17.0 CLIMATE CHANGE

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Natural large-scale climate shifts, or climate changes, such as those that resulted in past ice ages or warm interglacial periods, are driven by longterm alterations in the position of the Earth with respect to the Sun (Maxwell 1997). They can be reflected in changes in the composition of the Earth's atmosphere, particularly in greenhouse gases such as carbon dioxide and methane, which help to maintain surface temperatures in the range needed to support life. These gas concentrations are lowest during ice ages and highest during warm periods. This correlation is of concern because the atmospheric concentrations of these gases have increased sharply over the past 200 years, coincident with industrial development and the burning of fossil fuels (Figure 17-1). This increase has already affected the Earth's climate and this trend is expected to continue. Indeed, within the next century the atmospheric concentration of carbon dioxide may double.

The key temperature, hydrological, and storm-related indicators of global climate change are illustrated in Figure 17-2 and Figure 17-3, which also describe the degree of scientific certainty that the observed effects are real. Their direction and magnitude vary within and among regions.

The following sections examine current evidence for climate change in the Hudson Bay region, predictions for future climate change, and the effects these predicted changes might have on the marine ecosystem.

17.1 EVIDENCE FOR CLIMATE CHANGE

There is persuasive evidence that the climate is changing, in Canada and around the globe (e.g., McDonald et al. 1997; Zhang et al. 2000; Bonsal et al. 2001; IPCC 2001; Whitfield et al. 2002; Macdonald, 2003b), but statistical evidence for climate change in the Hudson Bay basin is limited (Cohen et al. 1994; Gagnon and Gough 2002). This does not mean that the marine ecosystem is not affected, rather that there have been few regional studies and that the wide variability of temperature and precipitation over time and space within the region makes relatively subtle long-term trends difficult to detect. Regional and national studies often aggregate the climate data over a year or a large geographical area. In an area like Hudson Bay, where the bay affects climate differently in the east and west, north and south, this can obscure local climatic trends by effectively increasing the range of natural variability of the region as a whole.

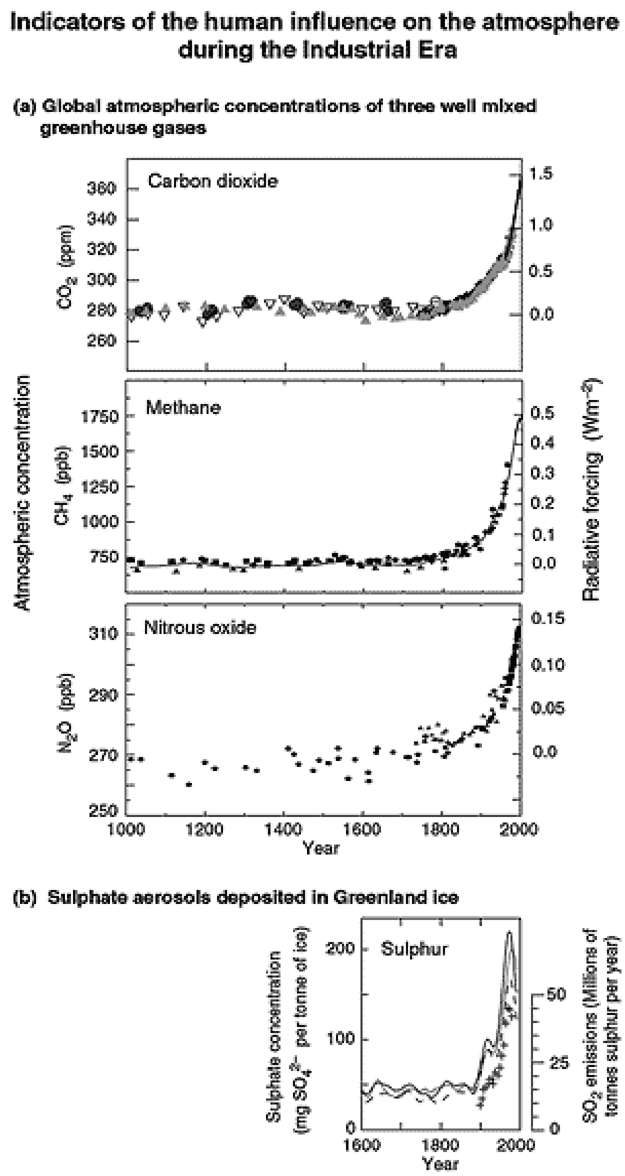

Figure 17-1. (a) Global trends in the concentration of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) over the past 1000 years. The estimated positive radiative forcing of the climate system from these gases is shown on the right-hand scale. (b) The influence of industrial emissions on atmospheric sulphate concentrations, which produce negative radiative forcing (from IPCC 2001).

