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The Changing Climate of the Arctic

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ABSTRACT. The first and strongest signs of global-scale climate change exist in the high latitudes of the planet. Evidence is now accumulating that the Arctic is warming, and responses are being observed across physical, biological, and social systems. The impact of climate change on oceanographic, sea-ice, and atmospheric processes is demonstrated in observational studies that highlight changes in temperature and salinity, which influence global oceanic circulation, also known as thermohaline circulation, as well as a continued decline in sea-ice extent and thickness, which influences communication between oceanic and atmospheric processes. Perspectives from Inuvialuit community representatives who have witnessed the effects of climate change underline the rapidity with which such changes have occurred in the North. An analysis of potential future impacts of climate change on marine and terrestrial ecosystems underscores the need for the establishment of effective adaptation strategies in the Arctic. Initiatives that link scientific knowledge and research with traditional knowledge are recommended to aid Canada's northern communities in developing such strategies.

Key words: Arctic climate change, marine science, sea ice, atmosphere, marine and terrestrial ecosystems

RÉSUMÉ. Les premiers signes et les signes les plus révélateurs attestant du changement climatique qui s'exerce à l'échelle planétaire se manifestent dans les hautes latitudes du globe. Il existe de plus en plus de preuves que l'Arctique se réchauffe, et diverses réactions s'observent tant au sein des systèmes physiques et biologiques que sociaux. Les incidences du changement climatique sur les processus océanographiques, la glace de mer et les processus atmosphériques s'avèrent évidentes dans le cadre d'études d'observation qui mettent l'accent sur les changements de température et de salinité, changements qui exercent une influence sur la circulation océanique mondiale – également appelée circulation thermohaline – ainsi que sur le déclin constant de l'étendue et de l'épaisseur de glace de mer, ce qui influence la communication entre les processus océaniques et les processus atmosphériques. Les perspectives de certains Inuvialuits qui ont été témoins des effets du changement climatique font mention de la rapidité avec laquelle ces changements se produisent dans le Nord. L'analyse des incidences éventuelles du changement climatique sur les écosystèmes marin et terrestre fait ressortir la nécessité de mettre en œuvre des stratégies d'adaptation efficaces dans l'Arctique. Des initiatives reliant les recherches et connaissances scientifiques aux connaissances traditionnelles sont recommandées afin de venir en aide aux collectivités du Nord canadien pour que celles-ci puissent aboutir à de telles stratégies.

Mots clés : changement climatique de l'Arctique, sciences de la mer, glace de mer, atmosphère, écosystèmes marin et terrestre

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INTRODUCTION

Scientific evidence for high-latitude climate change attests to changes in ocean currents, rising sea levels, increasing surface air temperature, decreasing sea-ice extent and thickness, and hemispheric-scale changes in atmospheric variability (Curry and Mauritzen, 2005; Francis et al., 2005; Meehl et al., 2005; Stroeve et al., 2005; Schiermeier, 2006). Investigation of changes in oceanographic, sea-ice, and atmospheric phenomena illustrates a collective response to global warming and increased levels of greenhouse gases.

The earth-ocean-atmosphere system is governed by the sun's radiation. However, the amount of that radiation reaching the earth varies, depending on location, season, and atmospheric absorption and reflection due to greenhouse gases and water vapour, including clouds (Fig. 1; IPCC, 2007). The amount of solar radiation absorbed by the surface depends on the type of surface cover (i.e., water or land), and this heat energy is transported by wind and ocean currents. The earth's radiation budget is governed by the balance between incoming solar radiation and out-going longwave radiation (Gill, 1982; IPCC, 2007). Thirty percent of the incoming solar radiation is reflected back to space by clouds, aerosols, and surface albedo; the remaining 70% is transmitted farther and absorbed by the atmosphere and surface of the earth (Fig. 1). Energy from the surface of the earth (390 Wm^{-2} in Fig. 1) is returned to the atmosphere through convection and longwave radiation, which is

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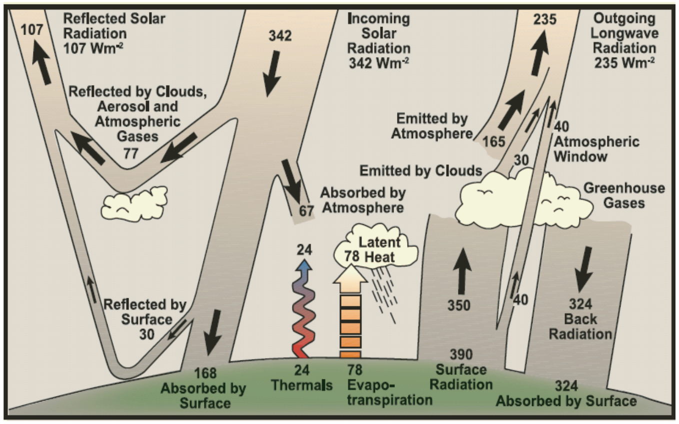

FIG. 1. The earth's annual and global mean energy balance in Watts per square meter (Wm^{-2}) (IPCC, 2007: Fig. 1.1).

absorbed by clouds and greenhouse gases (carbon dioxide, water vapour, methane, nitrous oxide, and chlorofluorocarbons). The term "greenhouse gas effect" refers to the fact that this blanket of gases acts much like a layer of glass, trapping heat as it reflects some of the longwave radiation back to the surface (324 Wm^{-2} in Fig. 1). The remaining longwave radiation is transmitted to space. Thus an increase in greenhouse gas concentrations increases the downward radiation from the atmosphere, resulting in warming of the earth's surface.

Atmospheric and oceanic circulation transport energy from the equator to high-latitudes. Atmospheric circulation in mid-latitudes transports energy poleward via transient disturbances (cyclones and anticyclones, or low- and high-pressure regions) to zonal (east-west) flow, including storm systems. The atmosphere also influences the ocean through winds that alter surface currents, as well as through both evaporation and precipitation that alter temperature and salinity, with implications for density-driven thermohaline circulation in the deep ocean (IPCC, 2007).

Changes to the earth's energy balance, known as "forcing mechanisms," are manifested in i) changes to incoming solar radiation, ii) changes to surface albedo, or "reflectivity" (the amount of radiation reflected from the earth) caused by changes in ice and snow cover, vegetation, and the presence of aerosols, and iii) changes to outgoing longwave radiation due to the presence of greenhouse gases. Climate change is a consequence of both natural forcing mechanisms (solar cycle, volcanic eruptions, and atmospheric variability) and anthropogenic ones (greenhouse gases, aerosols, carbon, and soot).

The Arctic plays an important role in the overall seasonal energy balance of the planet, and it works in concert with the Antarctic to set up the large-scale circulation patterns and teleconnections that make our planet habitable. It is important to note that Arctic climate change both affects global-scale climate change and is affected by it through feedback mechanisms. Of particular interest in the Arctic is "sudden climate change," an amplified response due to abrupt forcing or nonlinear feedback mechanisms. Phenomena such as loss in sea ice cover, which results in changes to surface albedo, and permafrost melt, which increases greenhouse gas concentrations, are the most notable causes (Hansen et al., 2007; Shindell, 2007). Throughout this paper, we examine a series of interrelated questions that arise directly from the growing evidence of Arctic climate change: 1) How will longer ice-free seasons and changing oceanic and atmospheric circulation affect northern coastal communities? 2) How is evidence for climate change reflected in the changed livelihoods of northern coastal communities? 3) What future impacts will climate change have on marine and terrestrial ecosystems in the Canadian Arctic? Our goal is to set the stage for future scientific and community observations of global climate change impacts in the Arctic that will help to establish effective adaptation strategies for one of our planet's most vulnerable regions.

SCIENTIFIC OBSERVATIONS OF ARCTIC CLIMATE CHANGE

Hemispheric-Scale Changes: The Ocean

Hemispheric-scale changes in ocean circulation highlight the impacts of climate change on the global climate system. A notable signature of a changing climate is found in thermohaline circulation, characterized by alternating cycles of warm surface waters and cool, deep waters in the Atlantic (Broecker et al., 1985; Colling, 2001; Schiermeier, 2006). During thermohaline circulation, warm, saline surface water is transported from the tropics to the North Atlantic, where a decrease in temperature at high latitudes results in an increase in density. When the cool, dense water is subjected to convection and mixing in the Greenland, Iceland, Norwegian, and Labrador seas, it sinks to form the North Atlantic Deep water, which returns at depth to the tropics, thereby establishing a "conveyer belt mechanism" (Hansen et al., 2004; IPCC, 2007). Changes to thermohaline circulation have the potential to induce rapid climate change through alterations to the conveyor belt mechanism, increased freshwater input to the North Atlantic, and subsequent changes to the temperature and salt content.

Recent studies show a weakening in thermohaline circulation, with increasing freshwater transport to the North Atlantic, due to changes in melt and ice export from the Arctic Ocean through the Canadian Archipelago and Fram Strait (Dickson et al., 2002; Curry and Mauritzen, 2005; Serreze et al., 2006). In particular, hydrographic studies demonstrate a decline in salinities (and thus density) in the North Atlantic over the last four decades. The sources of this decline are the Great Salinity Anomaly of 1970, associated with freshwater contributions of up to 10 000 km^3 from increased export of sea ice through Fram Strait, and frequent freshwater input to the North Atlantic during the 1980s and 1990s (Curry and Mauritzen, 2005).

