes and five are cold and cool forests (Kaplan 2001). The tundra biomes are: low- and high-shrub; erect dwarf-shrub; prostrate dwarf-shrub; cushion forbs, lichen and moss; and graminoid and forb.

2.2 The Arctic region and Arctic grid

The area defined as the Arctic for these experiments was defined by combining the Arctic boundary polygons of the Arctic Monitoring and Assessment Program (AMAP[1]) and Conservation of Arctic Flora and Fauna (CAFF[2]), using the southernmost defined boundary at any given point (Figure 1). This polygon defines the Arctic to cover northernmost Fennoscandia, northern European Russia, Siberia north of approximately 65°N, all of the Chutkotka peninsula, and most of Alaska. In Canada, the boundary of the Arctic includes all of Yukon Territory and the Mackenzie river valley, a zone of several hundred kilometres surrounding the Hudson Bay, and Quebec south to ca 52°N. All of Greenland, Iceland, and Svalbard, as well as smaller North Atlantic and Arctic islands are also covered by this definition.

For the vegetation modelling experiments performed in this report, the Arctic polygon was projected to a north polar aspect Lambert Equal-Area projection and gridded at 10-kilometre resolution. As described below, climate and land surface properties, a map of observed natural vegetation, and vegetation model output were projected and interpolated to this grid. The Arctic grid has nearly 1 million grid cells, of which ca 13.1×10^6 km^2 is ice-free land area. For analysis of regional changes in vegetation, I divided the total Arctic area into zones roughly relating to areas with climatological, topographical, or pedological similarity (Figure 1).

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[1] http://www.amap.no

[2] http://www.caff.is

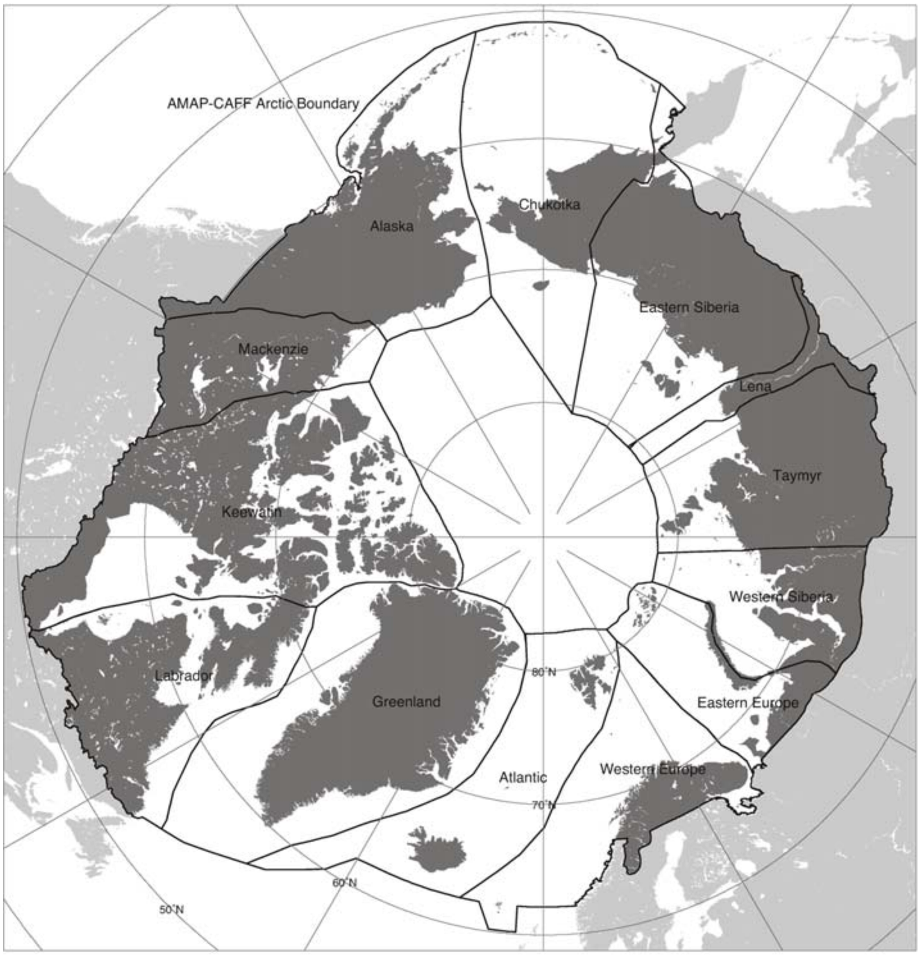

Figure 1. Arctic boundary and zones

2.3 The BIOME4 model

BIOME4 is a coupled carbon and water flux model that predicts steady state vegetation distribution, structure, and biogeochemistry, taking into account interaction between these effects (Kaplan 2001). The model is the latest generation of the BIOME series of global vegetation models, which have been applied to a wide range of problems in biogeography, biogeochemistry, and climate dynamics (Prentice et al. 1992; VEMAP 1995; Christensen et al. 1996; de Noblet et al. 1996; Haxeltine & Prentice 1996a; Haxeltine et al. 1996; Jolly & Haxeltine 1997; Harrison et al. 1998; Kaplan 2002; Kaplan et al. 2002). BIOME4 has been specifically developed with the intent of simulating the cold-climate, high-latitude vegetation (Kaplan et al. 2003). The driver-variables for BIOME4 are long-term averages of monthly mean temperature, surface short-wave insolation, and precipitation. In addition, the model requires information on soil water-holding capacity and saturated hydraulic conductivity, and a single value for annual-mean, spatially uniform atmospheric CO_2 concentration. While BIOME4 can be run for any area and at any spatial resolution, the model is generally designed to be used at continental to global scales.

Twelve plant functional types (PFT's) in BIOME4 represent broad, physiologically distinct classes, ranging from cushion forbs to tropical broadleaf trees (Figure 2). Each PFT is assigned a small number of bioclimatic limits which determine whether it could be present in a given grid cell, and therefore whether its potential net primary productivity (NPP) and leaf area index (LAI) are calculated. The PFTs also have a set of parameter values that define its carbon and water exchange characteristics. The computational core of BIOME4 is a coupled carbon and water flux scheme that determines the seasonal maximum LAI that maximizes NPP for any given PFT, based on a daily time step simulation of soil water balance and monthly mean calculations of canopy conductance, photosynthesis, respiration and phenological state (Haxeltine & Prentice 1996b). The model is sensitive to CO_2 concentration because of the responses of NPP and stomatal conductance to CO_2.

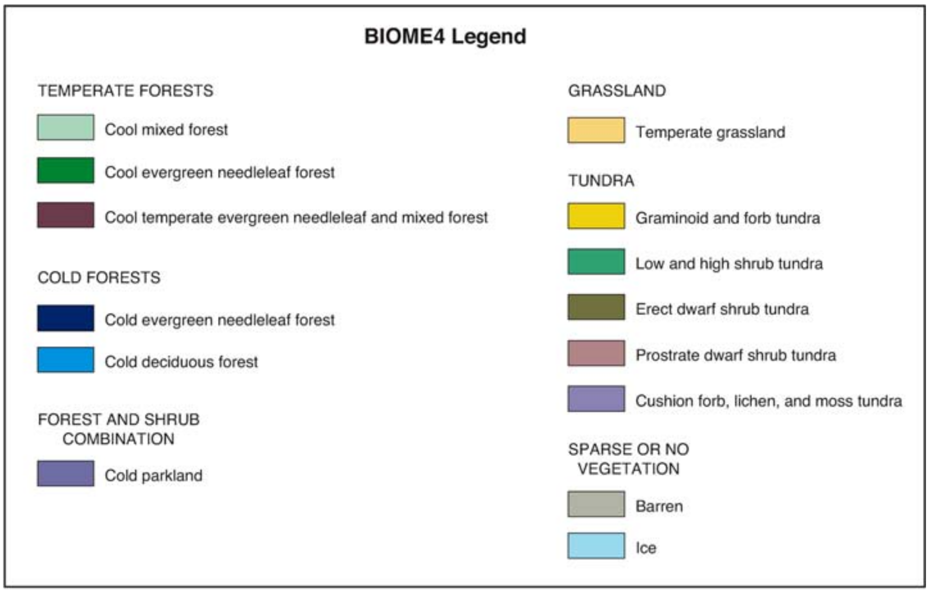

Figure 2. Legend for biome maps

To identify the biome for a given grid cell, the model ranks the tree and non-tree PFTs that were calculated for that grid cell. The ranking is defined according to a set of rules based on the computed biogeochemical variables, which include NPP, LAI, mean annual soil moisture, and an index of vulnerability to fire. The resulting ranked combinations of PFTs lead to an assignment to one of 27 biomes. The 28th cover type, ice sheets and glaciers, is prescribed.

2.4 Climate scenarios

2.4.1 Baseline climatology

I used gridded, long-term mean climatologies of temperature, precipitation, and surface short-wave insolation for the late 20th century for the present-day vegetation simulation and as a baseline for the 2° warming experiments. Temperature and precipitation data are from the CRU CL 2.0 data set, which is a mean over the period 1961-1990 (New et al. 2002). The CRU CL 2.0 data set is on a 10' geographic grid, which represents a horizontal grid-node spacing of approximately 10 kilometres at 60°N. Because of very sparse station density, particularly in the Arctic, in the CRU CL 2.0 interpolated fields of cloudiness, and suspected inaccuracies in using these data with BIOME4 (Kaplan et al. 2003), I have used a data set of surface shortwave insolation from the ISCCP/SRB project[3] instead (1983-1995 mean). This data set combines satellite-based observations of clouds with a sophisticated atmospheric radiative transfer scheme to produce surface insolation fields and is an improvement over previous, parameterized approaches (Kaplan et al. 2003). Although the ISCCP/SRB data covers a different time period than the temperature and precipitation fields and is on a somewhat coarse, 280 km equal-area grid, the paucity of climate stations and unreliability of using cloudiness data for approximating surface insolation in high latitudes makes use of this data set an improvement of previous sources. Additionally, as cloudiness is not a regular output of GCMs, but surface insolation is, the use of a surface insolation baseline data set simplified the calculation of future climate fields. Both data sets were projected to the 10-kilometre Arctic grid using bilinear interpolation.

2.4.2 2° warming scenarios

This report presents the vegetation distribution calculated in four future climate scenarios which represent different possibilities for the Arctic climate given a global 2°C warming. The scenarios are the product of an ensemble of seven GCMs, run under a series of different emissions scenarios (New, this volume; Table 1). For each model/scenario combination, time series of area-averaged temperature

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[3] http://eosweb.larc.nasa.gov/PRODOCS/srb/table_srb.html

were calculated for the globe, and subtracted from the steady-state pre-industrial control simulation for that model run. The resulting anomaly time series was then smoothed with a 21-year boxcar mean, and the time when this smoothed value reached 2°C was taken as the year of 2° warming (Y2C). For all of the model/scenario combinations, Y2C ranged between 2026 and 2060. Global data from 30-year mean fields centered on Y2C were then extracted for each model/scenario combination and, because of differing native resolution among GCMs, interpolated onto a standard 0.5 deg lat/lon grid. These GCM data for Y2C were then averaged together into an ensemble based on summary statistics of each run for the Arctic, defined all area north of 60°N.

The four scenarios used here were drawn from the ensemble of GCM simulations, and represent a range in the amplitude of the temperature anomaly in the Arctic: 10th percentile, 90th percentile, simple mean and robust mean. The method for calculating the percentiles assumed that the ensemble data at each grid point were normally distributed. To the ensemble mean, **z** standard deviations were added or subtracted, where **z** corresponds to a cumulative probability of 0.10 for the standard normal distribution. To calculate a robust estimate of the ensemble mean changes, a "robust mean" scenario was defined. This robust mean is a weighted average of each of the 10th, 25th, 50th, 75th and 90th percentiles:

$$R = 0.0833*p10 + 0.2083*p25 + 0.4166*p50 + 0.2083*p755\ 0.0833*p90$$

Where R is the robust mean value and p10, p25, etc. are the percentile values as calculated above. The four scenarios represent a range in the magnitude of the Arctic temperature anomaly under a 2°C global warming, with the 10th percentile having the smallest change from control, i.e. the "coolest," followed in magnitude of the temperature anomaly by the robust mean, simple mean, and 90th percentile or the "warmest." The climate anomalies were projected onto the 10-kilometre Arctic grid using bilinear interpolation.

2.5 Earth surface properties and CO_2 concentration

As input to BIOME4, I used the land area and glacier coverage defined by combining the FAO digital soil map of the world (FAO 1995) with the Circum-Arctic Vegetation Map (CAVM) (CAVM-Team 2003). The land ice area defined by the CAVM was considered definitive. The soil properties used by BIOME4 (water-holding capacity and saturated hydraulic conductivity) were taken from the maps of derived soil properties based on the FAO soil map and pedon databases (Reynolds et al. 1999). For areas not covered by the FAO and derived-properties maps, including Svalbard and Russian Arctic islands, the characteristic physical properties of soil were estimated (e.g. for cryosols).

In future climate change experiments with BIOME4, I did not attempt to estimate changes in land surface properties. This particularly applies to ice coverage, where the retreat or melting of Arctic land ice was not considered. Pedogenesis and soil erosion were not considered in this model analysis either.

The ambient mean-annual CO_2 concentration used by the model in the present-day scenario reflects a mid-20th century mean of 324 ppm. In future scenarios, I used a CO_2 concentration of 475 ppm, which is approximately the atmospheric CO_2 concentration calculated by a simple coupled carbon cycle model (Joos et al. 2001) in the mean year of the 2°C warming (i.e. year 2043).

2.6 Validation data sets

A vegetation map of present-day potential natural vegetation covering the Arctic area defined for this report was produced by combining information from two sources. Tundra vegetation distribution is based on the CAVM (CAVM-Team 2003). The distribution of other vegetation types and the location of the forest limit were defined from the Global Land Cover 2000 (GLC2000) map (JRC 2003), with minor modifications of nomenclature. The CAVM and GLC2000 maps have been created primarily from original remote sensing data, and were interpreted and classified by regional experts. Both source maps have been subject to extensive ground truthing and accuracy analysis. The resulting composite map may be considered the best currently available, and importantly this map does not contain any assumed bioclimatic relationships or model.

3 Results

3.1 Present day natural vegetation

The vegetation of the Arctic is characterized by a transition from boreal forests to tundra shrub lands that become progressively shorter in stature farther north. The coldest and most northerly parts of the Arctic are sparsely vegetated by cushion forbs, lichens and moss, and dominated by rocky barrens or permanent ice fields and glaciers.

In a quantitative comparison between the modern observed vegetation map (Figure 3) and the simulated vegetation map (Figure 4), 65.0% of grid cells (84036 grid cells excluding ice-covered areas) matched in biome classification. The matching percentages for grid cells assigned to specific forest biomes in the observed vegetation map were: cold evergreen needleleaf forest, 76.9%; cold deciduous forest, 77.7%; cold parkland, 91.0%. The biome cold parkland is a transition biome between cold evergreen forest and high and low shrub tundra. While not specifically classified in the observed vegetation map, where cold parkland was simulated by BIOME4, it was considered a match to the observed map when either cold evergreen needleleaf forest or high and low shrub tundra was simulated.