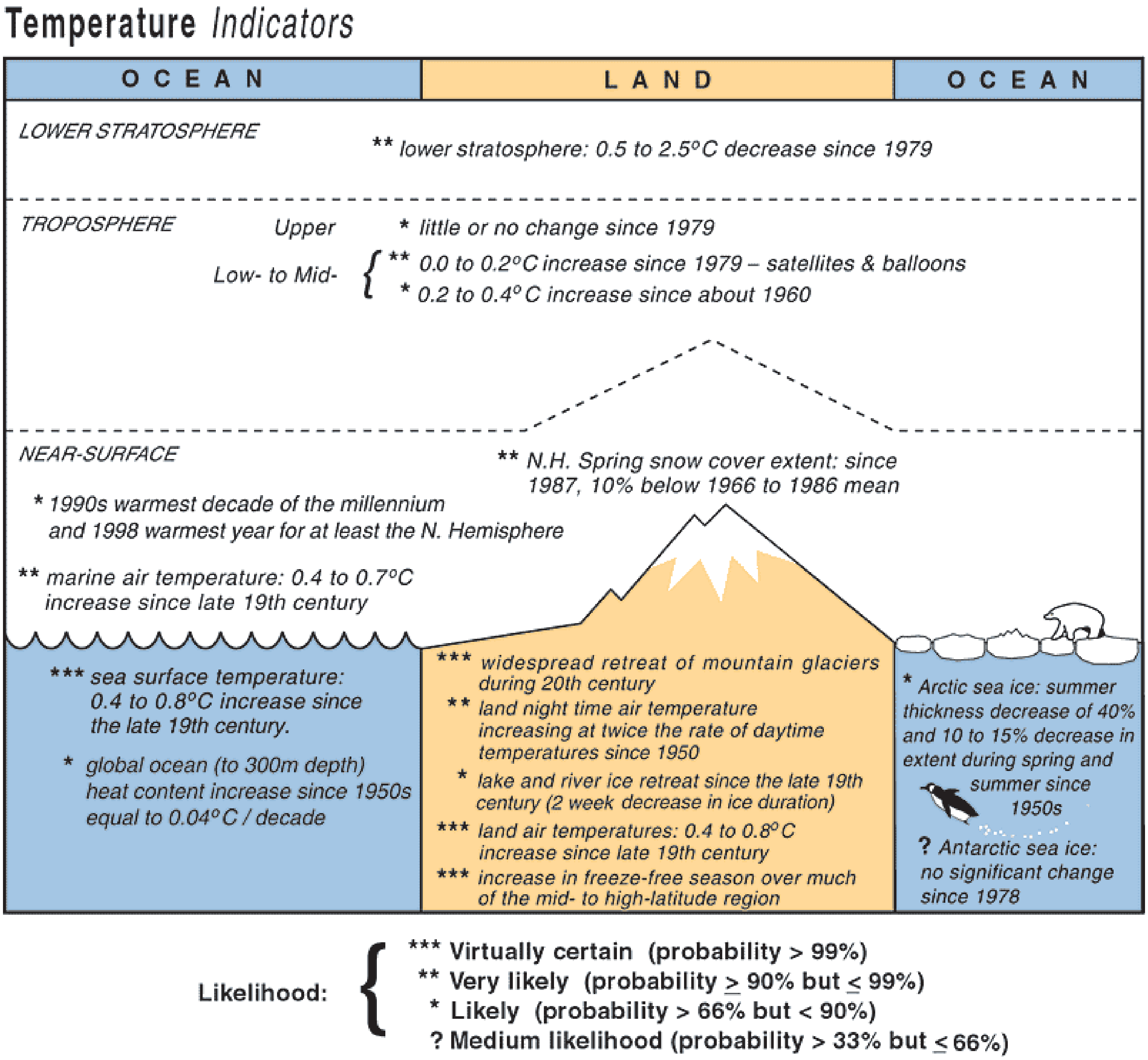

Figure 17-2. Temperature indicators of global climate change (from IPCC 2001).

Cohen et al. (1994) found evidence of warming in western Hudson Bay and cooling in the east, and of earlier ice-breakup at lakes southwest of Hudson Bay. When all the stations were combined, no trend in annual temperature was identified. They also presented evidence of increasing annual precipitation with trends toward greater precipitation in spring, summer, and autumn. None of these trends was analysed for statistical significance. The form of this precipitation, rain or snow, is vitally important as early spring rains can cause the collapse of seal breeding lairs (Stirling and Smith 2004). Other studies have analysed the temperature and precipitation records of Canadian stations during the twentieth century but have not found statistically significant trends in the Hudson Bay region (e.g., Zhang et al. 2000; Bonsal et al. 2001; Whitfield et al. 2002, 2004).

Streamflow is a useful indicator of climate change because, at the outlet of a basin, it integrates the effects on precipitation and evapotranspiration over the whole basin (Zhang et al. 2001). Changing streamflow into Hudson Bay provides some evidence for climate change but it is not coherent in time or space. Gagnon and