Modeling studies also suggest that even if greenhouse gas concentrations stabilize, sea level will rise 13 to 18 cm by the end of the 21st century because of thermal expansion alone, and from 40 to 60 cm when glacier melt is considered along with thermal expansion (IPCC, 2007). Less conservative estimates (based on paleoclimate records and evidence of disintegrating ice sheets, associated with increasing ice melt area on Greenland and increased discharge from ice streams) predict a sea-level rise on the order of meters, with devastating consequences for coastal communities (Hansen et al., 2007; Shindell, 2007). Phenomena such as the fracture of the Ayles Ice shelf in August 2005, due to the combined effects of increased temperatures and strong offshore winds (Copland et al., 2007), and the rapid melt of Greenland's glaciers and doubling in ice loss between 1995 and 2006 (Rignot and Kanagaratnam, 2006), attest to an increased vulnerability of Arctic glaciers to warming. Such an accelerated disintegration of ice sheets provides yet another example of the potential for abrupt climate change in the Arctic. This behaviour will also result in a further weakening of thermohaline circulation and potentially a slowing of the oceanic conveyor belt (Hakkinen and Rhines, 2004).

The North Atlantic is also the source for Arctic Ocean water masses, and the warm, saline Atlantic Water circulates cyclonically around the Arctic Ocean at depths of 150 to 900 m (Polyakov et al., 2005; Carmack et al., 2006). The Atlantic Water is isolated from the base of the sea ice by a cold halocline layer, which protects the ice from the large heat storage in the Atlantic Water layer. However, warming was initially detected in the Nansen Basin in 1990, and more recently in the Arctic Ocean in 2004 (Quadfasel et al., 1991; Polyakov et al., 2005). Temperature observations further demonstrated warming in the Atlantic Water layer in the Southern Canadian Basin in 1993, attributed to intrusions from the Eurasian Basin (Carmack et al., 1995), and in the Shukchi-Medelyev region in 1994 (Swift et al., 1997). Warm temperature anomalies were also observed near Fram Strait in 1999 and in the eastern Siberian shelf in 2004 (Polyakov et al., 2005; Shimada et al., 2006). Moreover, sudden warmings were observed in the Atlantic Water layer in 2004 (Dmitrenko et al., 2006), raising concerns that sea-ice melt may be enhanced by bottom melt in the western sector of the Arctic. The propagation of these abrupt, pulse-like warm anomalies in the Atlantic Water layer into the Arctic Ocean provides yet another signal of possible sudden climate change due to abrupt forcing and nonlinear feedback mechanisms.

It is the Atlantic Water that responds to large-scale teleconnection patterns such as the Northern Annular Mode (NAM) (Macdonald et al., 2005), as demonstrated in studies of salinity changes associated with an atmospheric circulation regime shift (Polyakov et al., 2005; Carmack et al., 2006). In particular, warming in the Atlantic Water layer in the 1990s, due to a dipolar (north-south) distribution of pressure associated with the NAM, resulted in a shift in the Pacific/Atlantic water boundary (McLaughlin et al., 1996; Macdonald et al., 2005). A significant decline in the cold halocline layer above the Atlantic Water layer was also observed in the 1990s. A partial recovery from 1998 to 2001 is thought to have been a consequence of changes in river extent due to prolonged changes in the wind field (Björk et al., 2002; Boyd et al., 2002). The cold halocline layer in the Arctic Ocean establishes the barrier that prevents mixing by convection of the warm Atlantic Water to the upper layers, thus allowing for sea-ice growth during the winter season. Its disappearance was therefore described as a signature of abrupt climate change because of the implications of its loss for ice growth in the Arctic Ocean (Serreze et al., 2000).

Continental shelves exhibit great sensitivity to climate change and variability. These regions where river discharge and melt onset and decay occur are instrumental in influencing thermohaline circulation (Carmack et al., 2006). Inflow shelves and the proximity of the continental shelf break to the ice edge render these regions of the Arctic Ocean the most sensitive to climate change (Carmack and Chapman, 2003). Longer ice-free seasons provide more opportunity for upwelling of nutrient-rich Pacific water from depths of 80–100 m, which is warmer and more saline than the shelf waters, resulting in enhanced melt and nutrient supply for production along the continental shelves (Carmack and Chapman, 2003). It is anticipated that increasing coastal erosion associated with the sea-level rise and increased storm surges in these open regions will influence sediment supply (Carmack et al., 2006). Inflow shelves are also significantly influenced by variations in the NAM. Moreover, the impacts of longer ice-free summers on thermohaline circulation include increased convection in winter and influence by winds in summer.

Global warming is amplified in the Arctic by ice–albedo feedback (Smith, 1998a). Climate modeling studies predict that in the 21st century, global temperature will increase on the order of 0.4˚C, and sea level will rise by an order of magnitude relative to the 20th century, even with CO_2 concentrations sustained at 2000 levels (Meehl et al., 2005). Significantly higher temperatures and sea-level rise as a consequence of thermal expansion are anticipated if an increase in CO_2 continues unabated, with a 3˚C increase in temperature for a "business-as-usual" increase in greenhouse gases, and as much as a 6˚C increase with a doubling in CO_2 concentrations (IPCC, 2001, 2007). In recent studies involving near-future simulations (Serreze and Francis, 2006), the apparent lack of evidence for an enhanced Arctic Ocean response to global warming is attributed to masking of amplified surface air temperatures (SATs) by ice cover and the thermal inertia of the upper ocean. Indeed, model projections for 2010 to 2029 indicate that currently observed decreases in sea-ice extent and thickness establish the necessary conditions for increased absorption of solar radiation during summer, reduced ice growth during autumn and winter, and a subsequent polar amplification in SAT (Serreze and Francis, 2006).

Hemispheric-Scale Changes: Sea Ice

Previous analyses of sea-ice concentration anomaly behaviour have demonstrated a significant reduction in sea-ice extent and thickness, with a trend in recent years toward later ice formation in autumn and earlier breakup in spring (Maslanik et al., 1996; Rothrock et al., 1999; Serreze et al., 2003; Drobot et al., 2006; Stroeve et al., 2007). Studies have indicated that the largest reduction (7% to 9% per decade) occurs in multi-year ice during summer months (Chapman and Walsh, 1993; Parkinson et al., 1999; Johannessen et al., 2004). Recent passive microwave satellite observations indicate a continued decline in sea-ice area and extent from 2002 to 2005. The record low was documented in autumn 2005 (Stroeve et al., 2005, 2007), and the sharpest decline in summer sea-ice extent was observed in September 2007 (NSIDC, 2007). This decline has been attributed to a number of mechanisms, ranging from a delayed response to large-scale teleconnection patterns such as the NAM, to a decrease in the average age of ice in the Arctic Basin (Rigor et al., 2002). Monthly sea-ice means illustrate the trend (slope) toward negative (lower than the 1978–2003 average) sea ice concentration anomalies in the Northern Hemisphere (Johannessen et al., 2004).

Maps of hemispheric trends in sea-ice concentration anomalies from 1979 to 2002, indicating a tendency for an increase or decrease in sea-ice concentrations over the last several decades, provide further evidence of reduction in sea-ice extent (Fig. 2). A reduction in sea ice is observed over most of the Arctic Basin, and particularly north of Alaska and in the Barents Sea. By contrast, an increase in sea-ice concentration is observed north of the Canadian Archipelago and to the west of Banks Island; this increase is attributed to compaction associated with motion of the central Arctic pack up against the Queen Elizabeth Islands. Noteworthy, however, is the significant reduction in sea ice in the area of most Arctic coastal communities. Sea-ice trends extended to 2008 would exhibit a more dramatic reduction reflecting the unprecedented decline in summer sea ice over the last three years. Longer coastal ice-free seasons will result in an increase in storm surges and coastal erosion, with important implications for northern coastal communities.

In addition to a reduction in the central Arctic pack, modeling studies have also noted a marked basin-wide thinning in sea ice (Laxon et al., 2003; Yu et al., 2004; Lindsay and Zhang, 2005), thought to be an artefact of positive ice-albedo feedback. The feedback mechanism is thought to be due to three processes: (1) increased temperatures over the last 50 years, (2) atmospheric forcing mechanisms such as the NAM and Pacific North American pattern, which redistributed thick multi-year ice and produced more open water, and (3) a subsequent increase in solar radiation absorption, resulting in the production of thinner first-year ice. In particular, a 43% reduction in sea-ice thickness was observed from 1988 to 2005, with maximum thinning extending from the Chukchi Sea to the Beaufort Sea and to Greenland. Lindsay and Zhang (2005) argue that a threshold was reached in 1989 as a consequence of increasing SAT, combined with a change in atmospheric variability that significantly influenced the internal system response. The resulting decline in sea-ice extent and thickness has since been sustained.

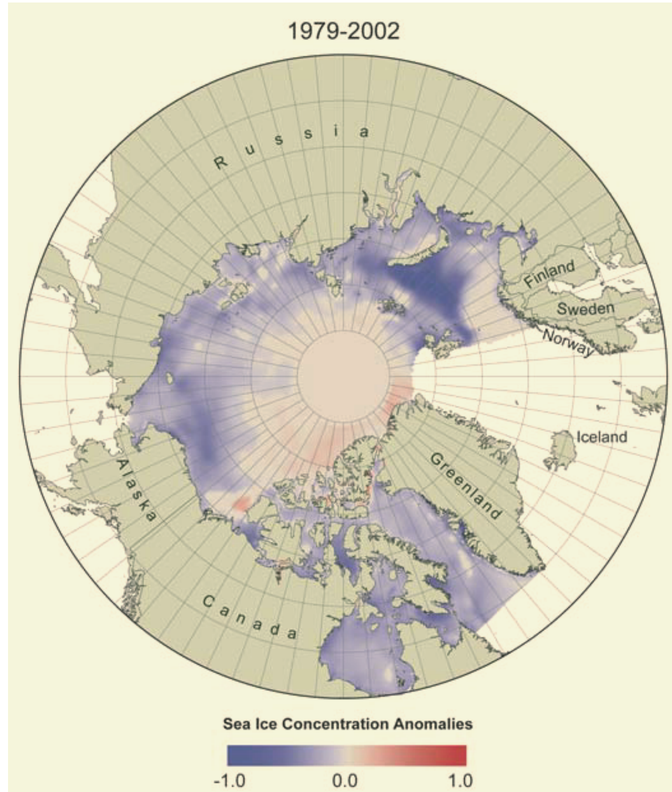

FIG. 2. Trends in sea-ice concentration anomalies in the Northern Hemisphere from 1979 to 2002. Increasing trends are depicted by warm shades and decreasing trends by cool shades.