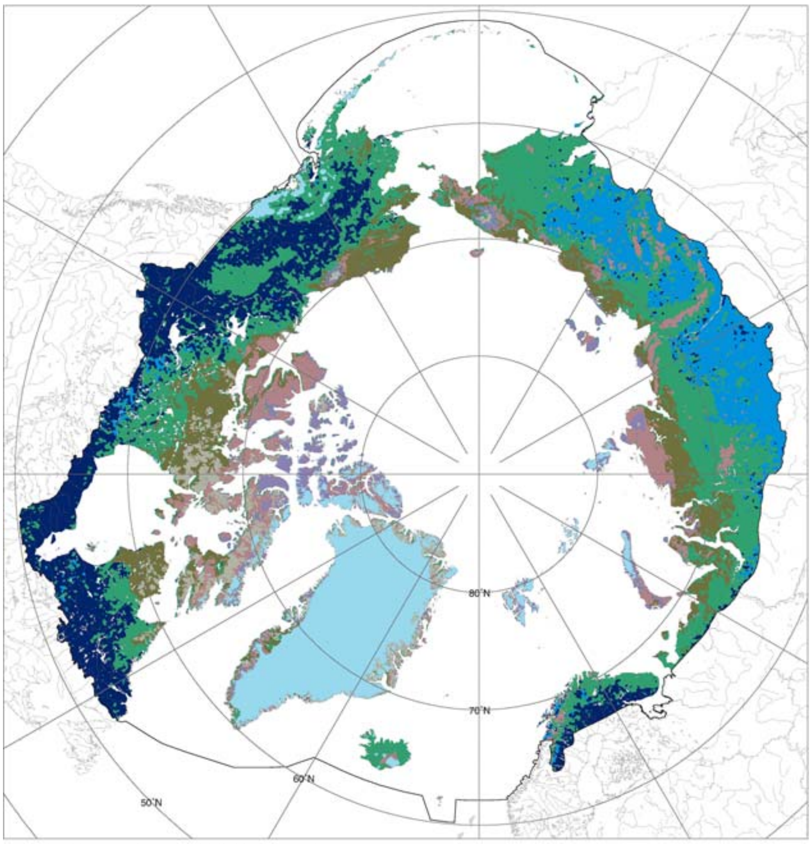

Figure 3. Observed CAVM/GLC2000 Arctic biomes

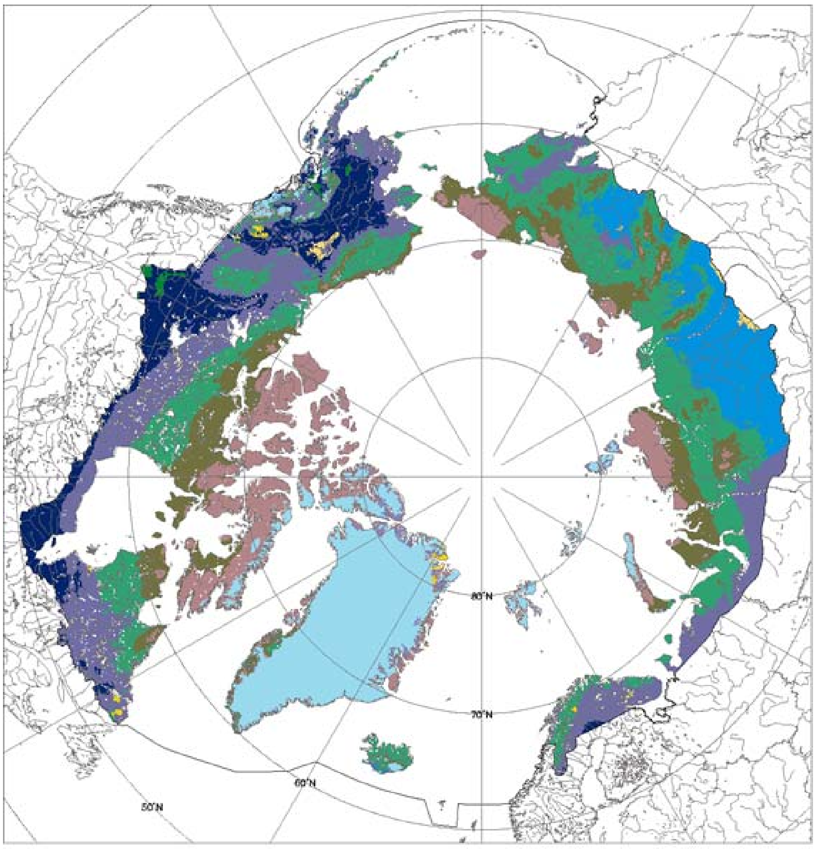

Figure 4. Simulated Arctic biomes at the present-day

Among the tundra biomes, high- and low-shrub tundra matched the observed map at 60.3% of the 10-kilometre grid cells, erect dwarf-shrub tundra at 43.2%, prostrate dwarf-shrub tundra at 40.9%, and cushion forb, lichen, and moss tundra at 26.2%. Major differences between the observed vegetation map and the simulation relate to the widespread observation of barren areas in Keewatin and on Baffin Island that were simulated as tundra vegetation by the model. This discrepancy is a product of the soils data used by the model, where a soil profile was defined for these areas, when in fact much of the area is barren because it is exposed bedrock. Other areas of disagreement include the under-simulation of the area of cushion forb lichen and moss tundra in the far northern Canadian archipelago, where prostrate dwarf-shrub tundra is simulated instead. A general lack of temperature-measuring stations in this region (New et al. 2002; Kaplan et al. 2003) may be responsible for warmer than actual temperatures in the driver data set, which would favour the shrub tundra over cushion forbs, lichen and moss tundra, which is found in only the harshest environments. Finally, the model tended to underestimate the area of prostrate dwarf-shrub tundra and cushion forb lichen and moss tundra in mountain regions, particularly in eastern Siberia.

3.2 Potential future changes under a global 2°C warming

In four scenarios illustrating a global 2°C warming, the potentially forested area of the Arctic increases significantly (Table 1). The increase in forest area ranged from ca 13% to nearly 90%, with a mean value approaching an increase in area of 9×10^6 km^2. Forests reach the Arctic coastline in all but the 10th percentile “cold” simulation (Figures 5-8). Trees are shown potentially invading Greenland and Chukotka, where only fragments of forest exist today (Table 2). In the 90th percentile “warm” simulation, the area of cold deciduous forest is strongly reduced by replacement with evergreen forests (Figure 9), a result also found in other studies (Cramer et al. 2001; Kaplan et al. 2003). In the three warmest scenarios, there is a large increase in temperate forest area in the Arctic, concurrent with expansion of the cold forest types; the overall expansion in forest area is largely at the expense of the tundra.

Table 1. Global changes in Arctic biome area.

	Forest		Tundra		Other	
	km^2 x 1000	% change	km^2 x 1000	% change	km^2 x 1000	% change
Present	5591.6		7366.2		136.5	
10th percentile “cool”	6314.5	12.9	6659.2	-9.6	120.6	-11.6
Robust mean	8710.3	55.8	4275.0	-42.0	109.0	-20.1
Mean	8839.2	58.1	4148.1	-43.7	107.0	-21.6
90th percentile “warm”	10485.7	87.5	2455.9	-66.7	152.7	11.9

Table 2. Percentage changes in Arctic biome area by region. Change in forest area in Greenland is very high because the small area of forest simulated in the control simulation (200 km^2).

	10th percentile “cool”		Robust mean		Mean		90th percentile “warm”	
	forest	*tundra*	*forest*	*tundra*	*forest*	*tundra*	*forest*	*tundra*
Alaska	5.1	-12.6	24.4	-64.9	24.7	-66.7	25.9	-86.7
Mackenzie	5.9	-19.9	15.1	-50.9	15.8	-53.3	24.8	-83.5
Keewatin	5.0	-1.6	38.2	-12.1	42.3	-13.4	103.6	-32.8
Labrador	7.0	-4.7	50.1	-37.9	52.7	-39.9	80.4	-61.5
Greenland	3000.0	-7.7	19050.0	-17.4	20050.0	-17.8	40200.0	-34.3
Atlantic	11.9	-7.2	236.5	-44.5	251.6	-44.8	511.9	-73.1
Western Europe	18.2	-42.2	37.2	-88.1	37.5	-88.9	38.8	-99.6
Eastern Europe	-21.0	27.7	50.7	-66.6	52.0	-68.4	62.8	-82.6
Western Siberia	36.9	-14.8	154.9	-62.3	158.9	-64.0	229.4	-92.3
Taymyr	37.4	-28.1	81.3	-61.1	82.1	-61.7	102.8	-77.3
Lena	25.7	-56.2	38.1	-100.0	38.1	-100.0	38.1	-100.0
Eastern Siberia	31.3	-10.9	149.0	-52.4	157.5	-55.6	240.6	-87.7
Chukotka	-29.9	8.6	123.3	-37.1	131.2	-39.5	239.7	-72.0

The 2°C warming experiments show major northward shifts of the shrub-dominated tundra biomes, with major reductions in the total area of erect and prostrate dwarf-shrub tundras, in many cases below $1\text{x}10^6$ km^2 (Figure 10). Cushion forb, lichen and moss tundra is nearly extinct in all but the coldest scenario. The tundra biomes become restricted to coastal and mountainous areas of the Arctic, disappearing almost completely from regions such as Western Europe and the Lena River valley, and with significant reductions in Alaska, Eastern Siberia, and the Mackenzie drainage. The area of cold parkland is reduced in the three warmest scenarios, mostly at the expense of forest, though in some areas with steep climatic gradients such as along coastlines, the cold parkland is reduced in favour of a sharper gradient between forest and tundra.