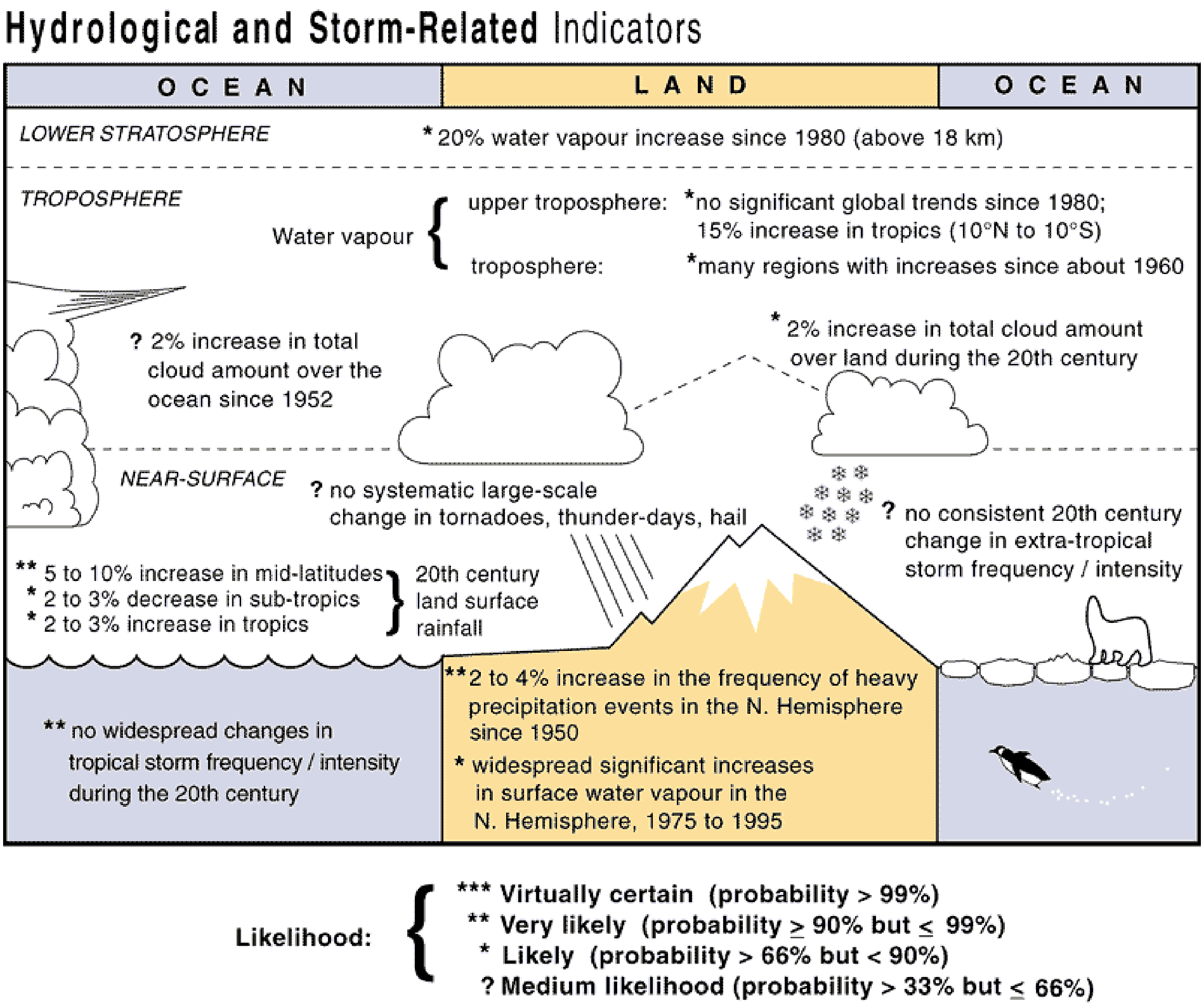

Figure 17-3. Hydrological and storm-related indicators of global climate change (from IPCC 2001).

Gough (2002) tested for relationships between streamflow, temperature, and precipitation over time at ten rivers that flow into Hudson Bay. None of them had been modified by hydroelectric development and all had at least 30 years of monthly flow records. The pattern of change they observed in streamflow was not consistent across the Hudson Bay basin but was correlated with changes in temperature and precipitation. A statistically significant spring warming trend was identified in a region that extends from Manitoba to Quebec. Within this region the Missinaibi, Island Lake, and De Pontois rivers showed a shift towards an earlier peak in spring discharge. In northwestern Hudson Bay, precipitation had increased significantly in all seasons such that the discharge of the Kazan River had increased in most months and on a yearly average. Zhang et al. (2001) found similar results for this region. In contrast, a decrease in river discharge was detected in central Manitoba, because of warmer temperatures and less rainfall. On the east side of Hudson Bay, statistically significant streamflow trends were detected for individual months, but the patterns were not coherent in time or space. The effects of climate change on streamflow in the Hudson Bay region are difficult to predict as they are not spatially uniform and are obscured when the Hudson Bay basin is treated as a single large region.

Changes in the sea level of Hudson Bay may provide evidence of global climate change. The sea level at Churchill has been monitored virtually continuously since 1940 (Tushingham 1992). It is the cumulative result of daily tidal variations, short term changes in river discharge and wind forcing, and the longterm effects of isostatic rebound, lithospheric adjustment since the last ice age, and changes in ocean volume due to land-based ice melt and thermal expansion (Gough and Robinson 2000). At Churchill, 43% of the monthly variation in sea level can be explained by local discharge from the Churchill River. The level is also affected in autumn by runoff from elsewhere in the basin, particularly James Bay. The amplitude of these seasonal changes increased in 1975 when flow was diverted from the Churchill River into the Nelson River, leading to lower pre-spring sea levels. Longterm variations in sea level may be related to thermal expansion or contraction of the oceans. To date there is no evidence that climate change has affected the sea level of Hudson Bay.

The most telling evidence of climate change in Hudson Bay is in the ice cover record (Chapman and Walsh 1993; Parkinson 2000a+b; Agnew et al. 2001; Parkinson and Cavelieri 2002; Gough et al. 2004). Satellite passive-microwave data have been used to calculate sea-ice extents over the period 1979-99 for Hudson Bay, which for the purposes of that study also included Foxe Basin and Hudson Strait (Parkinson and Cavelieri 2002). Over the 21-year period the yearly-average extent of sea ice concentrations with over 15% coverage was 798,000 km^2 with a decreasing trend of -4,300 ± 1,400 $km^2 \cdot a^{-1}$ (99%CI; P=0.01). The extent of the ice cover has been decreasing in June and July, and in November and December, indicating that the ice is melting earlier in the spring and forming later in the fall (Figure 17-4 and Figure 17-5). Most of the decline in the yearly averaged ice cover from 1979-96 occurred in the 1990's (Figure 17-6) (Parkinson 2000b). Over this 18-year period, the length of the sea ice season decreased in northwest Hudson Bay and along the southern coasts Hudson Bay and James Bay, but increased in east central Hudson Bay and near the Belcher Islands and Akimiski Island (Figure 17-7). Gough et al. (2004) found that the onset of breakup in southwestern Hudson Bay advanced by 3 days per decade over the period 1971 to 2003. There is wide variation in ice cover among years both seasonally, during breakup and freeze-up, and overall. While the satellite data reveal changes in the extent of the ice cover, they are not useful for determining changes in ice thickness, which is an important determinant of the volume of freshwater that is sequestered each year during ice formation and released in the spring.