The thinning of sea ice is further confirmed by observations that show an increase in ice 1 to 2 m thick and a decrease in ice 3 m thick (Yu et al., 2004). Investigation of thermodynamic oceanic contributions to sea-ice thickness indicate that longer summer melt seasons, a reduction in multi-year and ridged ice, and warmer Atlantic water account for continued thinning of the Arctic Ocean sea ice (Laxon et al., 2003; Yu et al., 2004). The unprecedented opening of a flaw lead in the Beaufort Sea ice pack, spanning approximately 100 km to the west of Banks Island, was recorded by the Canadian Ice Service (2008) in December 2007 (Fig. 3). This lead highlights the implications of a thinning, more mobile ice pack for ice cover in the Arctic Ocean, as well as the potential for increased influence of atmospheric forcing and storm activity that can continue to drive an accelerated response to climate change in the Arctic.

Inuit rely upon fast ice (sea ice attached to shore) for transportation, hunting, and cultural traditions. The regions of fast ice, already subject to changes in spring river discharge that modify the melting rate of offshore ice, are also being affected by the changes in atmospheric and

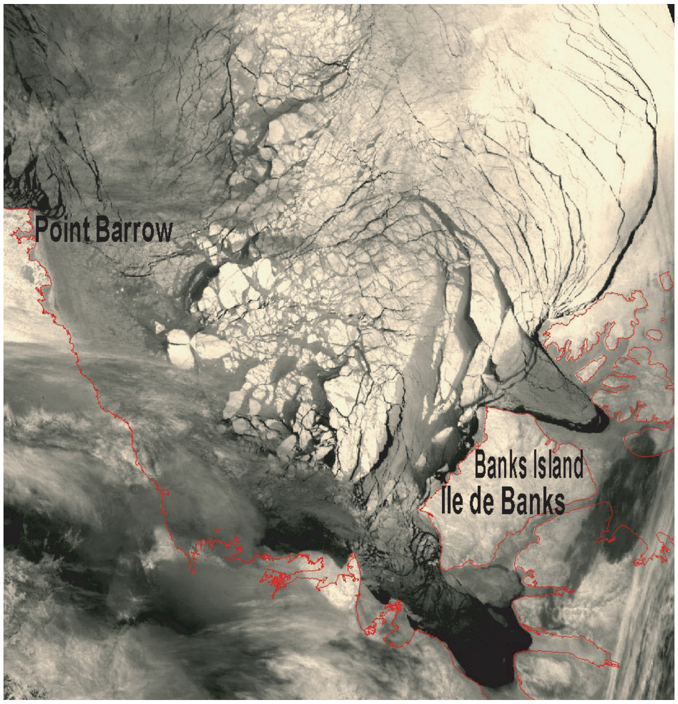

FIG. 3. NOAA image flaw lead to the west of Banks Island in January, 2008 (Environment Canada, Canadian Ice Service, http://www.ice.ec.gc.ca/app/WsvPageDsp. cfm?id=11892&Lang=eng).

oceanic forcing throughout the Northern Hemisphere (Dean et al., 1994; O'Brien et al., 2006). In general, there is a tendency for earlier onset of melt and the later onset of freeze-up of fast-ice areas (Johannessen et al., 2004). There is also evidence of change in snowfall over sea ice, which has particular implications for the development of habitats for seals (*Phoca hispida*) and polar bears (*Ursus maritimus*) (Barber and Iacozza, 2004) and for the transmission of photosynthetically active radiation used by sub-ice algae (Mundy et al., 2007). Indeed, studies of polar bear populations in the Canadian Arctic indicate that longer fasting seasons for polar bears associated with earlier melt onset dates provide one explanation for the increase in the number of polar bears observed in coastal communities as the bears search for alternative food sources (Stirling and Parkinson, 2006).

Hemispheric-Scale Changes: The Atmosphere

Annular modes, or hemispheric patterns of spatial variability, describe variations in atmospheric dynamics (Wallace and Thompson, 2002). The NAM provides an index of sea-level pressure variations, and it can be approximated by zonally averaged winds near ~55˚ N. The high NAM index is distinguished by strong westerlies, below-normal sea-level pressure over the Arctic, above-normal sea-level pressure over midlatitudes, and warmer-than-normal temperatures over northern Europe. By contrast, the negative NAM is distinguished by weak westerlies, above-normal sea-level pressure over the Arctic, and more frequent cold-temperature events.

Surface signatures of climate change have been linked to variations in the NAM. More precisely, recent studies have indicated that the shift from a low NAM index in the 1980s to a high-index NAM in the 1990s is connected to a net increase in cyclonic activity (storminess) in the 1990s (Walsh et al., 1996; Zhang et al., 2003, 2004), as well as to decadal-scale variations in such Arctic phenomena as sea-ice export through Fram Strait (Kwok and Rothrock, 1999; Dickson et al., 2002) and ice advection (Rigor et al., 2002). Wang et al. (2006) found that the regional signature of the NAM, the North Atlantic Oscillation, had a positive correlation with western Canada and a negative correlation with eastern Canada. SAT trends from observational studies also closely resemble decadal shifts in the NAM phase (Comiso, 2003; Comiso and Parkinson, 2004). However, the NAM index has been neutral since 1995, and weak correlations found between the NAM index and sea-ice extent and SAT suggest that a paradigm other than the NAM may be required to explain Arctic climate change (Overland and Wang, 2005; Comiso, 2006).

North Pacific atmospheric decadal variability is characterized by the Pacific North American pattern. Both the Pacific North American pattern and the NAM describe variability in sea-level pressure and circulation for the Northern Hemisphere, north of 20˚ N. Although 20th century Arctic circulation and SAT anomalies were described by the NAM and the Pacific North American pattern, winter SAT observations from 2000 to 2005 showed large temperature anomalies over the East Siberian Sea, consistent with a record reduction in sea-ice extent in this region (Stroeve et al., 2005) and in northeastern Canada (Overland and Wang, 2005). These temperature anomalies over the last six years were not linked to spatial patterns of variability (Overland and Wang, 2005; Comiso, 2006), but were thought to be the result of ice-albedo feedback mechanisms. Atmospheric forcing, manifested in anomalously strong winds and SAT, was also found to contribute to unusually low wintertime sea-ice extent (Comiso, 2006). McCabe et al. (2001) attribute this forcing to an increased influence of storm activity in Arctic regions in the last decade. Their view is confirmed in storm-tracking studies by Zhang et al. (2004), who noted not only an increase in Arctic cyclone activity in high latitudes and a decrease in mid latitudes from 1948 to 2002, but also a shift in storm tracks to the Arctic during summer, with stronger storms during winter. Zhang et al. (2004) also linked changes in Arctic storm activity to changes in sea-ice motion in the Beaufort Sea, namely a shift from the anticyclonic to the cyclonic circulation regime during the 1990s (Proshutinsky and Johnson, 1997). Persistence in the SAT patterns has resulted in warmer ocean temperatures and a shift from Arctic benthic to Subarctic pelagic ecosystems (Overland and Stabeno, 2004).

Recent studies have shown that the increase in SAT is responsible for an accelerated increase in the oceanic heat content and latent heat in Arctic waters attributable to decreasing sea-ice extent (Zhang, 2005). Changes in SAT

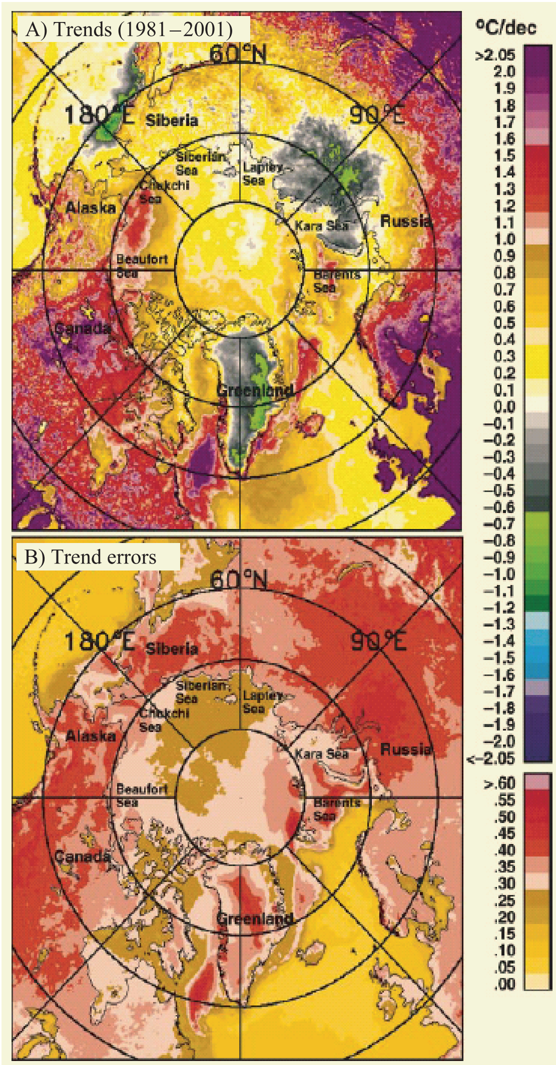

FIG. 4. Trends (slopes) and trend errors in surface air temperature anomalies from 1981 to 2001. Trends in units of °C/decade (Comiso, 2003: Fig. 5).