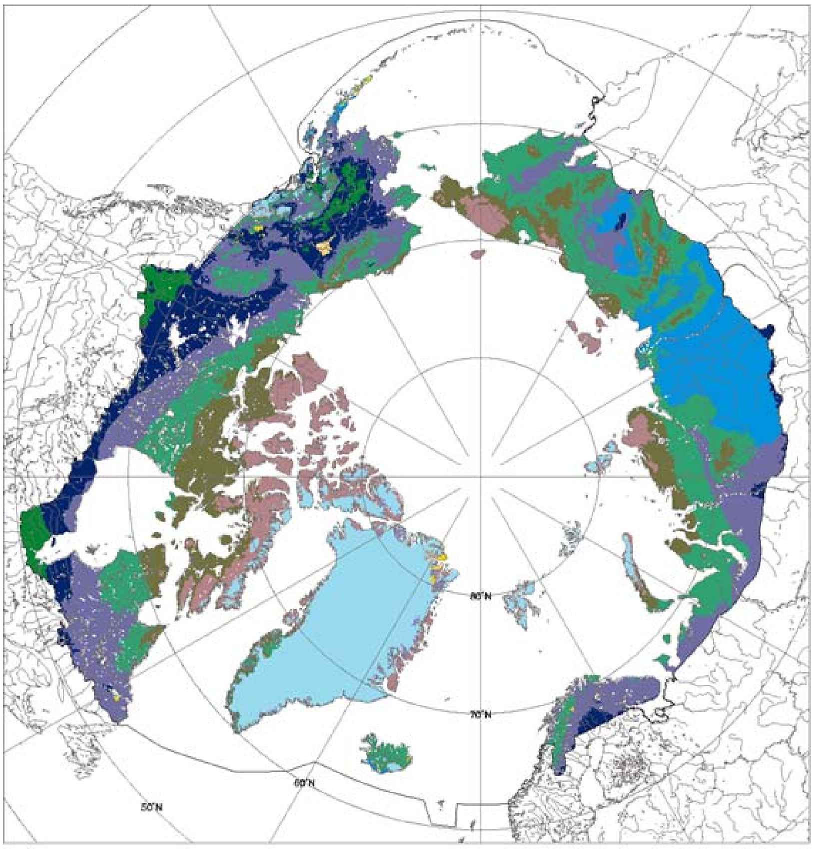

Figure 5. Simulated Arctic biomes under 10th percentile "cool" scenario

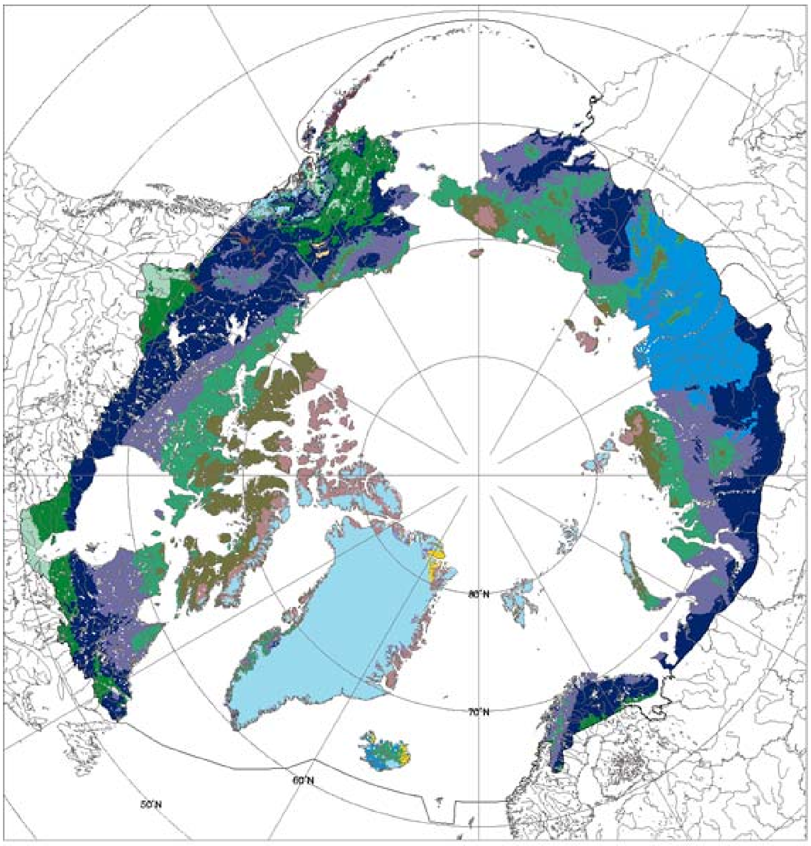

Figure 6. Simulated Arctic biomes under the robust mean scenario

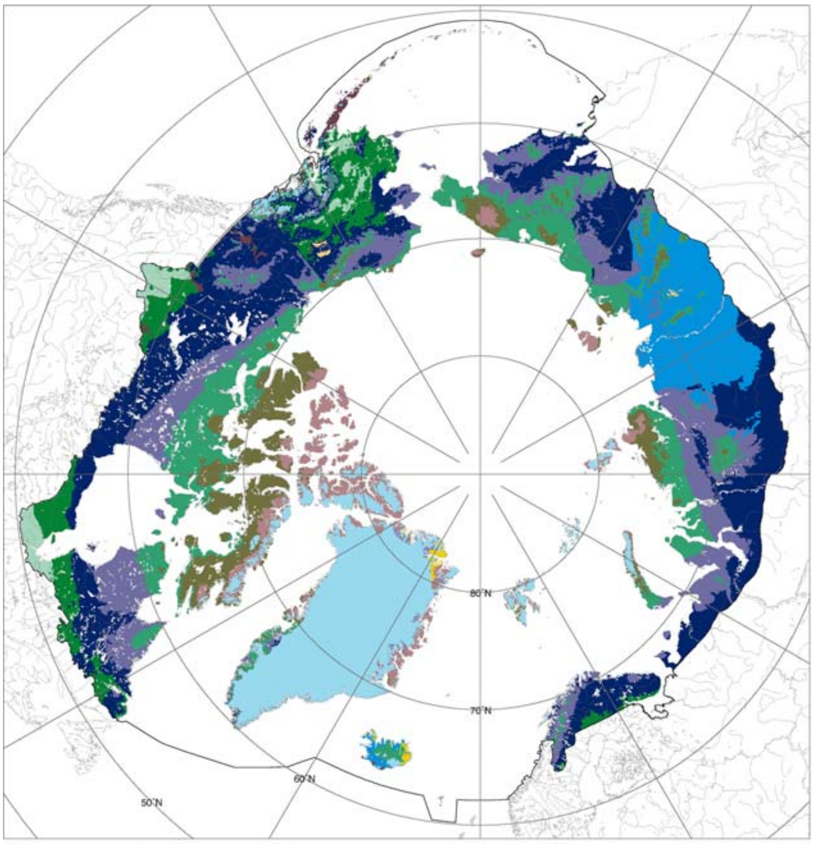

Figure 7. Simulated Arctic biomes under the mean scenario

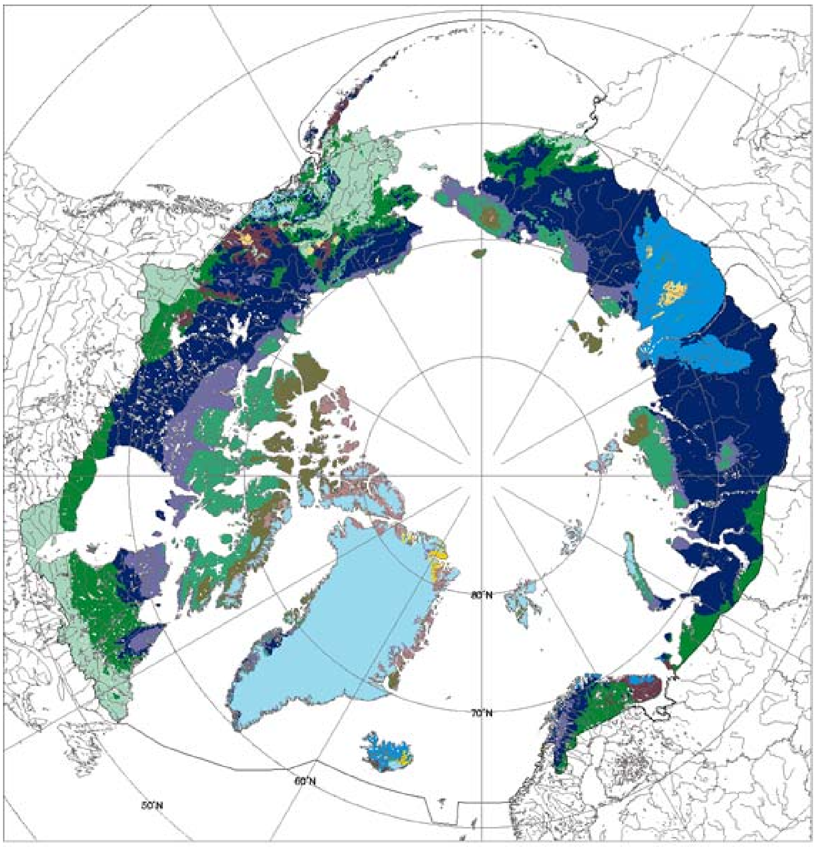

Figure 8. Simulated Arctic biomes under 90th percentile "warm" scenario

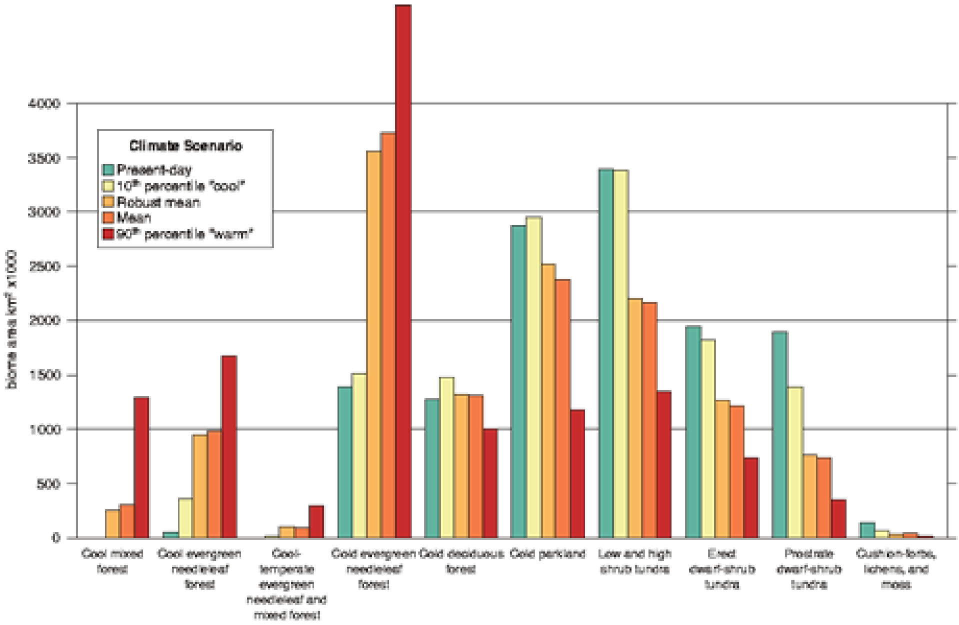

Figure 9. Area of Arctic biomes at present and under 2°C warming scenarios

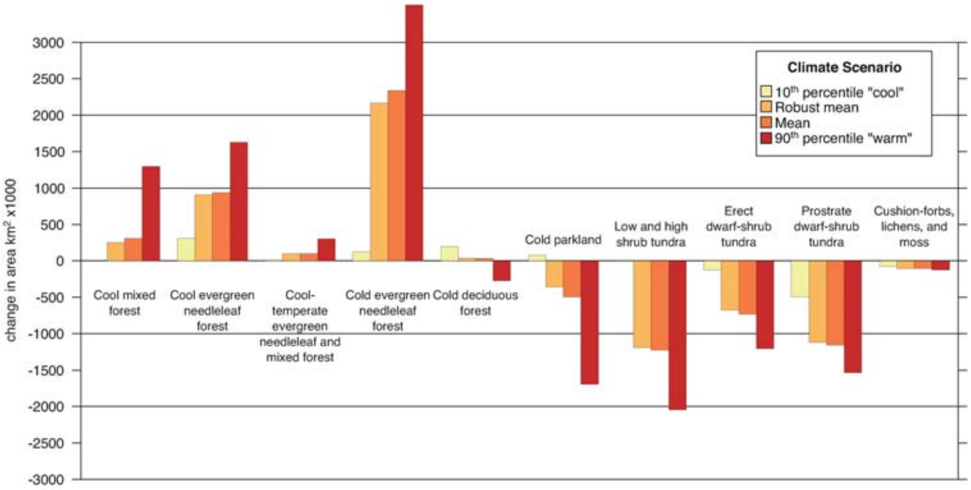

Figure 10. Area change of biomes under 2°C warming scenarios

4 Discussion

4.1 Present day

BIOME4 captures the main features of vegetation distribution in the Arctic region: the position of the northern forest limit, its composition in terms of evergreen versus deciduous trees, and the observed diversity and geographic extent of tundra vegetation types. In those regions where the model incorrectly simulates forest, primarily in hyper-maritime southwestern Alaska and in Chukotka, the influence of cool summer temperatures, permafrost, and waterlogged soils may suppress the growth of trees in a way that is not accounted for by the model. Future versions of the BIOME model will include simulation of wetlands and permafrost and may alleviate this discrepancy.

The boundary between prostrate dwarf-shrub tundra and cushion forb, lichen, and moss tundra seems to be misplaced in the Canadian Arctic archipelago, this may be a product of very sparse meteorological data in this region. Farther south, large areas observed to be barren bedrock are simulated as dwarf-shrub tundra types by the model; this discrepancy is caused by the soils data used to drive the model, which indicates the presence of soil where there is none. Work to improve circumpolar soils mapping is ongoing, and new soils maps may lead to better predictions of barren areas in Canada.

4.2 Effects of potential future climate change on Arctic vegetation

4.2.1 Invasion of new habitat and loss of original habitat

Forests invade a great deal of the Arctic in the scenarios of global 2°C warming, largely at the expense of tundra area. Cold evergreen needleleaf forests become the dominant biome in the Arctic in all but the coldest scenario, at the expense of all of the tundra types, but particularly the shrub tundras. In the most extreme warming scenario, tundra area is reduced to less than half its present-day extent. These changes in habitat are likely to have far-reaching consequences for animal and plant distributions and ecologies, human activities in the Arctic, and important feedbacks to the climate system. Increased forest area will lead to decreases in surface albedo and the changes in hydrologic regime. Shading of snow cover and protection from wind by forest canopies could cause later retention of snowpack into the spring and summer, and altered Arctic stream-flow patterns. The greater retention of long-wave radiation by forest compared to tundra is likely to increase the summertime depth of the active layer in permafrost regions and promote permafrost melting.

4.2.2 Species-level responses

Much of the difference between the cold forest and temperate forest types simulated in the 2°C warming scenarios will presumably result in the appearance of different tree species in existing forest area, though there will almost certainly be time lags associated with migration and establishment. While BIOME4 is not capable of simulating the presence or absence of particular tree species, it is likely that cool-temperate forest trees will become a part of the boreal forest mix. On the other hand, deciduous needleleaf tree species in the coldest parts of the Arctic, particularly *Larix spp*. in eastern Siberia are likely to diminish in importance when increased minimum winter temperatures and increase summer precipitation allow favorable conditions for the development of evergreen forests.

Tundra biomes likewise undergo changes in shrub species composition, as taller shrubs are favored under a warmer climate. However, phenotypic plasticity, e.g. among *Salix spp*., may preclude a shift to new species where plants rather take on a different growth form. Also, species distributions in the Arctic are often influenced by substrate (bedrock) chemistry (CAVM-Team 2003). In these areas, major shifts in tundra species composition would be unlikely to occur, and we would expect to see changes in vegetation density and productivity.

Increased biodiversity would also be a likely effect of future warming. Seen in these simulations as the appearance of temperate forest biomes in the Arctic, taxa from more species-rich ecosystems would move northward and augment (or supplant) existing species. However, these increases in species richness might be accompanied in the long term by extinctions of the original cold-adapted taxa as their habitat areas decrease in area.

4.2.3 Adaptive capacity of plants in relation to absolute and rate of climate change

In the 25-60 year time period to reach Y2C predicted by the model/scenario ensembles used here, it is unlikely that the development of new biome types, particularly forests, would be fully realized despite the climate change. Establishment and growth of trees at their climatic limit is expected to take 200-300 years (Chapin & Starfield 1997; Cramer et al. 2001). A time lag on this order has been shown in an experiment of vegetation change in the Arctic using the LPJ dynamic global vegetation model (Kittel et al. 2000). The simulations presented here therefore represent the potential state of Arctic vegetation after some transition period if stabilization of climate change could be achieved with 2°C global warming.

Under rapid climate change, we would also expect vegetation associations with no modern analogue to form temporarily during and after the transition period, as some smaller-scale studies have reported (Chapin & Starfield 1997; Epstein et al. 2000). Such phenomena could be investigated using fully coupled GCM-dynamic vegetation models.

4.3 Implications of vegetation responses in large-scale processes

4.3.1 Ecosystem structure and function

The major shifts in biome distribution in the Arctic simulated here are likely to be concurrent with changes in the physiology and structure of ecosystems, with longer growing seasons leading to enhanced annual productivity. Warmer climate and increasing CO_2 concentrations would likely also lead to increase density in forest canopies and faster nutrient cycling (Melillo et al. 1993; Oechel et al. 1994; Chapin et al. 1995b; Oechel et al. 2000). Changes in species composition in forest and tundra will lead to increased water use and the development of more complex multi-layered tree and shrub canopies. While a previous study with the same vegetation model found that the simulated direct physiological effect of CO_2 in northern vegetation types was small compared to the climate effect, the synergistic interaction of climate and CO_2 is likely have a stabilizing effect on the water use of northern vegetation, particularly in the driest regions, e.g. eastern Siberia and parts of Alaska. This result is seen in the general persistence of forest cover in these dry regions; in all but the warmest scenario, increases in the area of xerophytic biomes such as grasslands and shrublands were negligible.

4.3.2 Biophysical feedbacks to the climate system: changes in energy balance and albedo

Vegetation-atmosphere interactions may be important in determining the future climate of the Arctic (Oechel & Vourlitis 1994; Sturm et al. 2001a) and globally. Changes in the forest tundra transition in the order of those simulated here for the future had impacts on global climate at the mid-Holocene, where a modelling study showed increased north Asian tree cover reduced northern hemisphere equator-pole heat transport and even influenced southern hemisphere climate (Lynch et al. 2003). Levis et al. (2000) showed that vegetation feedbacks under a doubled-CO_2 climate could produce an additional 3 K warming during spring (April-May) in the region north of 60°N. Because the GCM simulations used to drive the vegetation model here did not include interactive, dynamic vegetation, this positive feedback would further increase temperature anomalies compared to those presented here. On the other hand, particularly in the warmest scenario, a shift to grassland or deciduous forests resulting from drier conditions and increased fire frequencies could cause negative feedbacks to warming through increased albedo and increased surface roughness (Chapin et al. 2000). Most of what is presented here does not indicate this type of vegetation change taking place. But longer-term climate change with more arid conditions, e.g. those under doubled CO_2 concentrations, could shift the balance towards these more xerophytic vegetation types.

4.3.3 Biogeochemical feedbacks to the climate system: changes in greenhouse gas sources and sinks

In a sensitivity study, I used the LPJ-DGVM to develop a simple but robust regression model relating NPP to carbon storage in plants and soils. Using this model, I estimated steady-state biomass simulated by BIOME4 in the control and 2°C warming scenarios. Carbon storage in plants and soils calculated by BIOME4 roughly doubles in the Arctic in the 2°C warming experiments compared to the present-day simulation, with a total potential increase of ca 600 Pg C in the robust mean and mean experiments, and over 1000 Pg C in the 90th percentile “warm” scenario. The increase in forest area and productivity is mainly responsible for these large changes in carbon storage, though shifts to taller and more dense tundra types will also sequester more carbon both above and below ground.

As discussed earlier, the time lag associated with the development of forests makes it unlikely that the increase in carbon storage in the Arctic will be fully realized over the next century. Also not included in this study is the possibility of large releases of carbon from frozen tundra peatlands, where typically a small percentage of annual vegetation productivity is sequestered into permafrost. Expected warmer year-round temperatures could induce widespread thawing of frozen soils, which could indeed be responsible for large releases of CO_2 from the Arctic landscape in the short term (Christensen et al. 1999). On a time scale of several centuries, however, development of forests and forest soils in areas that are currently occupied by tundra will significantly increase the amount of carbon sequestered in the Arctic.

5 Conclusions

The results presented here suggest that high-latitude ecosystems are sensitive to increased radiative forcing of climate due to increases in greenhouse gas concentrations. Palaeodata-model comparisons with the same classification scheme and vegetation model give confidence in the ability of the modelling procedure to simulate the potential consequences of greenhouse gas forcing for climate and vegetation in the Arctic. The four global 2°C warming experiments performed here all show dramatic changes in the landscape of the Arctic, with forests occupying much of the area of the Arctic covered by tundra today. Tundra distributions also change, with reductions in the area of the most extreme tundra types until near extinction in as little as a few decades. Biophysical implications of this vegetation change include reduced albedo, which would have important feebacks to the atmosphere, and changes in hydrological regimes because of increased snow retention. The increase in forest area in the Arctic would eventually be responsible for a large increase in carbon storage, though this may be offset by the thawing and oxidation of currently frozen organic soils. The changes in Arctic vegetation simulated here would almost certainly have ramifications for biodiversity, effects on animal populations and human activities.

Further work should include vegetation-atmosphere coupling, allowing for the different physical properties in different vegetation types (including the major differences among the tundra types). The tundra classification used here could provide an initial basis for quantifying these properties. Additional studies should also address the transient nature of the climate change, accounting for development of vegetation, pedogenesis and permafrost dynamics.

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IMPACT STUDIES OF A 2°C GLOBAL WARMING ON THE ARCTIC SEA ICE COVER

JOSEFINO C. COMISO*

Abstract

The possible impact of an increase in global temperatures of about 2°C, as may be caused by a doubling of atmospheric CO_2, is studied using historical satellite records of surface temperatures and sea ice from the late 1970s to 2003. Updated satellite data indicate that the perennial ice declined at rate of 9.2 % per decade, which is faster than previously reported, while concurrently Arctic surface temperatures have steadily been rising, except in some parts of northern Russia. Surface temperature is shown to be highly correlated with sea ice concentration in the seasonal sea-ice regions. Results of regression analysis indicate that for every 1ºC increase in temperature, the perennial ice area decreases by about 1.48×10^6 km^2, with the correlation coefficient being significant but only -0.57. Arctic warming is estimated to be about 0.46ºC per decade on average, but is shown to be off-centre with respect to the North Pole and prominent mainly in the western Arctic and North America. The length of melt has been increasing by 13 days per decade over sea-ice areas, suggesting a thinning in the ice cover. The length of melt also increased by 5 days per decade over Greenland, 7 days per decade over the permafrost areas of North America, but practically not at all throughout Eurasia. Statistically derived projections indicate that the perennial sea-ice cover would decline considerably in 2025, 2035, and 2060 when temperatures are predicted by models to reach a 2ºC global increase.

1 Introduction

The Arctic has been referred to as a “battleground” for climate change research because of possible amplification of a global change signal in the region (Budyko 1966). A large fraction of the region is always covered by ice and snow, the reflectivity (or albedo) of which is high compared to that of open ocean and some other land surfaces. The ice and snow cover is also an effective insulator that limits the exchange of heat and energy between the surface and the atmosphere. Moreover, the ice and snow cover is especially sensitive to slight changes in surface temperature, especially when the surface is at near melting temperatures. In this context, increases in surface temperature mean earlier onset of melt, delayed onset of freeze-up and, therefore, thinning or earlier disappearance of the snow and ice cover. Amplification of a global change signal in the Arctic on account of the high albedo and insulating capacity of the surface has been confirmed in numerical models (Manabe et al. 1992) and has been estimated to range from two to four times the global change depending on model and model configuration (Holland and Bitz 2003; also companion paper by New).