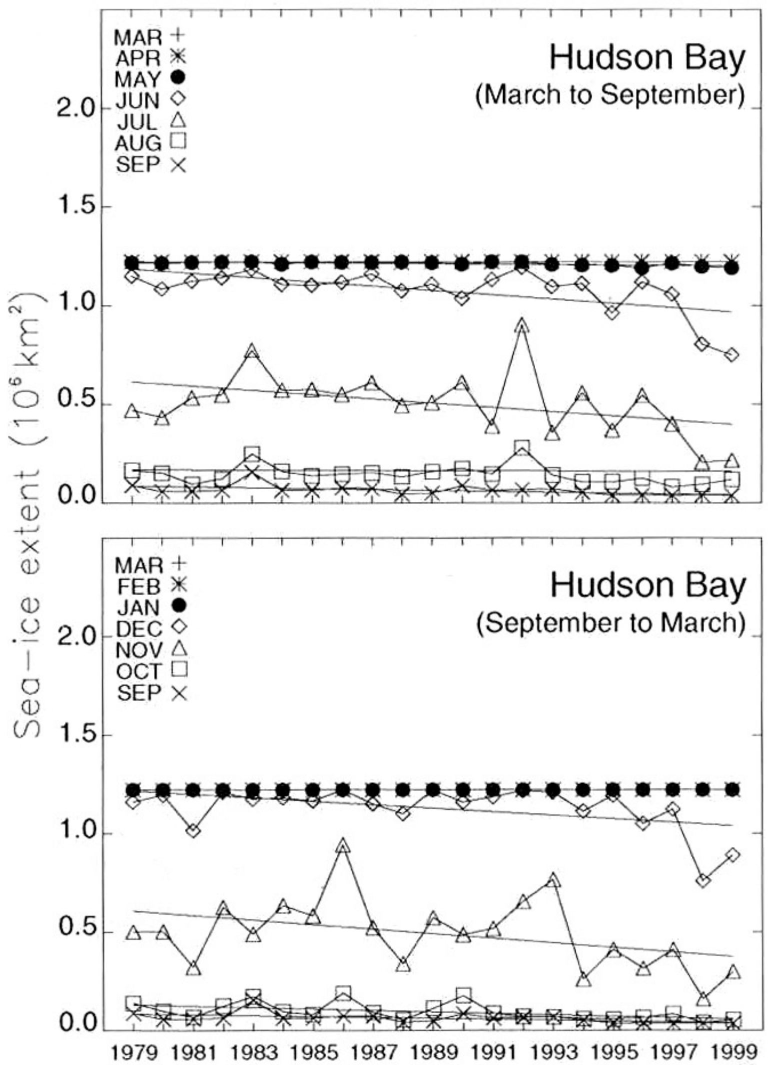

Figure 17-4. Time series of monthly sea-ice extents, arranged by month, the for Hudson Bay-James Bay-Foxe Basin-Hudson Strait area (from Parkinson and Cavelieri 2002:443). The top plot presents results from March-September, the bottom plot presents results for September-March. Lines of linear least-squares fit are included for each month.

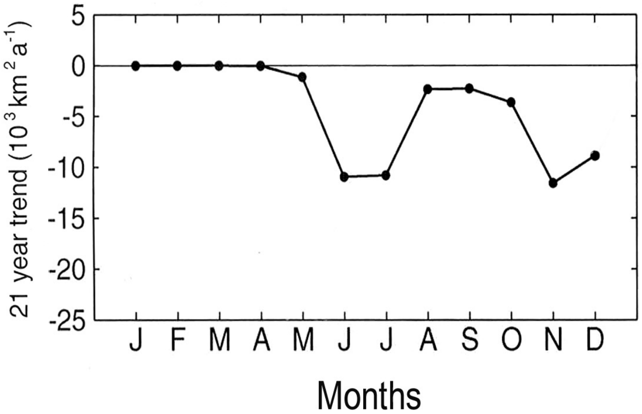

Figure 17-5. Trends, by month, in the sea-ice extent of the Hudson Bay-James Bay-Foxe Basin-Hudson Strait area calculated over the 21 years 1979-99 (from Parkinson and Cavalieri 2002:445). The trend values are the slopes of the lines of linear least-squares fit through the appropiate 21 monthly-average ice extents.

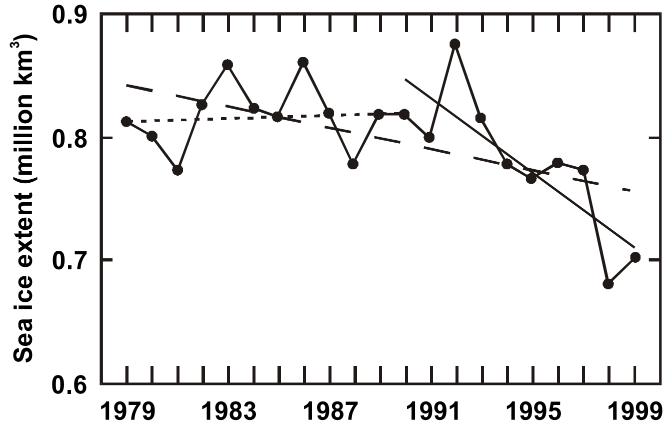

Figure 17-6. Times series of the yearly averaged extent of sea ice in Hudson Bay-James Bay-Foxe Basin-Hudson Strait from 1979-99 (from Parkinson 2000a:6). Lines of linear least squares fit are plotted for the full period (dashed) and for the 1979-90 (dotted) and 1990-99 (solid) subperiods.