observed in satellite data also highlight accelerated warming over the last several decades relative to a 100-year trend (Comiso, 2003). In particular, increases of 1.09 ± 0.22°C per decade for North America and 0.43 ± 0.22°C per decade for Eurasia have been computed (Fig. 4). Warming is observed over most of the Arctic Basin during spring, summer, and autumn, with significant spatial variability. Seasonal trend analyses show that greatest warming occurs during autumn in the Chukchi and Beaufort seas and is thought to be an artefact of continually decreasing ice cover. Warming in spring is attributed to a decline in perennial ice (Smith, 1998b). Significant warming is observed over the Beaufort Sea for all seasons. Cooling observed in winter over the Bering Sea, Alaska, and the Chukchi and Siberian seas is associated with an increase in sea ice, which may be linked to the aforementioned shift in multi-year ice to the western Arctic. SAT observations also indicate an increase in the melt season by 10–17 days per decade (Comiso, 2003).

Permafrost

The melting of permafrost, or permanently frozen subsoil, is also an essential consideration for Arctic climate change (FitzPatrick, 1997). As previously noted, the greenhouse gas methane released by melting permafrost, with a warming potential 60 times that of carbon dioxide over 20 years (Shindell, 2007), has the potential to induce abrupt climate change through nonlinear feedback mechanisms. Studies of regions experiencing melting permafrost documented an increase in methane of 20% to 60% from 1979 to 2000 in Sweden (Christensen et al., 2007). Permafrost temperature observations in the Arctic have documented changes ranging from 0.3° to 0.8° in the Mackenzie Delta at depths of 20–30 m between 1990 and 2002, and from 1° to 2° in Svalbard at depths of 2 m over the last 60 to 80 years, and data from global monitoring sites also indicate an increase in thickness of the active layer, the soil above permafrost that undergoes the freeze-thaw cycle (IPCC, 2007). Changes in permafrost and the active layer will have significant implications for Arctic infrastructure and housing. Schindler and Smol (2006) note that because of melting permafrost, the ice bridge over the Mackenzie River connecting Yellowknife to southern regions opens five weeks later now than in the 1950s.

Local-Scale Changes of the Southern Beaufort Sea

Numerous studies have illustrated the role of oceanic forcing on sea ice in the context of the Beaufort Gyre (LeDrew et al., 1991; Proshutinsky et al., 2002) and associated effects on the southern Beaufort Sea. A strengthened Beaufort Gyre is associated with the anticyclonic circulation regime, or low-index NAM phase (Fig. 5A; Macdonald et al., 2005). A weakening in the Beaufort Gyre associated with a cyclonic circulation regime, or high-index NAM phase (Fig. 5B; Macdonald et al., 2005), and observed from 1989 to 1997, reflects the coexistence of regions of high and low sea-level pressure in the Canadian Arctic in late summer and early autumn (Proshutinsky et al., 2002; Rigor et al., 2002). Moreover, strengthening of the Beaufort Gyre corresponds to an increase in the northeasterly winds, while its weakening corresponds to a decrease (Maslanik and Serreze, 1999; Drobot and Maslanik, 2003). Recent studies (Lukovich and Barber, 2006) demonstrate frequent reversals in the Beaufort Gyre in summer months, which are reflected, with a time lag of two to six weeks, in stratospheric phenomena. The consequence of this reversal in the gyre is likely linked to regional ice-albedo feedback. When the gyre operates in an anticyclonic fashion, the pack converges and the surface albedo remains high, protecting the pack ice from melting. When the gyre becomes cyclonic, there is a tendency for the ice to diverge, which lowers the surface albedo and promotes melting (Proshutinsky and Johnson, 1997).

The coupling of atmospheric and oceanic forcing also contributes to sea-ice variability in the southern Beaufort

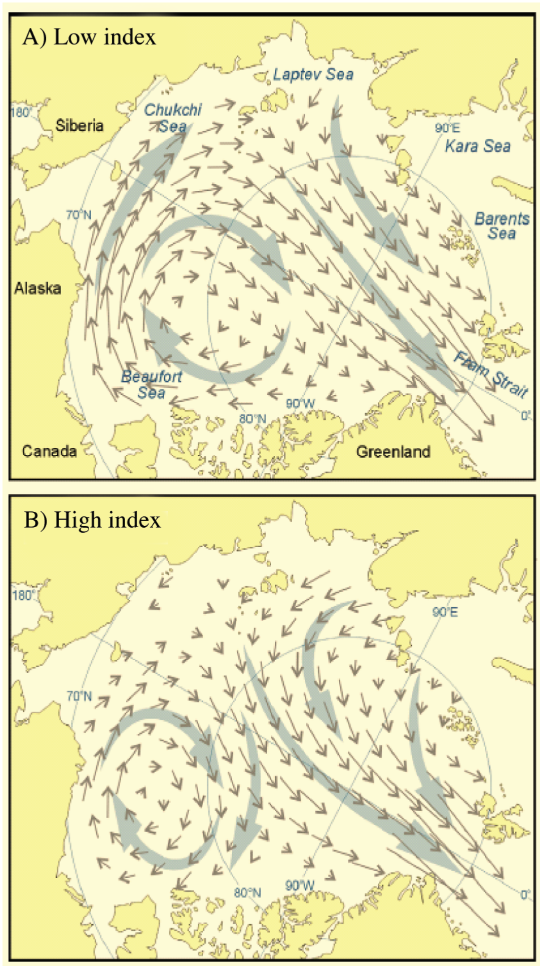

FIG. 5. Ice motion showing changes in the Transpolar Drift and Beaufort Gyre during the atmospheric (A) anticyclonic circulation regime (similar to the low-index Northern Annular Mode) and (B) cyclonic circulation regime (similar to the high-index Northern Annular Mode) (Macdonald et al., 2005: Fig. 14; reprinted with permission from Elsevier).

Sea. This phenomenon is apparent, for example, in coastal upwelling. A strengthened Beaufort Gyre associated with strong northeasterly winds gives rise to upwelling along the southern Beaufort Sea boundaries and downwelling in the central basin (Carmack and Kulikov, 1998; Proshutinsky et al., 2002). The opposite occurs for a weakened Beaufort Gyre. Carmack and Kulikov (1998) identified both the existence of northeasterly winds and the Mackenzie Canyon as key contributors to upwelling in the southeastern Beaufort Sea during the late summer and early autumn: flow driven by easterly winds interacts with the Mackenzie Canyon to generate shelf-ocean exchange. Modeling studies of summertime ice-edge retreat along the Canadian Shelf of the Beaufort Sea have further demonstrated that wind-driven upwelling is effective in generating shelf-basin exchange when the ice edge retreats beyond the continental shelf break (Carmack and Chapman, 2003).

Median ice concentrations from sea-ice charts and satellite imagery show that in the southern Beaufort Sea, landfast ice begins to form in November and continues to grow outward from the coast during December and January (Barber and Hanesiak, 2004). Landfast ice begins to decay in the Amundsen Gulf in mid June and disappears along the Tuktoyaktuk Peninsula in early July. However, the decay of landfast ice is also influenced by the Mackenzie River discharge: the thawing rivers flood surrounding sea ice and deposit sediments, which increase albedo and transport heat from the terrestrial to the marine environment (Dean et al., 1994; O'Brien et al., 2006).

Of particular interest in the southern Beaufort Sea is the interface between pack ice and landfast ice, which is governed by variability in the Beaufort Gyre. As landfast ice forms along the coast, shear zones develop between landfast and mobile pack ice. Although little variability was observed within the landfast or the pack-ice formation regions from 1979 to 2000, significant variability was observed at their interface owing to the motion of the central Arctic pack in response to large-scale teleconnection patterns. Greatest variability is observed in the polynya region to the west of Banks Island, also in response to circulation in the Beaufort Gyre. Studies have also shown that landfast ice along the Alaskan coast forms a month later than in the 1970s, which has important implications for offshore oil exploration and coastal erosion (Mahoney et al., 2007).

Sea-ice studies based on high and low ice indices (light ice and heavy ice) and dynamical considerations suggest that variations in landfast ice are associated with NAM indices. In particular, light ice years are associated with a high NAM index the preceding winter, reflecting a weakened Beaufort Gyre, and heavy ice years with a low NAM index the preceding winter from a strengthened Beaufort Gyre (Drobot and Maslanik, 2003). A southeasterly shift in the sea-level pressure high associated with the low NAM index results in a predominance of northeasterly winds and advection of ice away from the shore. By contrast, the high NAM index results in less ice advection. Thermodynamic processes also contribute to summertime ice conditions, with warmer temperatures during light ice years.