The last decade has been observed as the warmest since the beginning of the 20th century, with the years 1998 and 2002 being the two warmest years. Such a trend in temperature has been associated with anthropogenic greenhouse warming (Hansen 2004). The Arctic has indeed been showing signs that significant changes are occurring. The mountain glaciers have been retreating, permafrost has been thawing, snow cover has been diminishing, the Greenland ice sheet has been thinning and the Arctic sea ice cover has been declining (Comiso and Parkinson 2004). Using the long-term meteorological data available from several stations (Jones et al. 1999), the average surface air temperatures at latitudes greater than 60°N in the last 20 years have been shown to be increasing at a rate that is eight times higher than that of the last 100 years (Comiso 2003). This is in part caused by unusually warm temperatures during the 1930s. However, the latter is a more isolated warming confined to parts of the Northern Hemisphere, while the warming in the last 25 years appears to be more global in scope (M. Serreze, personal communication, 2004). A study by Johannesen et al. (2004) that made use of in situ surface temperature data concurrently with a numerical model also suggested that the warming episode earlier in the century was part of the natural climate variability while the more recent warming signal was a response to anthropogenic greenhouse forcing.

A doubling of CO_2 could mean an increase in global surface temperature of about 1° to 2°C, according to a comparative study by Holland and Blitz (2003) and New (2004), who made use of results from several Global Circulation Models (GSM). A 2°C increase would lead to an amplified

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increase of between 3° to 8°C in the average surface temperature of the Arctic. In this paper, we make use of historical satellite temperature and sea ice data and updates of the analyses presented in Comiso (2002) and Comiso (2003) to study the possible effects of increases in temperatures of these magnitudes to the extent and area of the sea ice cover. The lack of good agreement of the results of the different models is an indication that at least some of the numerical models need to be enhanced before they can be used to accurately predict the future state of the Arctic sea ice cover. There are a few models that match observational data much better than others (Johannessen et al. 2004), suggesting progress in the right direction. Nevertheless, we can gain unique insights into the actual state of the Arctic from satellite observational data which provide first-hand information on how the system has been changing over the last 25 years from day to day.

2 Satellite Infrared and Passive Microwave Observations

Satellite infrared and passive microwave sensors have provided continuous records of surface temperature and ice concentration, respectively, in the polar regions since the late 1970s (Parkinson et al. 1999; Comiso 2003). Data from these types of sensors are especially useful for large-scale seasonal, annual, and spatial variability studies because of synoptic coverage at a relatively high temporal resolution. Infrared data are noted for day/night coverage during cloud-free conditions at a moderate resolution (1-5 km) while passive microwave data provide day and night, virtually all-weather coverage with a relatively coarse resolution (about 25 km). The effect of coarse resolution in the latter is minimized through the use of an ice algorithm that estimates the fraction of open water within the field of view of the satellite. Both data sets went through a similar history of research development and have basically the same record lengths.

The monthly distributions of surface temperature and sea ice cover show the annual cycles associated with the change in seasons. There are other periodic patterns and phenomena, like the Northern Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) in the Arctic region (Venegas and Mysak 2000; Thompson and Wallace 1998) but the behaviour of the associated indices is not predictable, and unexpected shifts in the phases of these cycles can occur (Overland et al. 2002). Since our satellite record is only a little more than two decades in length, we will not do any harmonic decomposition of the data and will simply take into account the strong seasonal cycles when doing trend analysis.

2.1 Changes in Surface Temperature

Before the advent of satellite data, the only source of surface temperature data in the Arctic was from relatively sparse meteorological stations over land and a few Argos buoys on the sea ice (Chapman and Walsh 1993). The recent availability of historical data from a Russian ice station in the Central Arctic and other Russian land stations has enabled an improvement in statistics and led to the construction of interpolated data sets (e.g. IABP/POLES) on Arctic surface temperatures (Rigor et al. 2000, Johannessen et al. 2004) but the accuracy suffers in areas where there is little or no observed data. Satellite infrared data provide surface temperatures at good spatial and temporal resolution during clear sky conditions, and have sufficient accuracy to provide meaningful representation of the horizontal distribution of temperatures in the entire Arctic (Steffen et al. 1993; Wang and Key 2003; Comiso 2003). The longest record of satellite infrared data available is that provided by the Advanced Very High Resolution Radiometer (AVHRR). The lifetime of the sensor is about five to ten years but the record is maintained by having the current sensor replaced by an almost identical new one every time the former shows any sign of degradation in performance. Despite efforts to get the sensors consistently calibrated on the ground, the characteristics of the sensor are normally altered slightly after launch making it necessary to refine the calibration and improve the temporal consistency of the record. This was done through the use of in situ data as discussed in Comiso (2003). For this study, the data record used by Comiso has been updated to include more recent data. The entire data set is also further enhanced by improving on the consistency in the calibration through the use of a more comprehensive set of in situ data and by taking into account non-linearities in the calibration at high temperature values, especially in sub-polar regions.

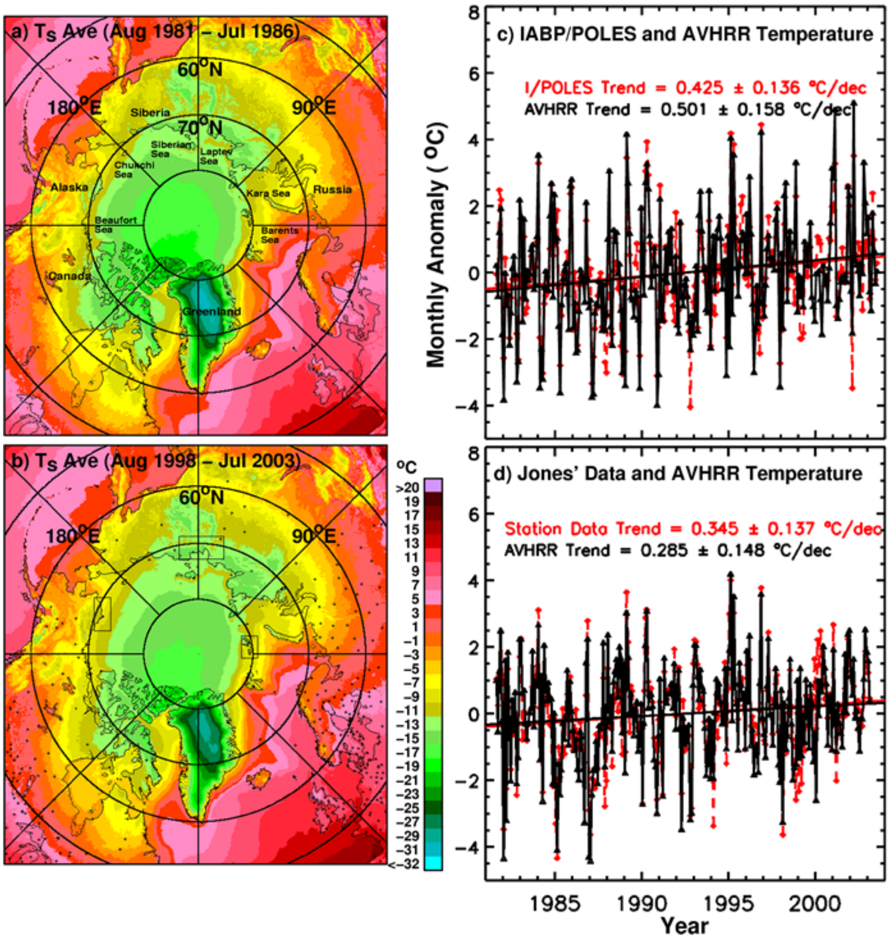

Figure 1. Color-coded maps of average surface temperatures from (a) August 1981 to July 1986 and (b) August 1998 to July 2003. Anomalies and trend results using (c) IABP/POLES data averaged over three locations and the corresponding AVHRR data averaged over the same locations; and (d) combined Jones et al. and Russian and corresponding AVHRR data.

Figures 1a and 1b show color-coded maps of the average of monthly surface temperatures over five-year periods, the first from August 1981 to July 1986 and the second from August 1998 to July 2003. The two maps show striking similarities presenting basically the same general features with the cold regions being consistently in the same areas. The retreat of some of the cold isotherms from the 1980s to the 1990s is, however, apparent, especially in the Central Arctic (e.g. green colours), showing a movement towards warmer temperatures during the two periods. To assess the long term consistency of the AVHRR data set, a comparison of monthly temperature anomalies and trends between the IABP/POLES data set and the corresponding AVHRR data are presented in Figure 1c at three study regions (see rectangular boxes in Fig. 1b) where there are in situ data in the Arctic as described in Comiso (2003). Over the same time period, the variability in the anomalies is similar with the IABP/POLES data showing an overall trend of 0.42 ± 0.14°C per decade, while the AVHRR data show a comparable and consistent trend of 0.50 ± 0.16°C per decade. Figure 1d shows a similar comparison of Jones et al (1999) data, including the Russian data, with AVHRR data (interpolated to the same location as the former) for the entire pan Arctic region (>60°N). The locations of the Jones data are indicated in Figure 1b as black cross marks. Again, the variabilities in the anomalies are consistent while the trends are in good agreement with the Jones data showing 0.35 ± 0.14°C per decade while the AVHRR data shows 0.29 ± 0.15°C per decade. While comparison of point measurements with AVHRR data shows generally consistent patterns and trends, the trend from point measurements do not always reflect the trend over the entire region. For example, the AVHRR and Jones data sets provide comparable anomaly distributions and very similar trend values of 0.4°C per decade in the sampled North American stations but the entire region (>60°N) yielded a trend of 0.8°C per decade, which is twice as high. Excluding open ocean regions, the AVHRR record shows that the Arctic (>60°N) has been warming at the rate of 0.46 ± 0.11°C per decade.

2.2 Changes in Sea Ice Cover

The variability in the extent and area of the sea ice cover in the Northern Hemisphere has been discussed extensively in the literature (e.g. Chapman and Walsh 1993; Bjorgo et al. 1997; Parkinson et al. 1999). These parameters are derived using ice concentration maps retrieved from satellite passive microwave data. By ice extent, we mean the total area of the ice covered portion of the ocean in which each data element has at least 15% sea ice concentration, while ice area is the total area in the ocean that is actually covered by sea ice. The seasonality of the ice cover is quite large with the ice extent ranging in value from a minimum of about 7 million km^2 at the end of the summer to a maximum of about 18 million km^2 during its peak in winter. The corresponding values in sea ice area are 6 million km^2 and 14 million km^2, respectively. Because of the large seasonality, monthly anomalies, derived by subtracting monthly climatologies from the values for each month, are used in annual variability and trend studies.

One of the most remarkable changes in the Arctic is the rapidly retreating perennial ice cover as reported by Comiso (2002). Perennial ice is defined as the sea ice that survives the summer and its extent and area are determined from the ice cover data during the minimum extent at the end of the summer. It consists mainly of the thick multi-year ice floes that are the mainstay of the Arctic sea ice cover. One of the important implications of retreating perennial ice is that as the fraction of multi-year ice floes decreases and the fraction of seasonal ice floes increases, the average thickness of the ice cover becomes thinner and more vulnerable to summer melt.

The study by Comiso (2002) showed that the extent and area of the perennial ice cover have declined at the rates of 6.5% per decade and 8.9% per decade, respectively, from 1978 to 2000. Johanessen et al. (1999) also reported a decline of 7% per decade in the multi-year ice cover observed in winter. More recent data indicate that the trend is ongoing with the perennial ice cover reaching its lowest value during the satellite era in 2002. This is consistent with observations of summer ice by Serreze et al. (2003). Furthermore, the perennial ice cover in 2003 was also nearly as low as in 2002 (Comiso and Parkinson 2004), suggesting that a recovery of the perennial ice cover is not in sight. To illustrate the magnitude of the change, Figures 2a and 2b show the Arctic perennial ice cover during its highest and lowest extents in 1980 and 2002 respectively. The two images show contrasting ice cover with the difference in the perennial ice areas being about 1.6 million km^2, about four times the size of California. Updated versions of the extent and area of the perennial ice cover presented in the Comiso (2002) paper are shown in Figure 2c and with the inclusion of data up to 2003, the extent now declines at 7.1 ± 1.8 % per decade while the ice area declines at 9.2 ± 1.7 % per decade. The errors cited are statistical, with the 95% confidence level being between -11.4% to -3.6% for extent, while the 95% confidence level is between -12.5% and -5.7% for ice area. The persistence of abnormally low perennial ice area since 1998 is intriguing and opens up the question of how long such a trend will continue into the future. Currently available data for 2004 (i.e. as of 12 September 2004) already indicate that the extent and area of the perennial ice cover for 2004 is also a record low and at least lower than that of 2003.

For comparison, Figure 2d shows plots of monthly anomalies of ice extent and ice area in the entire Northern Hemisphere for the period November 1978 through June 2004. Both plots show considerable variability, reflecting annual changes in growth and decay patterns. Linear regression analysis on the data reveals that the extent and area of the entire Northern Hemisphere ice cover have been declining but only at the rates of 2.4 ± 0.2 % per decade and 3.3 ± 0.2 % per decade, respectively. These trends are relatively low mainly because in winter, the ice cover has not been changing much and is even increasing in some areas like the Bering Sea. The annual changes in the ice cover are actually most pronounced in the spring and the summer when changes in surface temperature are also relatively large.

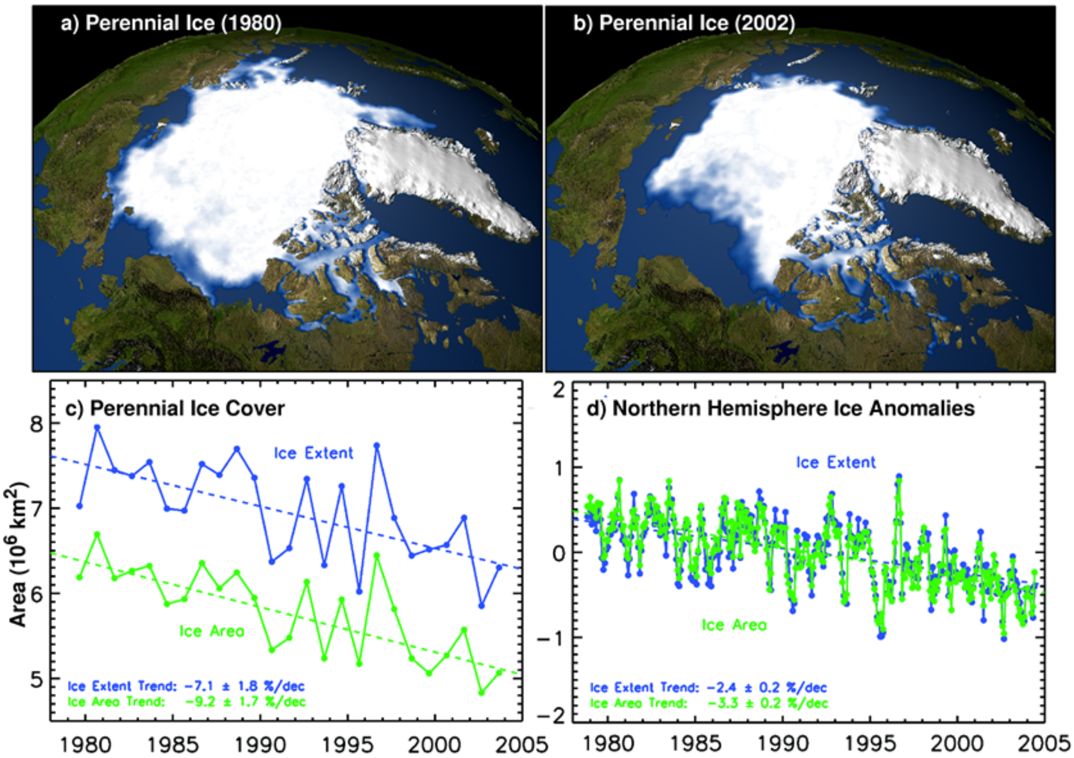

Figure 2. Ice concentration map (in arbitrary scale with white being 100% ice) of the perennial ice cover in (a) 1980 and (b) 2002 with MODIS land cover data used over land surfaces. (c) Arctic perennial ice extent and areas with trend lines and (d) monthly anomalies in the extent (blue) and area (green) with trend lines for the entire Northern Hemisphere.