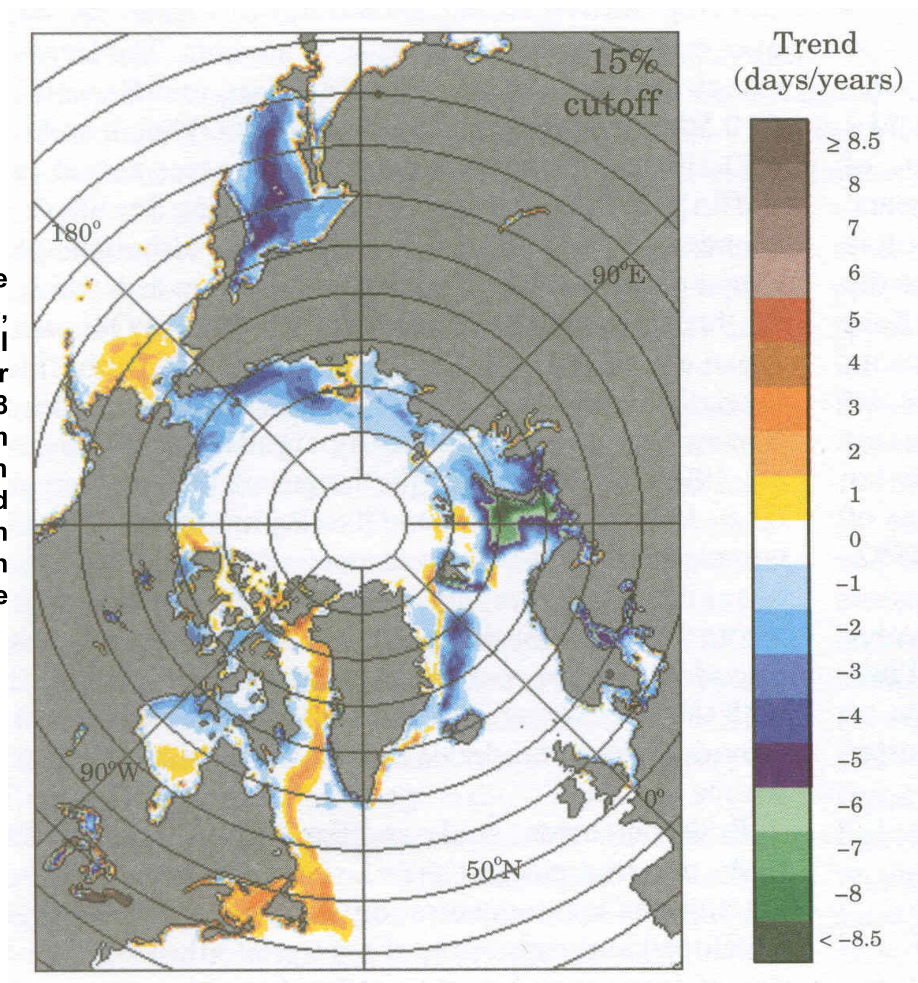

Figure 17-7.

Trends in the length of the sea ice season from 1979 through 1996, calculated at each 10 km^2 grid cell as the slope of the line of linear least squares fit through the 18 years of season length data (from Parkinson 2000b:353). The length of the sea ice season was defined as the number of days with calculated ice concentration =15%. Ice concentrations were derived from satellite data.

Climate change may also be affecting the polar bears in Hudson Bay and James Bay. As the top carnivores at the southern limits of their distribution, they are the "canaries in the coal mine" for regional climate change (Stirling and Derocher 1993). They require ice as a platform from which to hunt seals, as habitat on which to seek mates and breed, as a surface on which to travel long distances, and sometimes for maternity denning (Stirling and Derocher 1993; Stirling et al. 2004). The surface area of the seasonal ice cover determines the extent and quality of the bear's feeding habitat, and its duration determines how long they are able to feed and build up their fat stores. These stores must sustain them and their cubs from the time the ice melts and they are forced ashore, until it reforms in the fall and they can move offshore again to hunt—a period of about 4 months. Some bears eat a variety of vegetable and animal foods while on shore but these foods are not sufficient to sustain them year-round. Their dependence on ice cover makes polar bears very vulnerable to changes in its quality, distribution, and duration. Recent declines in body condition, reproductive rates, and cub survival (Figure 17-8), and an increase in polar bear-human interactions, suggest that the bears in western Hudson Bay are under increasing nutritional stress (Stirling et al. 1999; Calvert et al. 2001). These changes have been correlated with earlier breakup and later freeze-up that have prolonged the ice-free period, and thereby reduced feeding opportunities for the bears while increasing the length of their fast (Figure 17-9 and Figure 17-10). They likely are early impacts of climate change, but other factors have not been ruled out. Similar changes have not been observed in the Southern Hudson Bay Population that summers along the Ontario coast, where ice breaks up later (Obbard and Taylor unpubl. data cited in Calvert et al. 2001).