Modeling studies have also explored the impact of climate change on thickness and duration of landfast ice as monitored through thermodynamic considerations, namely changes in temperature and snowfall. Dumas et al. (2005) found that a temperature increase of 4˚C, with a 20% increase in snow accumulation rate, will result in a 24 cm reduction in mean maximal ice thickness and a three-week reduction in ice duration (SE ± 17 cm and ± 9 days, respectively). They note the implications of thinner landfast ice for load requirements on ice roads used in oil exploration, while also emphasizing the need for increased precipitation monitoring to account for spatial variability in snowfall, and thus provide more accurate assessments of ice thickness in the southern Beaufort Sea. Evidence for early melt and late onset of ice formation, in addition to thinner ice, suggests a continued decline in ice cover in coastal regions of the southern Beaufort Sea.

INUVIALUIT OBSERVATIONS OF CLIMATE CHANGE

As noted, satellite SAT observations show that some of the most profound warming is expected to take place in Canada's western Arctic (Comiso, 2003), home to the Inuvialuit people. This extensive warming trend will have major implications for the Inuvialuit, many of whom still actively harvest wildlife and consider traditional foods an important part of their diet. Significant changes to the extent of landfast ice caused by climate change will particularly affect fish harvesting (Usher, 2002). Inuvialuit traditional knowledge (TK) shows the impacts of changing temperatures on factors such as sea-ice extent, landscapes, wildlife, and wildlife habitat; the accelerated impact of climate change on these factors has been observed by younger generations in recent decades. Information on these observations, some of which is presented here, has been collected at various meetings and workshops over the past several years (Communities et al., 2005). However, it is important to note that information on TK of the Inuvialuit (and other Inuit groups) is not widely documented, and valuable information gathered from TK holders often takes the form of personal communications as events occur.

Sea Ice

Sea ice is an important part of the ecosystem for people in coastal areas. Inuvialuit use the ice for travel corridors and for hunting. Evidence for changing climatic conditions is reflected in Inuvialuit accounts of thinning ice and longer ice-free seasons. The reduction in sea-ice thickness determined from modeling studies and observations (Yu et al., 2004; Lindsay and Zhang, 2005) has also appeared in Inuvialuit observations of such natural phenomena as breathing holes for seals (Snowchange Project, 2004). Inuvialuit observations also indicate that sea ice is melting earlier in spring. Both sea-ice thinning and longer ice-free seasons have significant implications for the Inuvialuit communities because many resource species (e.g., seals, polar bears) are tied to the sea ice. An elder from Ulukhaktok (formerly Holman) stated (Snowchange Project, 2004):

> When I was younger, the ice started melting in June, and at times in late July, but now it starts melting in May. Now people must travel the ice late in the season with caution, as their TK is less reliable for predicting whether it is safe or not.

Similar accounts of evidence for climate change from Ulukhaktok inhabitants may also be found in Pearce et al. (2006). Longer ice-free seasons also affect major transportation corridors, such as the aforementioned Mackenzie River ice road. Delayed ice formation associated with longer ice-free seasons in recent decades also has important implications for northern coastal communities and the Inuvialuit in particular. For example, the sea did not freeze over at Ulukhaktok in 2000, and in 1998 there was no landfast ice in the Inuvialuit Settlement Region in late December, although there is usually some by November. The lack of ice severely restricts activities of residents from those Inuvialuit communities who travel and hunt within the seasonal ice zone. When ice does form, people report that there is more rough ice than there used to be (Communities et al., 2005). Changes in landfast ice formation present additional safety hazards. When there is less ice, the disappearance of ice as an insulating layer is thought to lead to more fog during certain times of year, which restricts the ability of people to travel on the ocean. As a result, people of northern communities are finding it more difficult to predict when fog will occur and how long it will last.

The unpredictability of conditions and the increasing unreliability of TK for making accurate predictions are a major source of stress and anxiety for Inuvialuit. Uncertainty about their safety is a psychological and physical barrier against participating in culturally important traditional activities on the land.

Snow Cover and Weather

People in all of the Inuvialuit Settlement Region communities report that there is less snow than in the past (Communities et al., 2005), which creates difficulties for overland travel routes and can lead to increased wear and tear on snowmobiles and sleds. One elder in Ulukhaktok stated that there is not enough snow any more to make good igloos, but only thinner ones of poor quality (Snowchange Project, 2004).

Observations widely reported in the Inuvialuit Settlement Region that it is not as cold as it used to be, and that cold snaps no longer last as long, are in keeping with scientific studies demonstrating significant warming trends in the Arctic in recent decades (Johannessen et al., 2004). Some residents also say that snowflakes are smaller than in the past (Snowchange Project, 2004). Snowfall also begins later: it previously started in September, but now comes in later months.

Inuvialuit observations also highlight changes in precipitation in recent decades. In the western Inuvialuit Settlement Region, conditions are drier, whereas in the eastern part the communities report more rain (Communities et al., 2005). Dry conditions in the west have resulted in fewer berries, lower water levels in rivers and lakes, warmer water temperatures thought to be affecting the condition of fish, and navigational hazards. Thunderstorms were also reported for the first time in Sachs Harbour in 1993–94 and have been occurring sporadically since then. Tuktoyaktuk and Aklavik are reporting more cumulonimbus clouds in the sky than have been known to occur previously (Communities et al., 2005). A recent tornado near Aklavik demonstrates an increase in northern community vulnerability to extreme weather events due to the changing climate. These reports are again consistent with scientific evidence of increased cyclonic activity and storminess recorded in recent decades (Macdonald et al., 2005).

Also significant are an increase in frequency of weather events such as freezing rain and icing around Inuvik, Paulatuk, and Sachs Harbour and the impact of these events on the condition of wildlife. A mass die-off of muskox (*Ovibos moschatus*) that occurred on Banks Island during the winter of 2004–05 is thought to have been caused by freezing rain in the autumn, which created a thick ice layer on the ground underneath the snow, thus preventing the muskoxen from accessing their food. The rougher ice mentioned in the previous section is said to result from high winds that break up sea ice during the early freeze. People in Paulatuk have also noticed a shift in the direction of the prevailing winds from the southwest to the west, affecting sea ice, water levels (through storm surges), and temperatures around the community (Communities et al., 2005), with an increase in frequency of storm surges around Tuktoyaktuk. These observations are consistent with changes in surface meridional winds shown in observational satellite data (Francis et al., 2005) and increases in storminess, or cyclonic activity, in the Beaufort Sea region (Macdonald et al., 2005). Shingle Point, a traditional beluga (*Delphinapterus leucas*) harvesting site for the community of Aklavik, had to be evacuated by helicopter on one occasion because of dangerous flooding conditions.

Transportation and Shipping/Navigation

As noted by Pearce et al. (2006) in the context of the Ulukhaktok community, uncertainty and unpredictability about travel conditions as a result of changing climatic conditions are a significant source of anxiety for the Inuvialuit. In the eastern Inuvialuit Settlement Region, Paulatuk and Ulukhaktok report that unpredictable ice is making autumn and spring travel more dangerous. Less ice on the ocean is creating more hazardous conditions for boaters because there is less protection from waves. However, these communities have different observations on water levels: people in Ulukhaktok are noticing that some rivers are now dry, whereas people in Paulatuk are noticing higher water levels (e.g., in the Hornaday River), leading to increases in erosion and sedimentation. Increased sedimentation is also observed in the western communities of Inuvik and Aklavik, and combined with lower water levels, it is making summer boat travel much more difficult. The drying of ponds will also have important implications for the Inuvialuit Settlement Region (Riordan et al., 2006; Smol and Douglas, 2007). A positive aspect of recent changes (e.g., the longer ice-free season) is a longer shipping season, which provides more time to supply communities. An accompanying disadvantage is greater opportunity for shipping of hazardous materials to Subarctic regions, with attendant risks.

Fishing and Harvesting

Inuvialuit in recent years have begun to notice changes in wildlife that they attribute to changes in the environment, particularly along coastal areas near the Mackenzie Basin. The quality of fish in general is viewed as declining, with residents often describing the fish meat as "soft" (Communities et al., 2005). Harvesters in Tuktoyaktuk have said they are catching fewer "herring" (*Clupea* spp.) and that these fish are thinner. Other communities report the same for other species of fish. Char (*Salvelinus alpinus*) around Paulatuk have more deformities and paler meat. It is suspected that contaminants may be the cause of these changes. People are now even starting to catch various species of salmon (e.g., chum [*Oncorhynchus keta*], coho [*O. kisutch*], and sockeye [*O. nerka*]) in different areas of the Inuvialuit Settlement Region (Babaluk et al., 2000).

Diminishing ice is thought to be affecting the health of seals and their pups around Ulukhaktok. With less ice, seals are not able to nurse their pups as much and seal condition is declining: seals are skinnier and the quality of their pelts is declining. Poor seal conditions, in turn, may be affecting the condition of polar bears whose main food source is seals. Polar bears are seen more often near towns as well, which creates risks for local residents and makes proper storage of meat and disposal of animal remains very important. Such behaviour, attributable to the fact that polar bears are not getting enough food on landfast ice and so are attracted to landfills and garbage dumps, is also noted by Stirling and Parkinson (2006). Grizzly bears (*Ursus arctos*) are also now being spotted more frequently on Banks and Victoria islands and even on the sea ice northwest of Banks Island in 2001. A grizzly bear was killed on the northern end of Banks Island several years ago. In the winter of 2006, a grizzly–polar bear hybrid was shot by a sport hunter near Sachs Harbour.