3 Relationships between Surface Temperature and Sea Ice Cover

It is intuitive to postulate that the observed decline in the sea ice cover is a natural consequence of the observed warming in the Arctic. The availability of coincident and co-registered satellite data of these variables makes it possible to establish the connection quantitatively. However, care in the interpretation of the data is necessary since the available data may be lacking in information content. In particular, we have detailed measurements of the ice extent and area but not of the thickness of the sea ice cover. Since increases in surface temperatures are more impacting to thin ice than to the thicker ice types on a short-term basis, inability to assess the corresponding changes in thickness is a drawback. Furthermore, the influence of temperature on the area of sea ice also has a lag, the length of which depends on ice type and thickness of both ice and its snow cover. The temperature of the sea ice surface is also basically constant during the summer and is almost always near melt temperatures. Thus, annual changes in the ice cover associated with changes in average surface temperature are sometimes not evident in the data until the ice melts out completely. In the other seasons when yearly variations are more likely, the surface can be so cold (except in late spring and early autumn) that even significant changes in temperature would have no effect on the ice area. Moreover, the growth and decay of the sea ice cover is also influenced by many other factors including wind strength and direction, ocean current, and tides. Annual changes in sea level pressure have been observed (Walsh et al. 1996) and changes in the rates of occurrences in storms can alter the vertical distribution of the underlying warmer water (Yang et al. 2004) thereby impacting the sea ice cover. The number of storms and the tracks of these storms have changed in relation to the Arctic and North Atlantic Oscillations, and changes in the NAO may have changed the upper ocean as discussed by Maslowski et al. (2000, 2001). The impact of changing wind directions can also be considerable since wind can cause the advection of sea ice floes to warm water where they melt (Rigors et al., 2002). The observed changes in wind circulation from cyclonic to anti-cyclonic along the Alaska coastline was studied by Comiso et al. (2003) and shown to correlate with large changes in the ice cover from 1996 to 1998.

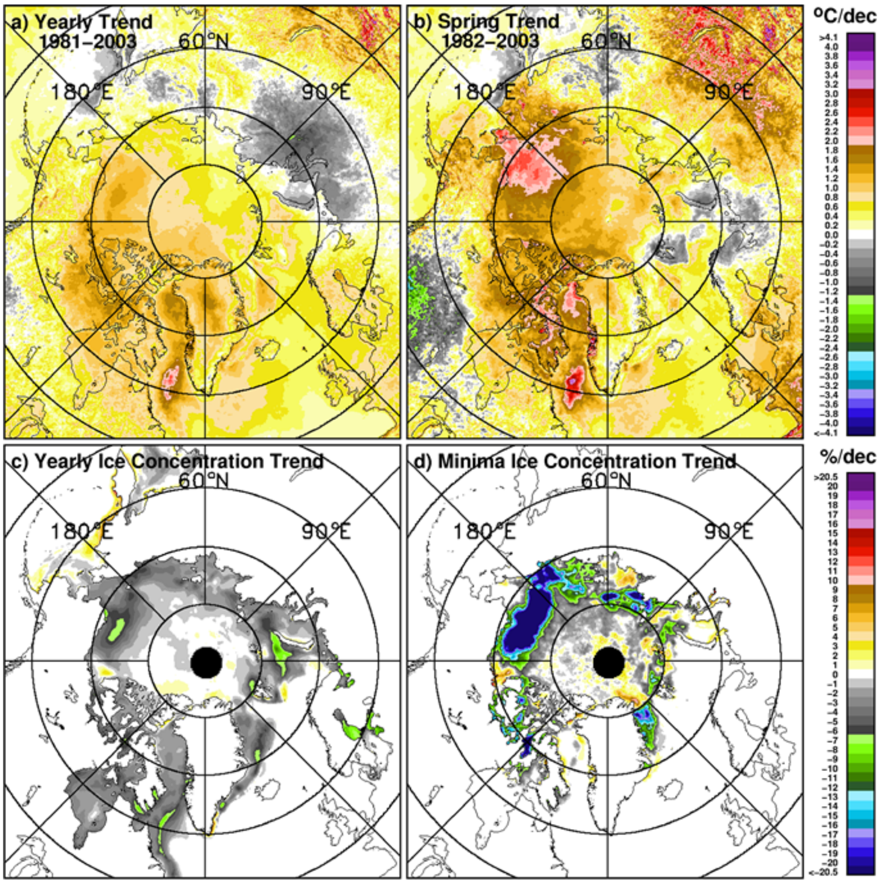

Figure 3. Color coded maps of trends in surface temperature (a) using monthly anomaly data (1981-2003) and (b) during spring (1981-2003); plus trends in sea ice concentrations (c) using monthly anomaly data (1979-2003) and (d) trends in the perennial ice cover (1979-2003).

The trends in surface temperature and sea ice concentration in the Arctic, as observed during the satellite era, are presented in Figure 3. Figure 3a is a spatially detailed representation of trends in surface temperature for the pan-Arctic region inferred from linear regression on the monthly anomalies from August 1981 to July 2003 on a pixel by pixel basis. The map shows a conspicuous lack of uniformity in the distribution of trends. Instead, there is an asymmetry in the distribution with the centre of warming activity being concentrated in the Western Arctic, Northern Canada, and Greenland. More modest trends are apparent in surrounding areas and are even negative in parts of Eurasia. The trend patterns are also different for different seasons, with the average trend in the entire Arctic (>60°N) being highest in spring at 0.81 ± 0.30°C per decade, moderate but significant in summer and autumn at 0.41 ± 0.23 and 0.45 ± 0.28°C per decade, respectively, and lowest and insignificant in winter at 0.27 ± 0.27°C per decade. The errors quoted are just statistical ones and do not include possible systematic errors. The spatial distribution in the trends in spring are shown in Figure 3b with those in North America and Western Arctic being considerably more enhanced than those of the yearly trend.

To gain insights into the possible relationships of surface temperature with the sea ice cover, Figure 3c shows the trend maps in the yearly ice concentration over the same period while Figure 3d shows the corresponding trends in the perennial ice cover as observed during ice minima in September for each year. Qualitatively, the patterns are coherent in that areas showing positive trends in temperature are generally in areas showing large decreases in ice concentration. The large positive trends in surface temperatures are in part caused by more open water surfaces in later years due to the retreat of the perennial ice cover. In some areas as in the Eastern Bering Sea (60ºN, 180ºE), where there is a slight cooling, the ice cover is also increasing. The trends in the ice concentration of the perennial ice cover show more dramatic decline than those for the yearly averaged ice cover,

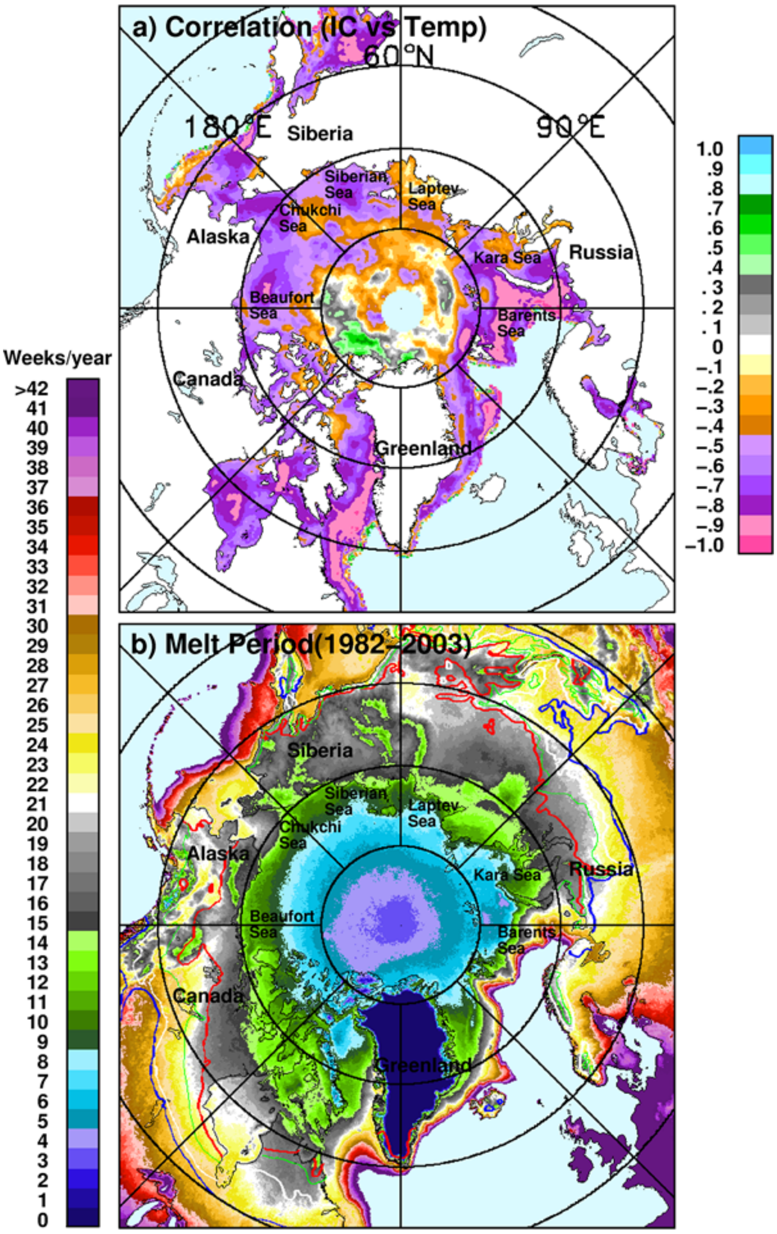

Figure 4. Color-coded maps of (a) correlation coefficients from regression analyses between ice concentration and surface temperature using yearly data from 1981 to 2003; and (b) climatological average (1982-2003) of the length of melt derived for each year by using weekly temperature data. The contour lines represent boundaries of sporadic (blue), discontinuous (green) and continuous (red) permafrost as inferred from UNEP data.

especially in the Western Arctic. It is also apparent that the ice trend is most negative in areas where there is a significantly enhanced warming in spring. In Figure 3c, sea ice concentration is shown to be increasing along the Canadian side of the Arctic Ocean where surface temperature is shown to be increasing. This may be an example of the effect of winds packing ice against coastal areas.

The correlation of monthly sea ice concentration with monthly surface temperature on a pixel-by-pixel basis, is generally strong as illustrated by the correlation map between these two variables as presented in Figure 4a. The correlations are especially high in the seasonal sea ice regions (the correlation coefficients being mainly negative and greater than 0.7) where the ice is relatively thinner than other areas. As expected, the correlation is not so good in the perennial ice region and sometimes even positive where thick ice floes are packed together and do melt completely and cause a change in ice concentration as the surface temperature goes above freezing. In the open water areas in the

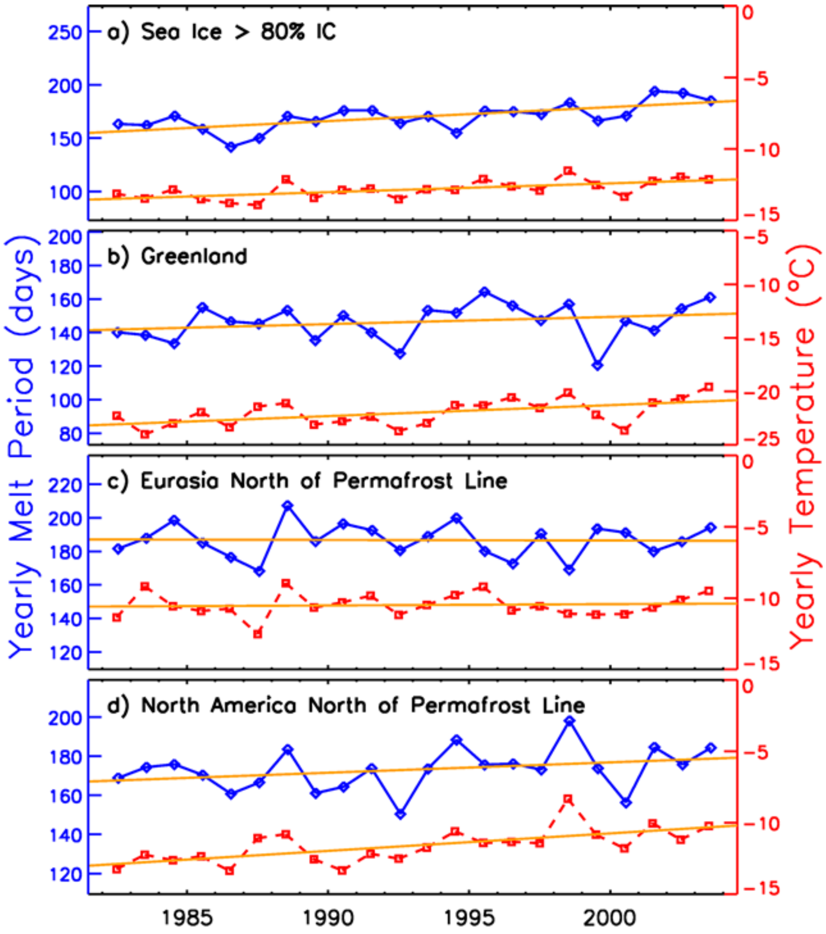

Figure 5. Yearly lengths of melt (in blue) over (a) sea ice (ice concentration >80%); (b) Greenland; (c) north of discontinuous permafrost in Eurasia; and (d) north of discontinuous permafrost in North America. The plots in red are yearly averages (January to December) of surface temperature for each year.

summer, there is also a slight bias since the concentration does not change as the surface temperature goes up by a few degrees C.

The length of melt period is also considered as an important factor affecting the sea ice cover, especially that of the ice thickness (Hakkinen and Mellor 1990; Laxon et al. 2003). Figure 4b shows the spatial distribution of the length of the melt period on average, using 1981-2003 AVHRR data. The length is minimal in Greenland, very low at the North Pole and vicinity, and increases progressively to the south. The trend map of the length of the melt period (not shown) indicate patterns similar to those of Figure 3a. To assess the trend in the length of the melt period, the areas with temperatures above freezing were calculated for each week and plotted as a function of time for each of the general regions: sea ice, Greenland, and in the discontinuous permafrost areas of Eurasia and North America (see red line). The width (i.e. 2σ) of the approximately Gaussian distribution of the areas for each year is estimated by fitting a Gaussian to each of the yearly distributions. Twice this width is used as a measure of the length of melt, as was done in Comiso (2003) and the results are presented in Figure 5. The length of melt is shown to be increasing at a relatively high rate of 13.1 days per decade for sea ice. This result is different from previous estimates for sea ice (e.g. Comiso, 2003) in that ocean areas that become ice-free in spring and summer are included in the analysis. The relatively high value is probably an important reason for the current rapid decline of the perennial ice cover. The length of melt is also observed to be increasing at 4.1 days per decade over Greenland, and 5.4 days per decade over the discontinuous permafrost areas in North America. In Eurasia, however, a slight but insignificant decrease of -0.3 days per decade is observed over the discontinuous permafrost region. It appears that the permafrost regions in North America are more vulnerable to thawing than those in Eurasia.

4 Regression studies of temperature and the perennial ice cover

To minimize a possible bias associated with the near constant temperature of open water within the ice pack, surface ice temperatures are calculated only for surfaces with sea ice concentrations greater than 80% when we evaluate the averages over the sea ice cover. This threshold was used instead of a higher value to allow for a more comprehensive study area and better statistics. The results actually yielded similar correlation values when the threshold was increased to greater than 90% or even higher. The resulting relationship is that for every 1°C increase in yearly temperature, the perennial ice cover decreases by 1.48×10^6 km^2. Such a result is intriguing considering that the decrease corresponds to about 30% of the area of the perennial ice cover in 2002. It should be noted, however, that while the correlation between surface ice temperature and the perennial sea ice cover is significant, it is not very strong, the correlation coefficient being only -0.57. This result implies that only 32% of the variations in the perennial ice cover are accounted for by a linear relationship with surface temperature. Correlation analyses, using summer and spring temperatures only, did not yield better results, the correlation coefficients being -0.56 and -0.51 respectively. The correlation with the winter temperature is significantly weaker, with the correlation coefficient being -0.22. Similar correlation analyses were also done using different combinations and time lag analysis, but the results show even weaker correlations with the highest correlation coefficient being only around -0.3. As pointed out earlier, the lack of a stronger direct relationship between surface temperature and the perennial ice cover is associated with the complexity in the system as discussed in the following section.