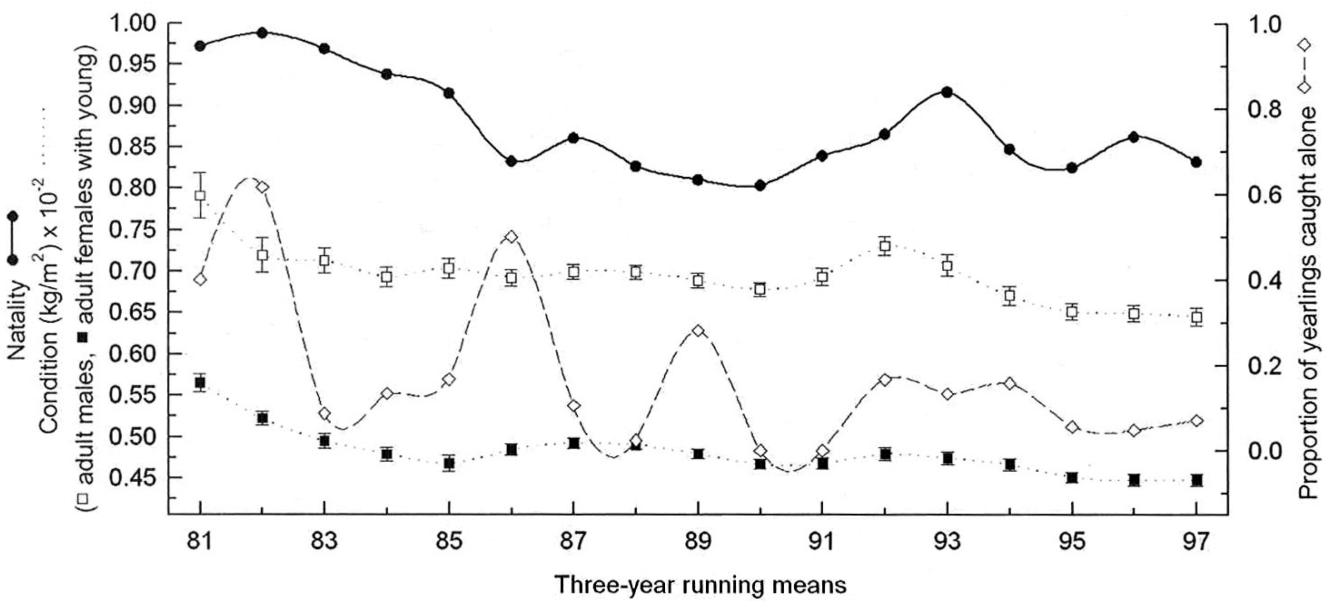

Figure 17-8. Trends in natality and condition of adult male and female polar bears, expressed as three-year running means, and the proportion of yearlings that were alone when captured in the fall (Stirling et al. 1999:302).

Ramsay and Stirling (1990) also documented a northward shift in the location of polar bear winter maternity dens in the area south of Cape Churchill, between 1970-76 and 1980-84. The reasons for this shift are not clear but the authors have suggested that they too might be related to changes in the sea ice.

Changes in the diet of thick-billed murre chicks at Coats Island suggests that the character of the fish community in northern Hudson Bay switched from Arctic to Subarctic circa 1997 (Gaston et al. 2003). The occurrence of Arctic cod, and benthic sculpins and zoarcids in their diet decreased, while that of capelin and sandlance increased (Figure 17-11). These changes were associated with a halving of the mid-July ice cover in Evans Strait over the period 1981-99, and may reflect the effects of a general warming of Hudson Bay waters on the relative abundance of these fish species. A reduction in prey availability, rather than abundance, cannot be

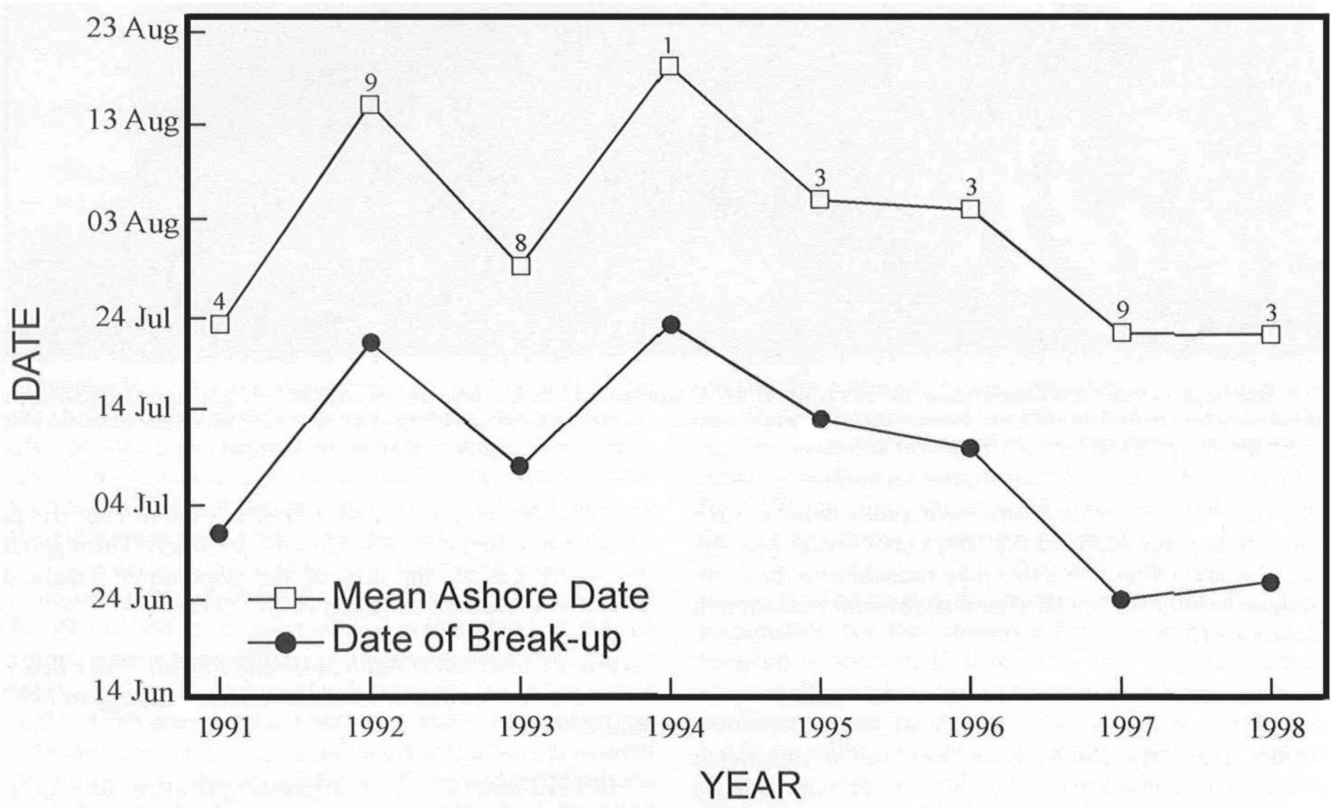

Figure 17-9. Mean date of ice breakup in the area of Hudson Bay where female polar bears with satellite collars spent at least 90% of their time each year (1991-98) and the mean dates the bears came ashore in those years (numbers above line = sample size) (from Stirling et al. 1999:299).