Inuvialuit have started seeing species in areas that are north of their normal range, such as American robins (*Turdus migratorius*) on Banks Island in the late 1990s, an oriole (*Icterus galbula*) in Inuvik in December 2000, an auklet (*Aethia* sp.) on the Tuktoyaktuk Peninsula, and yellow-rumped warblers (*Dendroica coronata*) on Banks Island in 1999 (Communities et al., 2005). Other interesting wildlife observations include long-tailed ducks (*Clangula hyemalis*) and thick-billed murres (*Uria lomvia*) seen in February 2001 near Ulukhaktok and presumed to have over-wintered in the area; belugas seen at Tuktoyaktuk on 15 June 1998, when they usually arrive in July; a steady shifting to the east of goose migration routes; insects being seen (and felt) more often in recent years on Victoria Island, which is normally too cold to support insect populations; increasing numbers of bearded seals (*Erignathus barbatus*) seen in the Mackenzie Delta, including one at Airport Lake near Inuvik in the autumn of 2001; and inexplicable accumulations of large numbers of living marine benthic invertebrate communities along the shore in recent years, which are one signature of northern marine ecosystem response to climate change.

CLIMATE CHANGE IMPACTS ON MARINE AND TERRESTRIAL ECOSYSTEMS

Changes in oceanic, atmospheric, and sea-ice phenomena in response to climate change will significantly influence terrestrial and marine ecosystems. We present predicted impacts of climate change on marine and terrestrial ecosystems to provide the basis of a framework for adaptation strategies that will effectively address and respond to such impacts.

Marine Ecosystems

Photosynthesis in Arctic seas occurs over a short period of several weeks, beginning with the development of ice algae at the ice-water interface in spring and followed by a phytoplankton bloom in the open waters in summer. Snow and sea ice limit photosynthesis by blocking light. Hence, the amount of microalgal biomass produced annually in a given region of the Arctic Ocean is directly proportional to the duration of the ice-free season, as indicated by various studies in different geographic regions of the Arctic (e.g., Rysgaard et al., 1999; Kern et al., 2005; Fortier et al., 2006). Near-zero sea temperatures also limit phytoplankton photosynthesis (Eppley, 1972). Accordingly, in modern times, and probably over most of the Holocene (André Rochon, Université du Québec à Rimouski, pers. comm. 2006), the Arctic Ocean has been characterized by an overall relatively low (e.g., Andersen, 1989) and extremely seasonal primary production; the bulk of the new, exportable microalgal biomass is produced during a few weeks in summer (e.g., Arrigo and van Dijken, 2004).

Over the present century, as the ice-free season lengthens and the summer surface layer warms up, primary production and the availability of microalgal biomass to grazers will start earlier and last longer. The overall amount of microalgal biomass produced over the annual cycle should increase in general, but not spectacularly, because the summer exhaustion of nutrients will limit primary production, as in the North Pacific and North Atlantic (Tremblay et al., 2006). Investigation of productivity on the Canadian Shelf in the Beaufort Sea demonstrates an exhaustion of nutrients in the upper mixed layer, with maximum chlorophyll at a depth of 20 to 40 m in summer (Carmack et al., 2004). In regions where nutrients are renewed by particular oceanographic processes, continuous light in summer may result in a long season of primary production that could sustain large fishery resources, as in the Norwegian and Barents seas. This scenario is verified in the case of the North Water in northern Baffin Bay, where a long ice-free season (up to four months) during the midnight sun, coupled with frequent renewal of nutrients in the surface layer, sustains an extraordinarily long season of primary production by Arctic standards (Klein et al., 2002; Tremblay et al., 2006). Interestingly, up to 79% of this primary production is exploited by grazers in the surface layer, and this efficient transfer of energy to the trophic web explains the remarkable abundance of marine mammals and birds in and around the North Water (Tremblay et al., 2006).

The low-diversity zooplankton of the Arctic Ocean shows highly specialized adaptations to survive sub-zero temperatures and the extreme seasonality of primary production. For example, large calanoid copepods, the primary grazers of microalgae, have developed sophisticated adaptive (life-history) strategies to (1) match the production of their offspring with peak availability of phytoplankton, (2) maximize summer growth and accumulation of energy in the form of lipid reserves, and (3) minimize energy expenditures during the long winter months when food is unavailable (see Conover and Huntley, 1991 for a review). Regional relaxations of the harsh conditions prevailing in Arctic seas accelerate development and increase population abundance of key species. For example, the higher availability of microalgal food and a warmer surface layer accelerate the recruitment and development of herbivorous copepods in the ice-free North Water relative to non-polynya regions (Ringuette et al., 2002). Similarly, non-limiting food and relatively warm surface waters favour the survival of the planktonic larvae of arctic cod (*Boreogadus saida*) in the Northeast Water of the Greenland Sea (Michaud et al., 1996; Fortier et al., 2006).

As the ice regresses and conditions become more favourable for zooplankton grazers (as seen in polynyas), an increasing fraction of the vertical carbon flux will be diverted into the pelagic trophic web. Benthos-rich Arctic shelves could shift to an ecosystem dominated by pelagic processes (Carroll and Carroll, 2003; Piepenburg, 2005). Benthos-dependent marine fauna such as diving ducks, walruses (*Odobenus rosmarus*), gray whales (*Eschrichtius robustus*), and bearded seals will be the first animals to feel the impact of such an ecosystem shift (Laidre et al., 2008). The first stages of this spectacular transformation, including increased sea and air temperatures, reduced sea ice, increased pelagic fish populations, reduced benthos, and the displacement of marine mammal populations, have taken place in as little as a decade on the shallow northern Bering Sea shelf and are expected to spread soon into the region of the Arctic Basin that is influenced by Pacific water (Grebmeier et al., 2006). Indeed, these changes are in keeping with the catastrophic reduction in sea-ice cover (from 60–80% to 15–30%) observed in the western Pacific since 1997, associated with increased SATs in spring and ice-cover variability (Shimada et al., 2006).

Thus, over the next several decades, a progressive reduction of the sea-ice cover and a warming of the surface layer of Arctic seas should benefit the highly specialized pelagic fauna of the Arctic by relaxing the extreme conditions that have been prevailing over recent evolutionary times. For example, the relatively good present condition of 11 of the 13 polar bear populations in the Canadian Arctic (Taylor, 2006) could reflect some general increase in the frequency of leads that make seals available to them

(Derocher et al., 2004), or an improvement of the biological productivity that sustains the production of seals, or both. Similarly, the production of calves by gray whales increases with the duration of the ice-free season on their feeding grounds in the Bering Sea (Perryman et al., 2002). Initially, at least, a lighter sea-ice regime should favour the reproduction of this species. In general, this bolstering of the pelagic ecosystem is expected to occur at the expense of the benthos. Such a displacement of benthic in favour of pelagic ecosystems as a consequence of longer ice-free seasons parallels that found in the East Siberian Sea (Overland and Stabeno, 2004).

However, in the longer term, and perhaps by the end of this century, the continued shrinking of the sea-ice habitat could mean population reductions for ice-adapted Arctic specialists and their replacement by boreal and temperate generalists moving into the Arctic Basin from the Atlantic and the Pacific (Tynan and DeMaster, 1997; Derocher et al., 2004; Barber et al., 2006). In the Beaufort Sea and in northwestern Hudson Bay, where the ice-free season has lengthened most, significant losses of body mass and reduced reproductive success in local populations of seals and polar bears have been linked to a lengthening of the ice-free season (e.g., Stirling, 2005; Ferguson et al., 2005). Inuvialuit hunters have noted the migration of polar bears to local communities in search of food (see above). As well, evidence is accumulating of a northward migration of southern assemblages in response to a shift in ocean climate. The analysis of long-term records of zooplankton collected automatically from commercial ships crossing the North Atlantic indicates that, from 1960 to 1999, warm-water copepods moved north by as much as 10˚ of latitude, with a concomitant reduction in the abundance of cold-water species, which presumably were displaced towards the Arctic Basin (Beaugrand et al., 2002). Climate-related northward shifts in the distribution of North Sea fish species have paralleled the northward migration of copepods (Perry et al., 2005). In Hudson Bay, a shift in the diet of thick-billed murres from an Arctic fish assemblage dominated by arctic cod to a boreal assemblage dominated by capelin (*Mallotus villosus*) has been linked to the lengthening of the ice-free season (Gaston et al., 2003). In the Pacific sector of the Arctic, the recent warming trend has favoured the salmon fisheries of Alaska, and Pacific salmon species have been recorded farther east in the Arctic Basin than ever (Babaluk et al., 2000). A reduction of the winter sea-ice extent is expected to bring a rapid transition on Arctic shelves from an arctic cod-dominated ecosystem to an ecosystem dominated by walleye (*Sander vitreus*)/pollock (*Theragra chalcogramma*) in the Pacific Sector and another dominated by Atlantic cod (*Gadus morhua*)/capelin in the Atlantic Sector (Hunt and Megrey, 2005). The acceleration in the northward regression of winter sea ice that began in 2005 and 2006 (NSIDC, 2006) could be a harbinger of this transformation. Finally, a continued reduction in the ice cover, after initially favouring the reproduction of the gray whale as noted above, will reduce the biomass of its benthic prey by diverting the energy flow to the pelagic ecosystem.

Annual landings of fish (commercial and subsistence) in the Northwest Territories and Nunavut are presently valued at $12 million (IPCC, 2001). Changes in the location, volume, and species of catches (fish, marine mammals and birds) related to a reduction of sea ice and the warming of the coastal ocean will affect existing fisheries and favour the development of new fisheries. For example, the distribution of species such as the northern shrimp (*Pandalus borealis*), which supports a lucrative fishery in southern Greenland, could shift northward. As global fisheries decline, the value of new Arctic resources could soar, providing new opportunities to Northerners. However, strong policies will be required to prevent the southern corporative industry from taking control of these resources and importing to the North the wasteful exploitation practices that led to the commercial extinction of most stocks in Canada and worldwide (Fortier, 1994).