5 Feedback Effects, Modeling Studies, and Projections

The ice-albedo feedback has been cited as one of the most important feedbacks in the Arctic, especially since 42% of the greenhouse warming in the region has been attributed to this feedback by models. More specifically, as the perennial ice cover retreats, the effective albedo of the Arctic region decreases due to more open water and melt ponds, causing the absorption of more solar energy, causing a warmer ocean and ice surface that in turn causes more melt and a further retreat of the ice cover. Also, as the Arctic warms, the length of the melt period increases, hastening further thinning and decline in the ice cover. Furthermore, as the ice gets thinner, break-ups becomes more frequent, throughout the year, causing the formation of more leads that causes the release of more heat to the atmosphere that in turn causes warmer air temperature. Such processes will continue until there is a drastic reversal in temperature and wind patterns. The restoration of the perennial ice cover would require sustained cooling, especially in the summer, to allow for more of the thinner seasonal ice cover to survive the summer and become multi-year ice. There are other feedbacks that are relevant, such as cloud feedbacks, the sign depending on whether the clouds are low (which causes a cooling) or high (which causes a warming) as discussed by New in the companion paper. The ice-albedo feedback as applied in the Beaufort, Chukchi, and Siberia Seas, however, requires special attention, because of the abnormally large open water areas in the late summer in the region during the last three years (2002 to 2004).

Many advances in GCMs have occurred in recent years but it is apparent that more work needs to be done, as suggested by the lack of consistency in the predictions of different models (Holland and Bitz 2003; companion paper by New). The problem is that there are too many physical processes that need to be accounted for, and the different parameters for these processes set by models inevitably lead to different results. To cite a specific problem, the Arctic system is especially sensitive to the thickness of sea ice and hence the model whose sea ice cover is thin compared to those of others would have more sensitivity to greenhouse warming. Until the different models use similar ice thickness distributions, which is currently not the case (Holland and Bitz 2003; companion paper by New), they are not expected to provide identical results. It is encouraging, however, that all the models predict an amplified warming in the Arctic, and some results are comparable with those of observations (Johannessen et al. 2004).

The AVHRR data indicate that the Arctic region has been warming at the rate of about 0.46°C per decade. Regression results also yielded that for every degree change in temperature, the perennial ice cover declines by 1.48×10^6 km^2. If the amplification in the warming is known, it is straightforward to estimate the magnitude of the retreat in the perennial ice cover if the change is linear. But the rate of warming has been changing, being lower at the beginning of the last century and significantly higher in the last decade. In this study, we will use the results of New (companion paper) which are based on more the recent modelling study, that provide us with more specific dates when a doubling in CO_2 occurs. According to New, a 2ºC global warming is projected by models to occur between the years 2026 to 2060.

To obtain an assessment of how the sea ice cover might be impacted during this time period, we make use of the statistics derived from 25-years of continuous and spatially detailed satellite data. A similar assessment was done in Comiso (2002) to get a forecast for the perennial ice cover in 2050. The technique we use for this current study is slightly different from the decadal projection used in the Comiso (2002) study. Our method is still relatively crude and simple and our assumption of a linear trend probably not valid. However, the near-term projections may produce a more realistic representation of nature than is currently predicted by models. For the longer term, adjustments in the dates may be necessary because of non-linear effects and the possibility of a rebound.

The satellite ice-concentration maps during ice minima were used to assess the movement of the marginal ice zone at longitudes a degree apart. Along each longitude, the ice edge is identified and the trend for the northward advance of the ice edge is calculated using linear regression techniques. Five-year running averages were used to minimize the noise and a smoothing is done on the results to minimize large changes in the trend from one longitude to another. Except for the region north of Greenland and the adjacent part of the Canadian archipelago where the ice edge is basically adjacent to land, the resulting trend values are used to make the projections.

The current five-year average for the perennial ice cover (i.e. from 1999 to 2003) is presented in Figure 6a. Starting with this 5-year average (representing 2001), a projection for the future of the perennial ice cover is done using results from the trend analysis on the ice edge/marginal ice zones. Figures 6b to 6d provide our projection of how the perennial ice cover might look like for the years 2025, 2035 and 2060. In the images, the changes are basically around the peripheral seas at the ice edge moving progressively to the north with time as dictated by the results of the regression analysis. Again, it is important to note that this projection is mainly statistical and assumes a linear trend which may not be a realistic assumption. The accuracy of this projection is difficult to assess but statistical analysis indicate that at a 95% confidence level, the trend in the decrease in the perennial ice area is between -5.7%/decade and -12.5% per decade. It is interesting to note, that the general characteristics of the perennial ice cover in 2002 to 2003 are consistent with the predictions of the Comiso (2002) study. Our current prediction is also showing good consistency with the perennial ice cover in 2004, the extent of which appears to be the second lowest during the satellite era. It should also be noted that the projected ice distributions provide patterns which are similar to those projected by some models (e.g. Johannessen et al. 2004)

6 Discussions and Conclusions

Global warming in the Arctic is to a certain degree already manifested by observed retreat of ice and snow, melt of glaciers, thawing of permafrost, and retreat of the sea ice cover. We are currently observing rapidly retreating perennial sea ice during the 25-year observational period when the surface temperature concurrently went up by about 1ºC. An update of data used in previous reports shows that the perennial ice cover continued to decline at an even faster rate of 9.2 % per decade, while the surface temperature has been steadily going up in most places except parts of northern Russia. It is also apparent that the most rapid retreat in the perennial ice cover has been occurring in the Beaufort Sea region while warming is going on in adjacent regions, including North America and Greenland. Some slight cooling is actually going on in parts of the Eastern Arctic, especially in Eastern Russia, but this may be generally due in part because the center of warming activity is shifted to the Western Arctic and North America and off-centre with respect to the North Pole. This result is intriguing and may mean that the physics of the polar amplification due to feedback effects is more complex than previously assumed, especially in models.

The length of melt patterns, however, appears to be more symmetrical with the North Pole and progressively increases to the south, except in Greenland and glacier areas. The length of melt, which has been shown to be sensitive to the thickness of the sea ice cover, is observed to be increasing at a rapid rate of 13.1 days per decade over sea ice regions. It is also increasing at the rate of 4.3 and 5.3

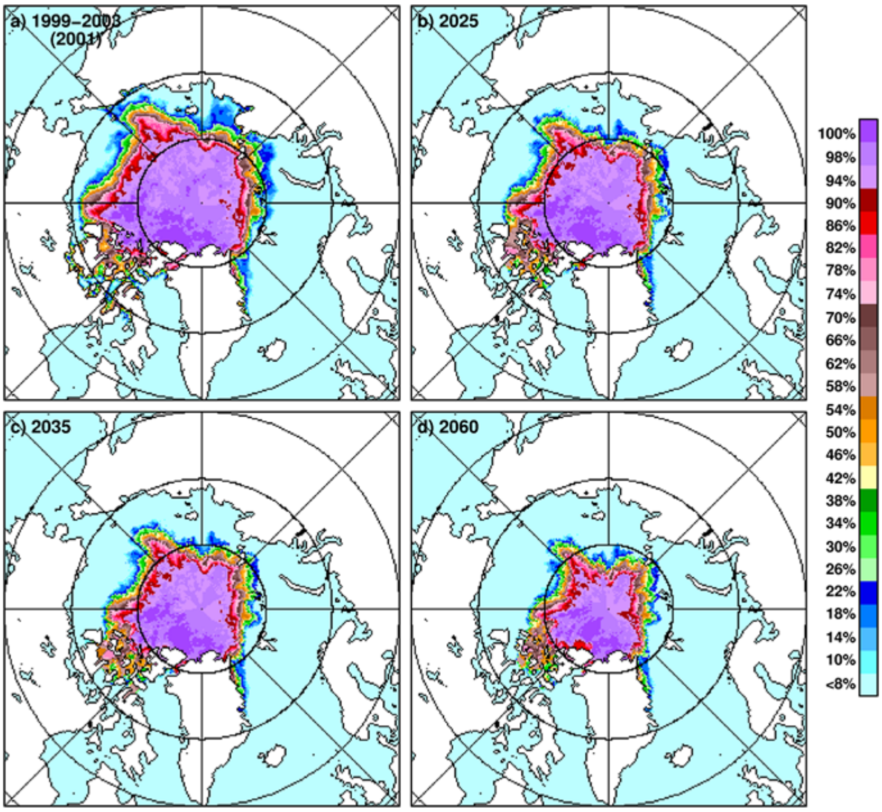

Figure 6. Color coded map of the average of the Arctic perennial ice cover from 1998 to 2003 (a) plus projections of a five-year running average of the perennial ice concentration data from 1978 to 2003 for the years (b) 2025; (c) 2035; and (d) 2060. A small circular area around the North Pole with no data because of satellite orbit inclination has been filled up using spatial interpolation.

days per decade in Greenland and the permafrost regions of North America while the change is negligible over the permafrost regions of Eurasia.

Results of linear regression analysis suggest that for every 1ºC increase in surface temperature, the area of the perennial ice cover decreases by about 1.48×10^6 km^2. The correlation of the two variables is significant but not very high with the correlation coefficient being only 0.57, but this is not totally unexpected. Temperature affects not only area but also volume and when the ice is very thick, for example, increases in temperature may not be reflected as decreases in ice area until the ice is thin enough to melt completely. The correlation analysis on a pixel by pixel basis shows very high correlation between sea ice concentration and temperature in the seasonal ice region, where the ice cover is relatively thin and melts completely in summer, but not in the perennial ice area where the ice is thick and may not show corresponding changes in area. Moreover, the growth and decay of sea ice is affected by other factors such as wind, ocean current, cloud cover and tides. For example, changes in wind circulation could cause ice to be advected to warmer oceans during some years and not in other years. Also, an increase in the frequency of storms may alter the characteristics of the upper ocean and cause a change in the melt patterns for the sea ice.

Using statistical analysis, currently observed distribution of the perennial ice cover is projected into the years 2025, 2035, and 2060, when a 2ºC global warming is expected to occur (companion paper by New), and the results show ever increasing open ocean areas in the Beaufort, Siberian, Laptev and Kara Seas. The impact of such a largely increasing open water area could be profound. It could mean changes in the ocean circulation, marine productivity, ecology, ocean circulation and the climate of the region. It could also allow for much more extensive shipping and human activities in the region. A discussion of specific details of the impacts and mitigation strategies would require a separate study. The linear regression model used in the projection technique may not be a realistic model for the complex Arctic system but the results could provide useful insights into how the Arctic ice may change on a short-term basis, especially since previous projections successfully reproduced recent data. Again, we point out that the technique does not allow for the sea ice cover to rebound, which is a possibility, especially in response to AO and NAO. However, if the trend continues, the ice-albedo feedback effects may dominate and the projections would provide us with a good idea of what perennial ice could be like after a doubling in atmospheric CO_2.

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RESPONDING TO GLOBAL CLIMATE CHANGE:

THE PERSPECTIVE OF THE INUIT CIRCUMPOLAR CONFERENCE ON THE ARCTIC CLIMATE IMPACT ASSESSMENT

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> The world can tell us everything we want to know. The only problem for the world is that it doesn't have a voice. But the world's indicators are there. They are always talking to us.
>
> Quitsak Tarkiasuk

1. Introduction

The Arctic Climate Impact Assessment (ACIA) prepared by the eight-nation Arctic Council was formally presented to council ministers at their biennial meeting in Reykjavik, Iceland, on 24 November 2004 (AMAP, 2004a). Two weeks later the assessment featured prominently in the Conference of Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) in Buenos Aires, Argentina. Projecting wholesale changes to the Arctic environment and to the social, economic, and cultural circumstances of the region's residents, particularly Indigenous peoples, the ACIA-generated media coverage worldwide. This paper outlines the perspective of the Inuit Circumpolar Conference (ICC) on the policy recommendations that accompanied the ACIA.

2. Background

In February 2003, the Governing Council of the United Nations Environment Programme (UNEP) adopted resolution 22/11, Sustainable Development of the Arctic. Overly general in language, as such resolutions tend to be, it nevertheless focused attention on a region of the world that has been historically low among UNEP's priorities. The resolution recognized the "increasing global importance of the Arctic in a global environmental context," singled out the region's Indigenous peoples for attention, and requested its executive director to "provide continuous assessment and early warning on emerging issues related to the Arctic environment, in particular its impact on the global environment."

This resolution is indicative of an important fact: scientists and policy-makers increasingly appreciate that the impacts of human-induced climate change globally can be seen and experienced first in the Arctic, for this region is a "barometer" of the globe's environmental health. Inuit would add that they are the mercury in the barometer.

UNEP's welcome interest in the Arctic follows the 2001 conclusion of the Intergovernmental Panel on Climate Change (IPCC):

> *Climate change in polar regions is expected to be among the largest and most rapid of any regions on the Earth, and will cause major physical, ecological, sociological, and economic impacts especially in the Arctic, Antarctic Peninsula and Southern Ocean.*

The ACIA supports and elaborates on this conclusion.

That observable and measurable changes to the Arctic's ecology are occurring as a consequence of global climate change is no longer debated. Instead, difficult questions are being asked by Arctic residents, particularly Indigenous peoples, including:

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- What are the long-term implications of projected climate change to health, economy, and culture?
- How can Arctic residents adapt to the impacts of projected climate change?
- What are the cultural and social limits to adaptation?
- What policies and programmes are needed to increase resilience and adaptability to climate change?
- What needs to be done globally to slow and reverse human-induced climate change?
- What role may Arctic Indigenous peoples play in persuading national governments around the world to address climate change as a matter of urgency?

3. Observations by Inuit

Some commentators and a few scientists remain unconvinced that climate change is taking place and that global emissions of greenhouse gases are at least a contributory cause. Observations by Inuit should help to convince the skeptics that climate change is a reality.

Inuit hunters are keen observers of the natural environment. They have to be; they depend on it for food. University and government scientists as well as Inuit organizations have documented the extent and intensity of land and ocean use by Inuit and their detailed knowledge of animal behaviour and biology, particularly of harvested species, and of ecological relationships.

The traditional knowledge (TK) and experience of the Inuit is now broadly accepted as legitimate, accurate, and useful, although until recently it was dismissed by some scientists as anecdotal and unreliable. Inuit have repeatedly offered to share what they know of their environment in the expectation that their observations will assist governments to manage natural resources. The literature on the management of natural resources is now rich with examples and case studies of TK, and many practitioners stress the need to combine traditional knowledge and science, to the benefit of both. Some recent examples of TK illustrate well the utility of Inuit observations.

Sachs Harbour, Banks Island

In 1999 the Winnipeg-based International Institute for Sustainable Development (IISD) and the Inuvialuit community of Sachs Harbour on Banks Island, Northwest Territories, initiated a project to record and illustrate community observations of climate change. The resulting video in which Inuvialuit quietly but with firm authority point out what is happening to their immediate environment was shown to delegates at the 2000 Conference of Parties (COP) to the UNFCCC in The Hague.

Community residents reported all manner of climate change-related environmental alterations, beginning in the mid-to-late 1980s. While the media and some non-government organizations have popularized the image of fewer and thinner polar bears as emblematic of climate change in the Arctic, Inuvialuit in Sachs Harbour spoke of commonplace and cumulative changes that threaten their cultural future: melting permafrost resulting in beach slumping; increased snowfalls; longer sea ice-free seasons; new species of birds, ducks, and fish (barn owls, mallard and pin-tailed ducks, and salmon) “invading” the community; a decline in the lemming population, the basic food for Arctic fox and a valuable harvested species; and generally a warming trend (Jolly et al. 2002).

That kerosene and fuel oil no longer resemble milk and jelly in mid-winter is the compelling indicator of climate change offered by long-time resident Andy Carpenter. Environmental indicators used for generations to predict weather and aid hunting and travel over sea ice no longer work reliably. With temperature and precipitation increasingly unpredictable and the look and feel of the land becoming unfamiliar, it is increasingly difficult for Inuvialuit to read the land and follow the seasons.