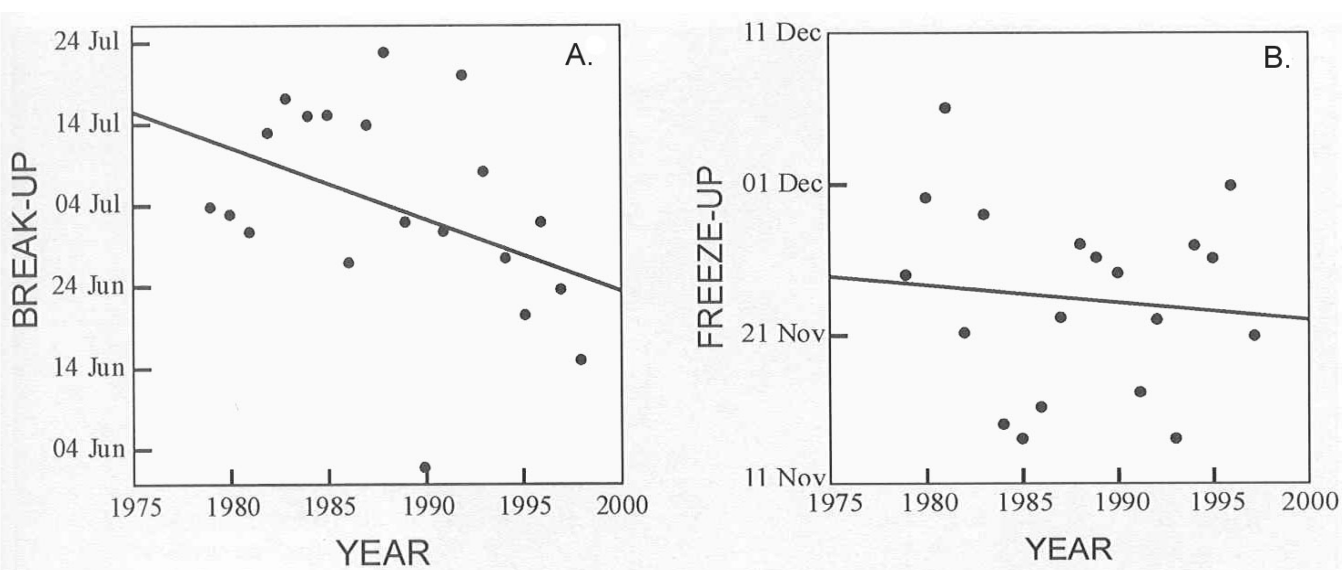

Figure 17-10. Dates of (A) breakup and (B) freeze-up of sea ice in western Hudson Bay (1979-98) (from Stirling et al. 1999:299).

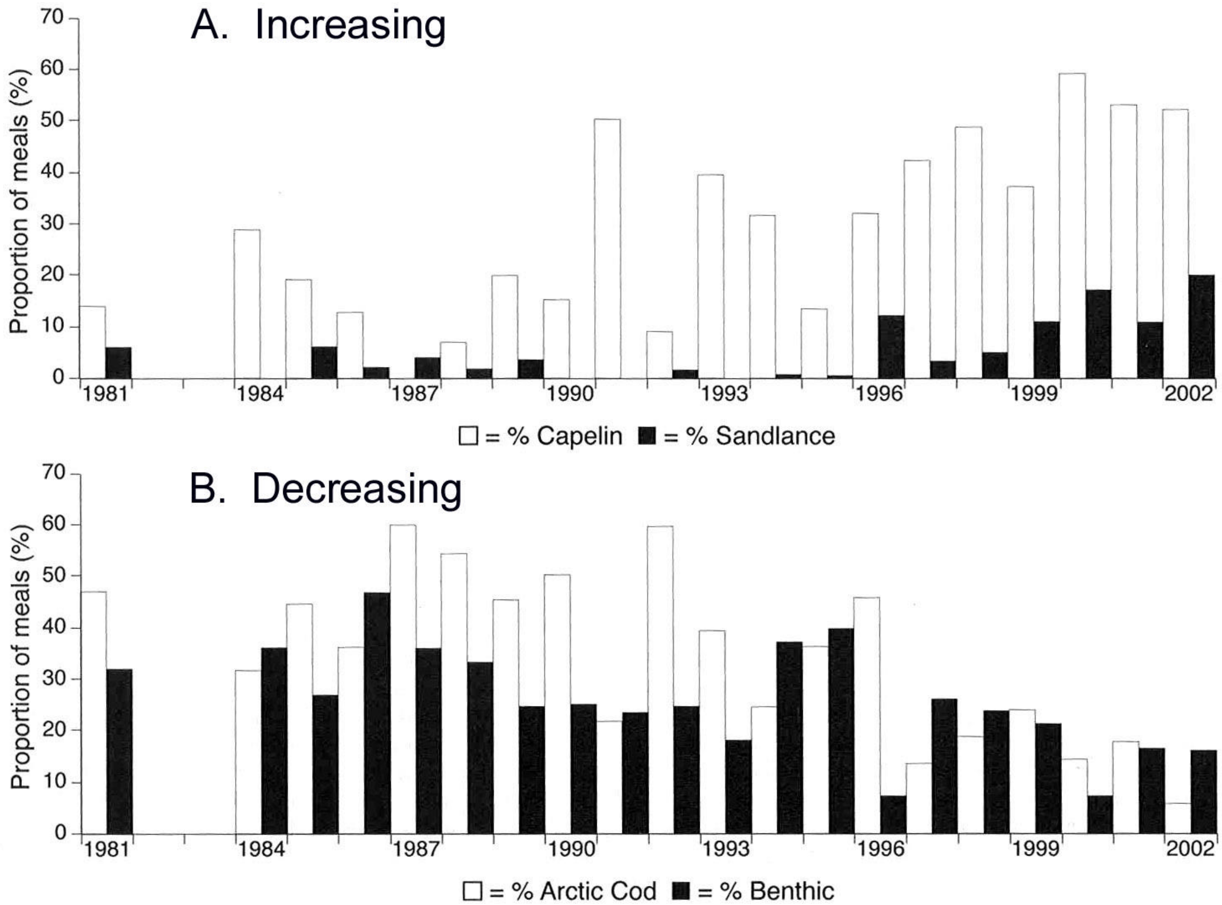

Figure 17-11. Proportion of different fish taxa in the diet of thick-billed murre chicks at Coats Island since 1981: A) increasing (capelin and sandlance); B) decreasing (Arctic cod and benthic genera = sculpins and zoarcids) (from Gaston et al. 2003:230).