Marine ecosystems will also be affected by the opening of northern sea routes, including the Northwest Passage. Lighter ice conditions and a longer ice-free season will soon open the poorly charted waters of the Canadian High Arctic to shipping, thus increasing risks of oil spills and introduction of exotic species: record sea ice reduction made the Northwest Passage navigable between August and November 2007 (CBC, 2007). Conditions for offshore oil and gas exploration and production will also improve, again increasing risks of spills. Oil pollution is of particular concern because impacts on the low-diversity, low-resilience, vertebrate-dominated Arctic marine food web are essentially unknown (AMAP, 1998).

Transport of toxic microalgae by ship ballast water increases the occurrence of paralytic, diarrheic, and amnesic poisoning of humans worldwide. The introduction of toxic microalgae to the Arctic is of particular concern because bivalves that concentrate the toxin are a common staple food of Northerners, and the toxins of some common Atlantic species of algae (e.g., *Alexandrium tamarense*) reach record toxicities at low temperatures (Maranda et al., 1985).

The potential opening of the Northwest Passage is renewing challenges to Canadian sovereignty over the channels of the Arctic Archipelago. Canada has little choice but to re-affirm its right and duty to control navigation to limit the multiplication of the environmental disasters that are bound to occur in such treacherous waters (Barber et al., 2006). The costs of suitable navigational aids, charts, ports, and satellite controls will be large, as will those for pilot, ice-breaking, and escort services in the remote Canadian Arctic, but navigation could generate major socio-economic opportunities, employment, and new capacity and expertise for Northerners.

Terrestrial Ecosystems

Arctic terrestrial ecosystems provide essential services to northern communities, especially northern aboriginal communities, which depend on wildlife resources for food. They are also important at the global scale in terms of the energy and carbon balances (Chapin et al., 2000). For example, these Arctic systems have accumulated carbon over the Holocene because of slow decomposition (Marion and Oechel, 1993); they contain about 10% of the soil carbon on the planet and nearly 40% of the soil carbon in Canada (Shaver et al., 1992; Tarnocai, 1999; Chapin et al., 2004). This soil carbon accumulation is equal to nearly 30% of the carbon held in the earth's atmosphere (Chapin et al., 2004). Low temperatures and short growing seasons are strong filters for species diversity, and these ecosystems have fewer species than southern terrestrial biomes. However, Arctic terrestrial ecosystems are important stores of biodiversity for some groups, such as bryophytes and lichens (ACIA, 2005). One of the defining features of these landscapes is the presence of continuous permafrost, which strongly influences the rate of various processes in the thin active layer that melts each summer (Wookey, 2002). A warming climate is expected to change these systems drastically, and in many areas such as the Inuvialuit Settlement Region, changes are clearly underway. Evidence includes the erosion of coastlines at rates of 3–10 m per year (Carmack and Macdonald, 2002) and the delayed opening of transportation routes such as the aforementioned ice bridge over the Mackenzie River between Yellowknife and the south (Schindler and Smol, 2006; IPCC, 2007). Several recent publications have reviewed the effects of climate variability and change on Arctic terrestrial systems (e.g., Serreze et al., 2000; Chapin et al., 2004; ACIA, 2005; Hinzman et al., 2005), and all contain much detail on the evidence for and implications of change. Here, we concentrate on examples that highlight recent changes in terrestrial systems and the potential implications at local to global scales.

Locally, as noted, Northerners are seeing changes in the phenology of ecosystem components, including earlier spring snowmelt, later arrival of freezing temperatures in the autumn, and changes in the arrival dates of migratory species (Fox, 2002; Jolly et al., 2002). These changes have also been measured at the regional scale, with snowmelt occurring earlier in many parts of the Arctic. For example, the growing season has increased by 8–12 days in northern Alaska primarily because of earlier snowmelt (Stone et al., 2002; Chapin et al., 2005). Timing of leaf-out and flowering has also advanced, and change in plant biomass is detectable at regional scales (Myneni et al., 1997; Jia et al., 2003). Advances in plant phenology have also been reported in warming experiments conducted throughout the tundra (Henry and Molau, 1997; Arft et al., 1999), providing important verification of other observations.

The warming tundra also results in changes in the biodiversity of these systems. As noted above for the Inuvialuit Settlement Region, northern residents are encountering new southern species, especially insects and birds (Fox, 2002; Jolly et al., 2002), but mammals such as red fox (*Vulpes vulpes*) and moose (*Alces alces*) are also being reported farther north. Changes in biodiversity are also noted in areas of Arctic Alaska over the past 50 years (Sturm et al., 2001a) and in long-term field experiments (Chapin et al., 1995; Walker et al., 2006). One of the most important changes has been an increase in the biomass of shrub species, especially deciduous shrubs such as birch (*Betula* spp.), willow (*Salix* spp.), and alder (*Alnus* spp.), in the forest tundra and Low Arctic of northwestern North America (Sturm et al., 2001a; T. Lantz and co-workers, University of British Columbia, unpubl. data). The increased cover and height of woody species will have important implications for the structure and function of these systems. The shade they produce will have a negative effect on tundra ground flora, such as lichens and mosses, which are sensitive to changes in light. Significant decreases in the cover of lichens and mosses have also been reported from warming experiments (Cornelissen et al., 2001; Walker et al., 2006). These reductions and differential species responses to the warming caused a significant decrease in measurements of biodiversity in many such experiments conducted as part of the International Tundra Experiment (Fig. 6) (Walker et al., 2006). Losses of lichen biomass in forest tundra and tundra regions could have important implications for the thousands of migrating caribou in Arctic North America, as they depend on lichen as important forage.

The warming Arctic climate will likely result in a series of cascading effects on tundra ecosystem processes, including changes in soil nitrogen mineralization, trace gas fluxes, plant growth, reproduction and phenology, and alterations in species composition and abundance with effects on net primary production (Hinzman et al., 2005). Changes in the carbon balance of tundra systems will affect feedbacks to global climate (ACIA, 2005; Chapin et al., 2005). The large store of carbon in permafrost soils could be released to the atmosphere as those soils become warmer, the active layer deepens, and rates of microbial processes increase. Experimental studies have shown that soil respiration tends to increase more rapidly than photosynthetic rates in response to warming, especially in well-drained soils (Grogan and Chapin, 2000; Welker et al., 2004; Oberbauer et al., 2007). The rates of carbon uptake and loss are dependent on the availability of soil nutrients, especially nitrogen. In most instances, decomposition and mineralization rates increase in warmer soils (Rustad et al., 2001; Schmidt et al., 2001), especially in well-drained, mesic soils. Hence, changes in soil moisture conditions will have important effects on processes involved in the carbon balance of tundra ecosystems (Chapin et al., 2005). Drastic changes, including flooding or drying, can result from melting of ice-rich permafrost (Lawrence and Slater, 2005), and these changes can switch the system from a carbon source to a carbon sink or vice versa (Chapin et al., 2005).

Changes in carbon and nutrient dynamics and moisture conditions will both affect and be affected by changes in the composition and abundance of plant and other species (Walker et al., 2006). The increase in the abundance of

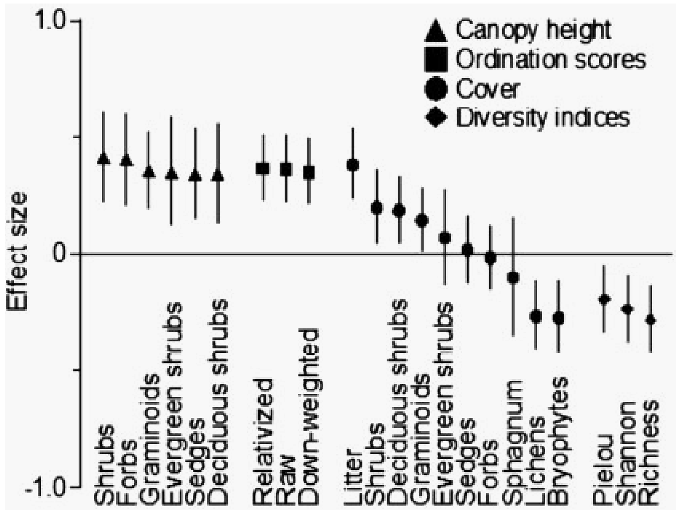

FIG. 6. Meta-analysis of warming experiments at 11 sites in the International Tundra Experiment (ITEX) (Walker et al., 2006: Fig. 2; © U.S. National Academy of Sciences, 2006). Significant increases or decreases are indicated if there is no overlap with the zero line.