Nunavut Tunngavik Incorporated Climate Change Workshop

Nunavut Tunngavik Incorporated (NTI), the Inuit organization that implements the 1993 Nunavut Land Claims Agreement, sponsored a two-day workshop in Cambridge Bay in March 2001, bringing together elders and hunters from 15 Nunavut communities (Nunavut Tunngavik

Incorporated, 2004). Participants reported widespread environmental change in Nunavut as a result of changing climate and weather and repeated many of the observations made by Inuvialuit in Sachs Harbour. Key observations included melting permafrost and retreating glaciers and ice sheets on Baffin Island; new species of birds in summer; longer ice-free seasons in Hudson Bay; a shorter period when snowmobiles can be used on sea ice; more pronounced wind storms; and strengthening sun. Elders joked about the need for Inuit hunters to use stronger sunscreen lotion, which suggests growing problems with UV-B radiation. The workshop concluded that Inuit must prepare for climate change and the social and economic developments that will surely follow, particularly the use of the Northwest Passage by cargo vessels.

Voices from the Bay

A particularly ambitious, rigorously conducted, award-winning, and often-quoted TK study of environmental change in the Arctic is reported in *Voices from the Bay*, published in 1997 by the Canadian Arctic Resources Committee and the Environmental Committee of the Municipality of Sanikiluaq on the Belcher Islands in Hudson Bay (McDonald et al. 1997). This study brought together 78 Inuit and Cree hunters and elders from 28 communities on the shores of Hudson and James bays in 17 workshops over a two-year period. The book is based on a geographical information system and computer-assisted analysis of a 2,000-page, 800,000-word database.

Appendix 1 summarizes environmental observations recorded in the study. Particularly interesting observations include wholesale changes in location, number, and duration of polynyas—open water areas in winter—in eastern Hudson Bay and changing flyways of Canada and snow geese. The study provides a complex model of sea-ice formation and ablation related to temperature, currents, wind, and tides and concludes that alterations to weather and climate in the bioregion are by no means uniform.

Alaska Native Science Commission

Established in 1993, the Alaska Native Science Commission has conducted numerous TK projects to explain the environmental observations of Alaskan natives. Since the 1970s the natives of Alaska have noticed and reported environmental changes outside the bounds of “normal” variability. Hunters have fallen through sea ice; the famed Iditarod long-distance dog race has been moved farther north because of lack of snow; the speed and magnitude of shore erosion has increased; new species of insects including spruce beetles have attacked forests; and in some regions ice cellars for storing country food have, as a result of melting permafrost, lost their ability to preserve.

The plight of Shishmaref, rapidly being washed into the Bering Sea because of increased coastal erosion, has attracted much comment in Alaska and beyond. Since 1977, 18 homes in the community have been relocated at significant cost, both financial and psychological. Relocating the community is estimated to cost more than US$120 million.

Heather Miller of Nome summed up climate change in northern Alaska:

> *The seasons are getting very fast and are all mixed up. The last few years my grandmother was living she said that there was not enough time to put things away like there used to be. When we are done with the willow leaves then comes the sourdocks. These seasons are in too much of a hurry now* (Alaska Native Science Commission).

Conclusions from the Case Studies

Each case study illustrates an important fact: much of the impact of climate change on Inuit and other Arctic Indigenous peoples will be channelled through ecological changes to which they will have to adapt (Fenge 2001). Already Inuit are altering their hunting patterns to accommodate changes to the ice regime and distribution of harvested species, both marine and terrestrial. We can expect significant changes in Inuit land and resource use from that documented in Alaska in the 1960s preparatory to the 1971 Alaska Native Claims Settlement Act and in northern Canada in the 1977 report of the Inuit Land Use and Occupancy Project, preparatory to the 1984 Inuvialuit Final Agreement and the 1993 Nunavut Agreement.

4. The Arctic Climate Impact Assessment

Faced with growing concern about the implications of global climate change, the Arctic Council,, at its meeting in Barrow, Alaska, in October 2000, initiated an ambitious and comprehensive assessment of climate change (Arctic Council, 2000). The ambit of this assessment was outlined in the political declaration signed by ministers of foreign affairs:

> *3. Endorse and adopt the Arctic Climate Impact Assessment (ACIA), a joint project of the Arctic Monitoring and Assessment Programme (AMAP) and the Conservation of Arctic Flora and Fauna (CAFF) Working Group, in cooperation with the International Arctic Science Committee, and*
>
> *acknowledge the establishment of the ACIA Steering Committee to coordinate the ACIA, and express our gratitude to the United States for financing a substantial portion of the ACIA Secretariat;*
>
> *request the ACIA to evaluate and synthesize knowledge on climate variability and change and increased ultraviolet radiation, and support policy-making processes and the work of the Intergovernmental Panel on Climate Change;*
>
> *further request that the assessment address environmental, human health, social, cultural and economic impacts and consequences, including policy recommendations; and*
>
> *approve the goals and objectives contained in the ACIA Implementation Plan and request that the AMAP and CAFF Working Groups, in consultation with the Sustainable Development Working Group, promote the availability of the necessary social and economic expertise to complete the assessment.*

Developed during 1999 and 2000, the ACIA Implementation Plan promised three reports: a science assessment, a summary or overview volume, and a policy report. The applied nature of the exercise was clear from the outset. Ministers approved an assessment that would address cultural impacts—reflecting the existence of Indigenous peoples in the circumpolar Arctic—and requested policy recommendations.

Enjoying a secretariat based at the University of Alaska at Fairbanks, and under the chair of Bob Corell of Harvard University and the World Meteorological Institute, the ACIA was prepared by more than 300 scientists from 15 countries. Six Indigenous people's organizations—Aleut International Association, Arctic Athabascan Council, Gwich'in Council International, Inuit Circumpolar Conference, Russian Association of Indigenous Peoples of the North, and the Saami Council—enjoy "permanent participant" status in the council. As such they were actively involved in the ACIA, which drew upon both TK and science.

In light of global publicity and commentary, much of it uncomplimentary, on the position of the Government of the United States toward climate change and its refusal to ratify the Kyoto Protocol to the UNFCCC, it is only fair to applaud the effective participation of American academics and researchers in the ACIA, and to acknowledge the significant financial contribution by the United States to this circumpolar exercise.

5. Key Findings of the Arctic Climate Impact Assessment

Table 1 summarizes the key findings of the ACIA. From an Inuit perspective the key to understanding this comprehensive and detailed assessment lies in projections of the impact of climate change on the sea-ice environment.

Numerous researchers have documented the depletion of summer sea ice in the Arctic Ocean. The media have invariably connected these projections to potential future use of the Northwest and Northeast passages and the Arctic Ocean by general cargo vessels and the resulting environmental and geopolitical implications. The prospects of oil tankers plying the Arctic Ocean is something that all, even those not yet convinced of the reality of climate change, must surely view with concern.

Although unable to predict accurately when summer sea-ice depletion will permit regular shipping transits through the Arctic Ocean, the ACIA is clear that climate change in the Arctic is happening now. As a result of even conservative projections of the rate and magnitude of global climate change, the habitat of marine mammals will be fundamentally altered. The ACIA summary volume succinctly (ACIA, 2004) states:

> *Marine species dependent on sea ice, including polar bears, ice-living seals, walrus, and some marine birds, are very likely to decline, with* some facing extinction (emphasis added).

Table 1
Arctic Climate Impact Assessment: Key Findings

1. Arctic climate is now warming rapidly and much larger changes are projected.
2. Arctic warming and its consequences have worldwide implications
3. Arctic vegetation zone are very likely to shift, causing wide-ranging impacts.
4. Animal species' diversity, ranges, and distribution will change.
5. Many coastal communities and facilities face increasing exposure to storms.
6. Reduced sea ice very likely to increase marine transport and access to resources.
7. Thawing ground will disrupt transportation, buildings, and other infrastructure.
8. Indigenous communities are facing major economic and cultural impacts.
9. Elevated ultraviolet radiation levels will affect people, plants, and animals.
10. Multiple influences interact to cause impacts to people and ecosystems.

While navigating considerable social change in recent decades as the Arctic is incorporated into the global economy, the culture and economy of Inuit, particularly in the smaller communities, remains tied to Arctic wildlife. Hunting is important for the food it puts on the table and as an expression of an age-old culture. In a part of the world in which wage-paying jobs are scarce and imported food is at least expensive if not often exorbitant, highly nutritious country food shared with friends and relatives epitomizes what it means to be Inuit.

Polar bear, walrus, and particularly seals are key harvested species and their projected demise will result in major cultural trauma. The ACIA summary volume does not pull its punches:

> *For Inuit, warming is likely to disrupt* or even destroy their hunting and food sharing culture *as reduced sea ice causes the animals on which they depend to decline, become less accessible, and possibly become extinct* (emphasis added).

6. The Perspective of Arctic Indigenous Peoples

Drawing upon the precedent of the 2002 circumpolar contaminants assessment by the council's Arctic Monitoring and Assessment Programme (AMAP), the six Arctic Indigenous people's organizations submitted a statement to be included at the beginning of the science assessment and summary volumes. Rejected as being "too political," this statement said, in part:

> *To Arctic Indigenous peoples climate change is a cultural issue. We have survived in a harsh environment for thousands of years by listening to its cadence and adjusting to its rhythms. We are part of the environment and if, as a result of global climate change, the species of animals*

> *upon which we depend are greatly reduced in number or location or even disappear, we, as peoples would also become endangered as well.*
>
> *For some years we have seen and reported environmental and social impacts of global climate change. Climate change is already threatening our ways of life and poses everyday, practical questions, such as when and where to go hunting, and when and where not to travel. Indeed, the findings of the ACIA show that the Arctic climate is changing twice as fast as that of the rest of the world. There is very little time for Indigenous peoples and the resources on which we depend to adjust and adapt.*
>
> *Our environmental observations are supported in the ACIA. Our traditional knowledge—incorporating historical and contemporary observations—complements science-based observations. Both are reported in the ACIA, a unique and important feature of this assessment.*
>
> *In the face of climate change we will defend our cultures and ways of life by actively participating in concerted efforts to reduce human-induced causes of climate change. We encourage the Arctic states singly and collectively through the Arctic Council to help us to do so. It is of central importance that the Arctic states, armed with the ACIA, set an example to the world by reducing significantly their own emissions of greenhouse gases.*

Through their statement the six permanent participants urged Arctic states to:

- inject Arctic perspectives, as outlined in the ACIA, into the heart of the ongoing debate on the impacts and effects of global climate change;
- assist Arctic Indigenous peoples to bring their views, perspectives, and recommendations to international institutions mandated to combat the impacts and effects of global climate change;
- adopt and implement, as a matter of urgency, strategies to reduce the emission of greenhouse gases and to enhance carbon sinks;
- encourage Arctic Indigenous peoples to adapt to and manage the impacts of climate change by equipping them with information and budgets, by acknowledging their authority to make decisions to protect and promote their ways of life, and by working closely with their representative organizations; and
- instruct AMAP, CAFF, and the Sustainable Development Working Group to propose an ACIA follow-up research agenda.

7. ACIA Policy Recommendations

Pursuant to the Barrow Declaration, a policy-drafting committee including representatives of the eight Arctic states and six permanent participants was charged with drafting a policy report with recommendations for ministers based upon the unfolding ACIA. This committee met in New England, Copenhagen, and London in 2003—two years after the assessment process began—and prepared a short but comprehensive paper subsequently referred to as the “London draft” addressing mitigation; adaptation; research, observations, monitoring, and modelling; and communications and education. Chaired by two of the council’s working groups, this committee worked cooperatively, notwithstanding national differences in approach, policy, and priorities.

ICC was pleased with the attitude and accomplishments of the policy-drafting committee and, in particular, with the adoption of a framework that stressed mitigation as well as adaptation. Supported by all permanent participants, ICC suggested inclusion of a recommendation that Arctic states propose an amendment to either the preamble or an operative clause of the UNFCCC to acknowledge the significant impacts of climate change in the Arctic and on the region’s Indigenous peoples. The climate change convention singles out various portions of the globe but fails to mention the Arctic or acknowledge this region’s status as the globe’s climate change barometer. ICC proposed that the third preambular clause to the 2001 Stockholm Convention on persistent organic pollutants (POPs), which singles out the Arctic and its Indigenous peoples, be the model for an amendment to the UNFCCC.

At the third meeting of the committee, in Autumn 2003, the delegate of the United States said he was under instructions to table a one-page paper headed: “US Statement on Policy Document.” Undated, unsigned, and with no logo to identify a source institution, the statement identified a “fundamental flaw” in the policy-drafting process:

> *Specifically, we are seeking here* [in the policy working group] *to develop the scientific assessment and its summary in tandem with policy recommendations that logically should flow from them. Moreover, these policy recommendations should be developed only after governments have had an opportunity to consider the Scientific Document and the Synthesis Document on which they are based and draw their conclusions. In effect we are putting the cart alongside the horse with the risk that neither cart nor horse will arrive at the destination.*

If adopted, this position would have delayed consideration of policy recommendations to an unspecified date but certainly after presentation of the assessment to ministers. At odds with the political declaration through which ministers approved the assessment work plan, this position seemed to reflect the fact that the ACIA was, at that time, to be presented to national governments in October 2004, during the presidential election campaign in the United States. In response to the US statement, the president of ICC Alaska wrote to the Senior Arctic Official (SAO) of the United States:

> *It will surely appear to the Arctic Council that the United States intends to delay preparation and presentation of the policy document until after the presidential election. In doing so, the United States is opening itself to criticism that domestic political and electoral considerations override agreed ministerial directions. I can not imagine other Arctic states agreeing to change the rules of the game when completion of the ACIA, the overview report, and policy document are in sight. Indeed, the action you contemplate might even undercut completion of the science assessment. As a unilateral move by the Government of the United States, your action might even damage the Arctic Council itself* (Greene 2003).

The timing of the ministerial meeting was subsequently changed to late November 2004 (Inside EPA, 2003). At their October 2003 meeting, SAOs thanked the drafting group for its work and took upon themselves the responsibility to continue the exercise, although it was becoming unclear just what this meant. The chairman of the SAOs wrote to all states and permanent participants on 13 January 2004 suggesting how the process might continue:

> *…we have not put “paid” to the ACIA policy process, but will continue to work on the basis of the declaration of the Barrow Ministerial Meeting in 2000….SAOs will consider and prepare recommendations to Ministers for joint adoption at the fourth Ministerial meeting in the fall of 2004….it remains the prerogative of the SAOs to decide how the policy-work of the ACIA will be carried forward…This includes the question of whether to reactivate the PDT [Policy Drafting Team]…and...the form to be given to the recommendations to Ministers, including the question of whether they are called recommendations or something else….*(Palsson 2004).

ICC was immediately concerned about this statement. Backing away from the principle of policy recommendations was not, it concluded, consistent with the Barrow Declaration.

In April 2004, at an informal meeting of SAOs and permanent participants in Nuuk, all delegates, including the United States, agreed that the London draft was a point of departure for additional drafting. The chair of the SAOs solicited comments on the London draft and prepared and circulated in early August a “composite draft” that was discussed at a special meeting of SAOs and permanent participants in The Hague in late August.

The London draft combined explanations of the impacts of climate change based in the science assessment with clear policy recommendations. As foreshadowed in the chair’s January communication, the composite draft discussed in The Hague deleted recommendations and adopted a declaratory style used by council ministers in their biennial political declarations.

ICC registered its opposition to this development. A recommendatory report “stands alone” and so invites a response by ministers. A declaratory report, on the other hand, does not and invites an obvious question: just what are the policy recommendations to which the ministers are being asked to respond? At this stage it seemed that policy considerations would be addressed—ICC feared that “buried” might be a more accurate appraisal—in the SAOs general Arctic Council activities report to ministers.

In response, ICC wrote to the SAO chair on 10 September 2004:

> *It is our view that ministerial instructions in the Barrow and Inari Declarations and the council’s rules of procedure require the presentation to ministers of an ACIA policy report that stands alone* (Watt-Cloutier 2004a).

In defending the principle of policy recommendations in a stand alone report, ICC wrote to the chair of the SAOs:

> 1. *The original ACIA instructions issued by Arctic Council ministers in 2000 remain in effect;*
> 2. *these instructions require presentation to ministers of three ACIA documents—scientific, synthesis, and policy; and*
> 3. *the SAOs are required to act in accordance with the decisions and instructions of the council.*
>
> *The United States argues that a consensus among SAOs is needed for presentation of an ACIA stand-alone report, and it is withholding that consensus. The political declarations and rules of procedure to which the United States is party do not support this procedural proposition. Simply put, SAOs are unable to overturn decisions by ministers specified in political declarations. There is more than sufficient detail in the council’s political declarations and the approved ACIA work plan to support the conclusion that a stand-alone policy report with recommendations is what ministers requested. It is ICC’s view that ministers should get what they requested.*

Responding to a request from US Senator McCain, the ICC chair presented a well-received brief on 15 September to the United States Senate Committee on Commerce, Science and Transportation:

> *I ask you to look seriously at the Arctic for solutions to the global debate on Climate Change. More specifically I ask you to look at the role your Department of State is playing in the Arctic Council’s Arctic Climate Impact Assessment process—largely paid for by the United States. The assessment is path-breaking and it is crucial that the world know and understand what it says. Yet the Department of State is minimizing and undermining the effectiveness of this assessment process by refusing to allow recommendations to be published in a stand alone form just like the assessment itself. Yet, this is what ministers of foreign affairs directed when, in Barrow, Alaska, in October 2000, they approved the assessment* (Watt-Cloutier 2004b).

This presentation prompted the issuance of “press guidance” by the Department of State that “the US is not seeking to keep the ACIA report under wraps,” which in turn helped to persuade Senators McCain, Snowe, and Lautenberg to write to Secretary of State Colin Powell urging him to ensure that the United States operate from within rules defined in the Barrow Declaration.

ICC’s presentation and the resulting correspondence by the senators were widely covered by newspapers and radio in the United States and elsewhere. For the first time, national and international media focused on the ACIA and did so from the perspective of Inuit and other Arctic Indigenous peoples. Media interest in the ACIA increased in subsequent weeks.

ICC’s intervention in Washington, DC, and the media attention it generated resulted in a letter from the chair of the SAOs to all states and permanent participants. Clearly directed at ICC, although failing to mention the organization by name, the letter admonished:

> *Judging by recent reports in the media, it appears that information obtained in a privileged way through the access to closed meetings of Senior Arctic Officials and Permanent Participants, is being used for public effect….Such public disclosures…are fundamentally at odds with the practices in the Arctic Council* (Palsson 2004b).

Deeply disappointed and surprised to learn that this communication had been approved in advance by SAOs, ICC responded:

> *We are defending the most basic principle of the Arctic Council whereby the SAOs "shall coordinate, guide and monitor Arctic Council activities in accordance with the decisions and instructions of the Arctic Council."…we remain deeply concerned about the position brought forth at the SAO meetings suggesting a retreat from clear ministerial instructions….*
>
> *Further, I must question your reference to "information obtained in a privileged way." At no time have I or any representatives of the Inuit Circumpolar Conference made public any information regarding the substantive matters on the text of the ACIA policy document. My comments have been limited to defending the integrity of a process that can only be changed by ministerial consensus. If privilege can be claimed on this matter, it can only be claimed on discussions from a ministerial meeting.*
>
> *If the SAOs agree to abide by the ministerial direction set out in the Barrow Declaration for a stand alone report, I feel confident that we can successfully finalize policy recommendations, conclude the ACIA process, and report our success to ministers* (Watt-Cloutier 2004d).

SAOs and permanent participants met in Iceland in October but failed to agree on ACIA policy recommendations. Citing European participants in the process, *The New York Times* on 30 October revealed on its front page the key findings of the ACIA and raised, once again, the state and status of policy recommendations. With the presidential election in the United States then just days away, media around the world focused on the ACIA, putting it within the context of the administration's well-publicized opposition to ratification of the Kyoto Protocol to the UNFCCC. The official release of the ACIA on 8 November at a press conference in Washington, DC, and at a scientific conference in Iceland attended by more than 300 participants, generated even more publicity. Wire services ran stories suggesting the ACIA was a warning for the world. The stage was set for the ACIA policy recommendations end game when SAOs and permanent participants met in Reykjavik on 19 November, with Arctic Council ministers scheduled to meet the following week.

Labouring late into the night, all the Arctic states accepted a policy document and ministerial declaration endorsing its recommendations (Arctic Council, 2004b). While the policy report was declaratory in nature, general in tone, and short on specifics, ICC nevertheless characterized it as a "modest breakthrough" and as "more than we expected but less than we had hoped for." The other permanent participants issued statements along the same lines. A number of states said privately that it was global publicity arising from ICC's intervention before the US Senate Committee and the leak in Europe of the ACIA key findings that compelled Arctic states to come to a consensus on how to respond to the assessment.

8. The ACIA Policy Document and Reykjavik Declaration

The ACIA policy document bears significant resemblance to the "London draft" prepared 13 months previously. The need for action on both mitigation and adaptation is acknowledged as is "extensive communication and education about climate change and its impacts." While "further research, observations, monitoring and modeling is needed to refine and extend the ACIA findings," the document acknowledges:

> *To address the risks associated with climate change in the Arctic of the magnitude projected by the ACIA and other relevant studies, timely, measured and concerted action is needed to address global emissions.*

This is the key—and only—statement in the policy document that links climate change in the Arctic to human activities. To the disappointment of some, the policy document does not address targets or timetables for reduction of greenhouse gas emissions. When questioned, ministers responded that such debate was best left to COPs pursuant to the UNFCCC.

Nevertheless, the ACIA prompted SAOs to recommend to ministers that member states:

> *Adopt climate change mitigation strategies across relevant sectors. These strategies should address net greenhouse gas emissions and limit them in the long term to levels consistent with the ultimate objective of the UNFCCC…*

In relation to adaptation, the policy document accepts that "special attention" needs to be paid to "strengthen the adaptive capacities of Arctic residents" through "enhanced access to information, decision makers, and institutional capacity building." This section also points out the need for adaptation in light of "increased navigability of sea routes and access to resources." Further research on natural and social systems, the impacts of climate change, and of the vulnerability and resilience of Arctic residents is also promoted.

The final sections of the policy document address outreach and the role of the Arctic Council but neither specifies particular activities or actions.

While endorsing the policy recommendations and recognizing that "the Arctic climate is a critical component of the global climate system with worldwide implications," the Reykjavik Declaration adds little of substance (Arctic Council, 2004a). It notes "with concern" the impacts documented by the ACIA and unspectacularly concludes:

> *Climate change and other stressors present a range of challenges for Arctic residents, including Indigenous peoples, as well as risks to Arctic species and ecosystems.*

9. Featuring the Arctic to Give Global Climate Change a Human Face

Intentionally or unintentionally, the ACIA process and products resulted in a global airing of Arctic climate change perspectives and concerns, particularly those of the region's Indigenous peoples. The ACIA added credence, substance, and immediacy to UNEP's 2003 resolution calling for additional monitoring in the Arctic as a global priority. As Klaus Topfer, Executive Director of UNEP, sagely noted at the Arctic Council ministerial meeting, the ACIA was the first Arctic Council product to receive global attention. The chair of the IPCC said as much again in a letter to the chair of the ACIA upon release of the assessment. A compelling question now is whether, how, and how well the ACIA will inform and influence global debate on responses to climate change.

ICC has participated in four COPs to the UNFCCC, including COP 9 in Milan and COP 10 in Buenos Aires. Debate at COPs is mired in technicalities and formulae and has lost sight of the human and cultural dimensions to this issue. ICC wants to do what it can to refocus and reframe debate, but this is extraordinarily difficult in the face of entrenched positions and positional bargaining. The field is crowded, involved organizations are shrill and unforgiving, the gulf between the United States and western Europe on appropriate responses is wide, as is the gulf between the developed and developing worlds. Nevertheless, citizens of many countries, including the United States, favour assertive commitments and concrete action to combat climate change.

Human-induced climate change as analyzed and portrayed in the ACIA is a threat to everything that Inuit are and hope to become and to the age-old relationship between Inuit and the natural environment. Climate change is a matter of cultural survival to Inuit and to other Arctic Indigenous peoples. Might Inuit perspectives, including those referenced in the ACIA, be brought forward in ways that resonate with the public at large and with other regions of the world vulnerable to climate change to the aid of appointed and elected decision-makers? Are there helpful precedents?

While the first question warrants “maybe” as an answer, an unequivocal “yes” can be offered to the second in light of the involvement by Arctic Indigenous peoples in international efforts to address long-range transport of persistent organic pollutants (POPs). AMAP’s 1997 summary report, *Arctic Pollution Issues: A State of the Arctic Environment Report,* and its full-blown scientific assessment published in 1998 showed that many POPs released to the environment in tropical and temperate lands ended up in the Arctic, bioaccumulating and biomagnifying in the food web, particularly the marine food web. Inuit women eating large amounts of marine mammal fats from seals, walrus, narwhal and beluga whales—important harvested species—were ingesting significant quantities of POPs with worrisome but unknown health effects. These POPs passed through the placental barrier to unborn babies.

Armed with AMAP’s contaminants assessment, Inuit and other Arctic Indigenous peoples formed a coalition that participated actively and effectively in negotiations culminating in the 1998 POPs and heavy metals protocols to the UN Economic Commission for Europe Convention on Long-range Transboundary Atmospheric Pollution and the global convention on POPs signed in Stockholm in 2001.

At the second meeting of the POPs negotiations in Nairobi, Sheila Watt-Cloutier, then president of ICC Canada, presented Klaus Topfer, Executive Director of UNEP, with a carving of an Inuit mother and child. The chair of the negotiations put the carving on his desk at the front of the negotiations for the 1,000 or so delegates to consider during debate. The carving soon epitomized the “conscience” of the negotiations, and Inuit became the “human face” of the process. This was entirely fitting because, like climate change, POPs in the Arctic threaten age-old cultures and ways of life. Bringing Arctic perspectives to these negotiations is documented in *Northern Lights Against POPs: Combatting Toxic Threats in the Arctic,* published by ICC and McGill/Queen’s University Press in 2003 (Downie and Fenge 2003).

With the ACIA in hand, Inuit and other Arctic Indigenous peoples might be able to play a role in implementation and future evolution of the UNFCCC and other international conventions that address climate change similar to the role they played in the global POPs debate. Certainly there seems ample scope for Arctic interests to work closely with representatives of other regions vulnerable to climate change in future UNFCCC COPs.

In March 2004, the chair of ICC provided written testimony on climate change in the Arctic to the United States Senate Committee on Commerce, Science and Transportation. That testimony bears repeating:

> *What can Inuit do to convince the world to take long-term action that will have to go far beyond Kyoto? How do we convince the major emitters, such as the United States, of the risks we face in the Arctic? How can we bring some clarity of purpose and focus to a debate that seems mired in technical arguments and competing ideologies?*
>
> *We believe one route is to look at the international human rights regime that is in place to protect peoples from the very situation facing Inuit—the destruction of our culture. ICC is examining various regimes. We conclude that the 1948 American Declaration on the Rights and Duties of Man, supported by the Inter-American Commission on Human Rights, may provide an effective means for us to defend our culture and way of life.*
>
> *We do not suggest this route lightly, or in an adversarial spirit. The Arctic states account for 40 percent of the world’s greenhouse gas emissions, so it is appropriate for us to use our human rights to prompt a dialogue with them, particularly with the United States. It is our intent to educate not criticize, and to inform not complain. We hope that the language of human rights will bridge perspectives, not lead to more barricades and protest. After all, if we protect the Arctic we will save the world (Watt-Cloutier 2004c).*

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Appendix 1 – Regional Environmental Changes Observed by Inuit and Cree

	Eastern James Bay	**Eastern Hudson Bay**	**Hudson Strait**	**North-western Hudson Bay**	**Western Hudson Bay**	**Western James Bay**
Weather	• Shorter spring & fall season • Greater variability in fall • Colder winters in reservoir areas • Increased snowfall	• Persistence of cold weather into spring • Snow melts later • Spring and summer cooling trend • Less rain; fewer thunderstorms	• Greater variability; less predictable • Cooling trend • New snowfall cycle • Longer winters; snow melts late • Less rainfall	• Greater variability • Warmer and shorter winters • Snowfalls and melts earlier • Cool summers in early 1990s	• Longer winters • Colder springs • Snow melts faster	
Atmosphere	• Change in sky colour	• Change in sky colour • Sun's heat blocked by haze	• Change in sky colour • Sun's heat blocked by haze	• Change in sky colour	• Change in sky colour	• Change in sky colour
Sea ice	• Salinity changing along north-east coast • More freshwater ice forming in the bay • Less solid in La Grande River area; freezes later, breaks earlier	• Freezes faster • Solid ice cover is larger and thicker • Fewer polynyas • Floe edge melts before breaking up	• Freezes faster • Poorer quality • Landfast ice extends farther offshore • Polynyas freezes • Floe edge melts before breaking up			
Currents	• Weaker in Eastmain area • Swifter and less predictable north of La Grande River	• Weakening currents	• Weakening currents	• Weaker currents in Roes Welcome Sound		
Rivers	• Seasonal reversal in levels and flow • Decline in water quality • Unstable ice conditions on La Grande River; freezes later, breaks earlier • Vegetation dying along diverted rivers	• Decreased water levels and river flow	• Decreased water levels and river flow	• Decreased water levels and river flow	• Seasonal reversal in water levels and flow • Increased salinity, erosion and sediment in Nelson River • Decline in water quality	• Decreased water levels and river flow in southern James Bay rivers • Increased erosion and mud slides
Canada and snow geese	• Coastal and inland habitat changes • Coastal flyways have shifted eastward • Fewer being harvested in spring and fall • Large flocks of non-nesting/moulting geese along coastal flyway	• Smaller flocks of Canada geese arrive in Belcher Islands since 1984 • Increase in non-nesting/moulting geese in Belcher and Long islands	• New snow goose migration routes • Increase in number of moulting snow geese • Canada geese no longer nest in Soper River area	• More Canada geese in Repulse Bay area during summers of 1992 and 1993	• More snow geese migrating to and from the west • Habitat changes at Marsh Point staging area • Earlier and shorter fall migration	• Habitat changes in Moose Factory area • More snow geese flying in from the west • Canada geese arrive from the north first part of June • Change in fall migration patterns

	Eastern James Bay	**Eastern Hudson Bay**	**Hudson Strait**	**North-western Hudson Bay**	**Western Hudson Bay**	**Western James Bay**
Beluga Whale	• Decrease in numbers	• Decrease in numbers along coast • Moved to and travelling in currents farther offshore	• Decrease in numbers in Salluit area	• Decrease in numbers in Repulse Bay and Arviat area	• Increase in numbers in Fort Severn and Winisk estuaries • Decrease in numbers in Nelson River	
Fish	• Mercury contamination • Loss of adequate habitat for several species e.g., whitefish, sturgeon, pike • Morphological changes in sturgeon	• Decrease in Arctic char and Arctic cod in Inukjuak area		• decrease in Arctic cod in near-shore areas • Arctic cod no longer found in near-shore areas off Cape Smith and Repulse Bay	• Mercury contamination • Loss of habitat including spawning grounds • Change in taste of fish; some are inedible	• Morphological changes in sturgeon • Dried river channels
Polar Bear		• Increase in numbers since 1960s	• Decrease in numbers in Ivujivik area	• Increase in numbers • Appear leaner and more aggressive	• Thin-looking bears in York Factory area • Drink motor oil • Change in behaviour	• Recent increase in reproduction rates • Fearless of humans
Walrus	• No longer present in Wemindji area	• Shift away from Belcher Islands	• Increase in numbers around Nottingham Island	• Decrease in numbers near Arviat and Whale Cove • Increase in numbers near Coral Harbour and Chesterfield Inlet		• Decrease in numbers in Attawapiskat area
Moose	• Loss of habitat • Decrease in numbers • Change in body condition • Change in taste of meat	• In-migration from south-eastern James Bay			• Change in taste of meat • Greater number drowning • No moose at Marsh Point	
Caribou	• Change in body condition and behaviour • Increase in number of diseased livers and intestines • Change in diet • Change in taste of meat • More caribou • Along the coast	• Caribou from different areas mingle together • Very large herds • Travelling closer to coast • Change in diet • Change in taste of meat	• Increase in numbers • Increase in abnormal livers, e.g. spots and lumps • Change in diet	• Increase in numbers • Not intimidated by exploration activity • Feed close to exploration camps • Change in diet	• Increase in numbers • Pin Island herd is mixing with Woodland herd	

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