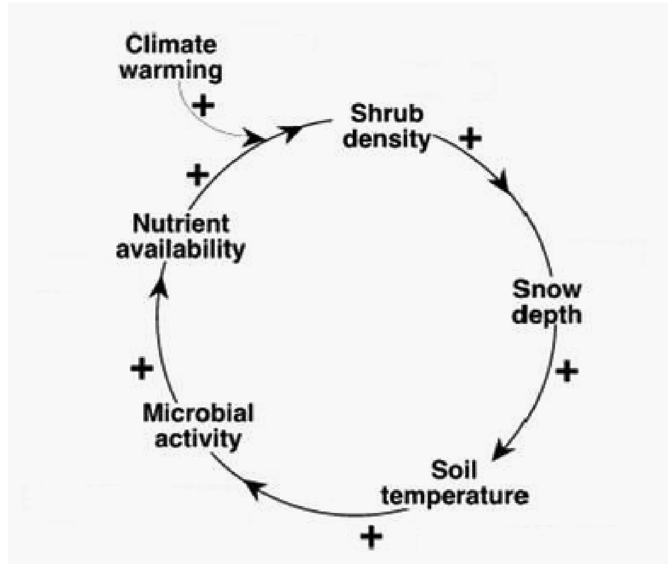

FIG. 7. Positive feedback loop due to increased shrub density in the forest tundra (Sturm et al., 2005: Fig. 9; © American Institute of Biological Sciences).

shrub species, especially in the forest tundra and Low Arctic regions of northwestern North America (Sturm et al., 2001b), and the change from herbaceous to woody tundra will affect feedbacks within the ecosystem, especially the quantity and quality of litter, as well as feedbacks between the tundra surface and the atmosphere (Sturm et al., 2001a, 2005). The taller shrubs will trap snow, providing greater insulation and increased soil temperatures in winter. This effect is likely to lead to positive feedbacks to shrub growth through increased microbial activity, especially decomposition and mineralization, leading to greater nutrient availability (Sturm et al., 2005) (Fig. 7). The greater density of leaves in a taller canopy will decrease the albedo of the surface and increase the amount of solar radiation absorbed; these local alterations could result in regional warming and affect global changes (Fig. 8). Chapin et al. (2005) estimated that the conversion of herbaceous tundra landscapes in northern Alaska to shrub tundra, coupled with continued earlier snowmelt dates, could result in an additional 9 W/m^2, or more than twice the warming caused by doubling the CO_2 concentration in the atmosphere (4.4 W/m^2). Total conversion to forest cover would actually increase warming by 26 W/m^2 (Chapin et al., 2005). These same effects can be expected throughout the Arctic, but especially in central and eastern Canada, where the treeline is expected to advance more than 100 km (Fig. 9) (ACIA, 2005). However, these changes will not be uniform in space or time along the forest tundra: they will depend on other factors affecting the establishment and growth of shrubs and trees in tundra landscapes (Payette et al., 2001), including local and landscape disturbances such as fire and permafrost degradation. Although the treeline is advancing in many areas of Alaska (Lloyd et al., 2002; Lloyd and Fastie, 2003), it has remained stagnant or declined in other regions such as northern Quebec because of regeneration responses to disturbance by fire (Lavoie and Payette, 1996). The rate of change to shrub-dominated tundra may also be mediated by the changes in structure and the increase in woody litter. Shading of the ground by taller, denser vegetation may result in cooler soil temperatures; in combination with an increase in low-quality litter (e.g., a high C:N ratio), such cooling could slow rates of decomposition and mineralization and the supply of nutrients for plant growth (Shaver et al., 1992; Chapin et al., 2005). However, recent evidence from northern Alaska indicates that the stimulation of shrub growth through the positive feedbacks mentioned above is likely to continue, and these feedbacks will result in losses of soil carbon (Chapin et al., 2005).

Much of the research on effects and evidence of climate change has been focused on low-Arctic systems, with many studies conducted near communities or in relatively accessible areas such as Alaska and northern Scandinavia. Polar deserts and other landscapes of the High Arctic, which comprise about 26% of the Arctic terrestrial land area, will also respond to climate change, and responses there are expected to be similar to those in more southern areas. However, the landscapes of the High Arctic are dominated by bare ground with greatly reduced plant cover, except in polar oases where local topography and microclimates support more complete plant cover (Bliss and Matveyeva, 1992; Freedman et al., 1994; Wookey and Robinson, 1997; ACIA, 2005). Increased temperatures and longer growing seasons will result in greater growth and reproductive effort in High Arctic plants, which should lead to expansion of vegetation into the barren polar deserts and semi-deserts. In a meta-analysis of warming experiments, High Arctic plant species showed greater reproductive responses than Low Arctic plants, while growth responses were greater in the Low Arctic (Arft et al., 1999). A recent study of long-term warming experiments

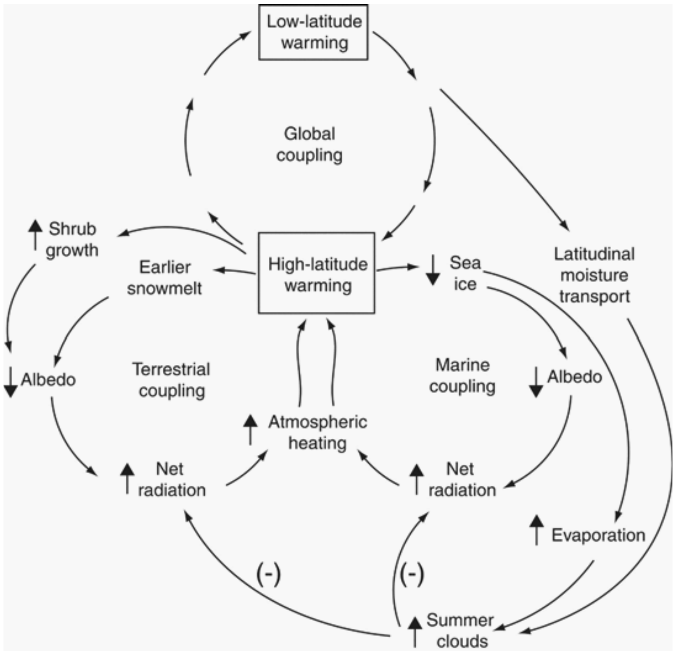

FIG. 8. Feedback loops involved in warming of high-latitude systems (Chapin et al., 2005: Fig. 2; reprinted with permission from AAAS). The influences on each process are considered to be positive unless noted by (-).

FIG. 9. Polar view of the present treeline (solid line) and its projected position (dotted line) as a result of doubling of CO_2 in the atmosphere (ACIA, 2005: Fig. 3.1).

in the Canadian High Arctic showed significantly increased seed production and viability in most species (R. Klady and G.H.R. Henry, University of British Columbia, unpubl. data). Greater production of viable seed will be a major biological driver (sensu Svoboda and Henry, 1987) for increased plant cover. However, factors such as the lack of significant soil development, low soil moisture and nutrient availability, and shallow winter snow cover will continue to restrict establishment and growth of vascular plants in many High Arctic locations. In addition, distance and physical barriers will limit dispersal of southern species to the High Arctic (Wookey and Robinson, 1997). With continued climate change, these and other "resistances" should be reduced, allowing for development of greater plant cover in the High Arctic; however, changes will be slower than in the Low Arctic.

The conversion of High Arctic landscapes from bare ground to vegetation will change local and regional carbon and energy balances and affect populations of resident and migratory herbivores. However, studies conducted in the High Arctic are not yet sufficient to allow an informed appraisal of the impacts. Welker et al. (2004) found that experimental warming at a High Arctic coastal lowland increased both photosynthesis and ecosystem respiration, but the net exchange depended on moisture conditions and showed strong annual variability. Further research will be required to understand the spatial and temporal variability in carbon dynamics in these systems. The increased plant cover will provide more forage for herbivores, including muskoxen and caribou, and for migratory birds. However, populations of these species will likely still be controlled largely by stochastic events, such as extreme weather.

CONCLUSIONS AND RECOMMENDATIONS

The world's reliance on fossil fuels is increasing greenhouse gases at an alarming rate. The climate variability and change associated with these anthropogenic inputs is affecting both marine and terrestrial ecosystems in the Arctic and putting the daily lives and cultural stability of Inuit peoples at risk. The recognition of climate change in the Arctic is clear, from both scientific and indigenous perspectives. Canada and the international community must take note of these changes and act accordingly. We can expect that three elements—mitigation, adaptation, and suffering—will be required to address the changes already underway in the Arctic. Knowledge can inform mitigation and adaptation so as to minimize future suffering to natural and anthropogenic systems in the Arctic. Towards this end the authors recommend the following:

1. Re-establish and expand climate-reporting stations, the network of gauged river systems emptying into the Arctic Ocean, marine monitoring stations, and terrestrial monitoring stations in Arctic Canada. Data from these stations are critical to understanding the spatial and temporal variability in climate change. In particular, automated gauges would provide critical information on the hydrological cycle of our northern terrestrial environments and its impact on the Arctic marine system. Marine observatories would provide unique data on important interrelationships of biogeochemical cycling, marine productivity, ocean climate, and climate change.

2. Establish an iterative community-science-policy process that facilitates the translation from community and scientific observations to policy. This process would be established through periodic community consultations that drive Arctic research, training and education that equip those living in northern communities with the tools necessary to ensure ongoing monitoring of climate change indicators, and modeling studies that provide predictions based on community and scientific observations. Recommendations based on consultations, observations, and model outputs or scenarios would provide decision makers with information essential to developing effective adaptation strategies for the Canadian Arctic.
3. To accomplish points 1 and 2, the Government of Canada should partner with provincial and territorial governments to create a single Polar Research Institute for Canada. The Polar Institute would include Inuit-based research organizations, the relevant federal and territorial departments, the two territorial research institutes, and Canadian universities. The Institute would need to have access to funding for research, operations, and management. Its primary goal would be to conduct research and to integrate, communicate, and coordinate climate-change science in the Arctic and in our interactions with other countries. Development of such an Institute could be a major contribution to the legacy of the International Polar Year.

The effects of global warming have arrived in the Arctic, and these changes will bring both positive and negative consequences. The choice of how high future temperatures will rise rests with our generation. We are at a crossroads, where the way in which our global civilizations shepherd resources intersects the way economic growth affects our habitat. The evidence for the Arctic response to global warming dictates that we immediately develop effective international polices that will limit greenhouse gas emissions and thereby minimize the risk to ourselves, our future, and our habitat.

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