ruled out as the cause of this change but two lines of evidence indicate otherwise. First, murres in the High Arctic that feed their chicks mainly on Arctic cod do so well after the ice goes, suggesting that these fish should be available to the murres in Hudson Bay despite the increase in open water. Second, 2002 was a late ice year and the proportion of cod in the diet remained low, suggesting that the late breakup does not make cod more available. Concident with these changes, in 2001 and 2002, the razorbill (*Alca torda*) was showing signs of colonizing Coats Island (Woo and Gaston cited in Gaston et al. 2003). This Atlantic seabird feeds heavily on capelin and sandlance, and had not previously been reported from Hudson Bay.

Inuit and Cree in Hudson Bay and James Bay have observed a number of environmental changes, particularly related to weather, that are consistent with the scientific observations of climate change (Table 17-1)(McDonald et al. 1997). They suggest that the climate is cooling in the east and warming in the west and northwest. Changes in the migratory timing and patterns of geese may also be related in part to climate change. Traditional knowledge can complement scientific approaches to understanding climate in Arctic Canada by providing local expertise, climatic history and baseline data, and local monitoring (Reidlinger and Berkes 2001; see also Duerden and Kuhn 1998). It also provides information that is useful for framing studies and interpreting data.

Table 17-1. Environmental changes observed in James Bay, Hudson Bay, and Hudson Strait by Inuit and Cree (modified from McDonald et al. 1997).

	Eastern James Bay	Eastern Hudson Bay	Hudson Strait	Northwestern Hudson Bay	Western Hudson Bay	Western James Bay
Weather	• shorter spring and fall seasons; • greater variability in fall; • colder winters in reservoir areas; • increased snowfall.	• cold weather persists into spring; • snow melts later • spring and summer cooling trend • less rain, fewer thunder-storms	• greater variability: • less predictable • cooling trend; • new snowfall cycle; • longer winters, snow melts later; • less rainfall.	• greater variability; • warmer, shorter winters; • snow falls and melts earlier; • cool summers in early 1990s.	• longer winters; colder springs; snow melts faster.	• shorter and warmer winters; • spring wind shifts several times a day.
Atmosphere	• change in sky colour.	• change in sky colour • sun's heat blocked by haze.	• change in sky colour.	• change in sky colour.	• change in sky colour.	• change in sky colour.
Sea Level	• salinity changing along north-east coast ; • more freshwater ice 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 freeze; • 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 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; • more non-nesting/moulting geese in Belcher and Long islands.	• new snow goose migration routes; • more 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 and 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
Beluga whale	• fewer	• fewer along coast; • moved to and travelling in currents farther offshore	• fewer in Salluit area	• fewer in Repulse Bay and Arviat area	• more in Fort Severn and Winisk estuaries; • fewer in Nelsen River estuary	
Fish	• mercury contamination; • loss of adequate habitat for several species, e.g.,, whitefish; • morphological changes in sturgeon.	• fewer Arctic char and Arctic cod in Inukjuak area		• fewer 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

17.2 CLIMATE CHANGE PREDICTIONS

Many scientists agree that there is a high probability of global warming during the next century. They are less certain about its causative factors, rate, extent, and regional effects given the complexity of the climate system and limited understanding of the crucial role played by the world's oceans. Improving our ability to predict these effects has become a research priority in Canada and elsewhere (e.g., Cohen et al. 1994; Hansell et al. 1998; Curry 2004).

While greenhouse warming is a relatively gradual process (>100 y), oceanographers have cautioned that it may have a destabilizing effect on world ocean circulation that could lead to abrupt (<10 y) regional cooling (Schmitt 2000; Gagosian 2003; Curry 2004). These sorts of non-linear threshold effects in environmental conditions may become more evident in the event of climate change (Woo et al. 1992; Jefferies et al. 1995; Schindler 2001). They can be directly or inversely related to the climate signal and, because they are difficult to predict given the complexity of feedback, are a significant source of uncertainty in modelling predictions. Rapid habitat destruction (desertification, trophic cascades) by goose populations along the Hudson By coast is one example of a threshold response triggered by weather (Jefferies et al. 1995).

Elaborate computer models have been developed to improve understanding of how the climate may respond to increases in greenhouse gas concentrations. These "general circulation models or GCMs" often simulate the type of climate that might exist if global concentrations of carbon dioxide were twice their pre-industrial levels. They use mathematical equations to represent physical processes of the climate system—particularly those involving radiation, heat and motion and the water cycle; and to calculate the interactions between these processes. Strictly speaking, they are not predictive models but rather a means of determining the sensitivity of the climate system to a change in one of its key elements (Cohen et al. 1994). In spite of their sophistication, they can only approximate reality given the complexity of the climate system and current understanding of climatic processes. They do, however, offer some predictive value and are the only practical and timely means of investigating the complete climate system and its response to the forces that affect it.

While sometimes disagreeing about the details, all of these models predict that the Earth would be warmer on average if the concentration of atmospheric carbon dioxide doubles, more so near the poles, and that it would experience overall increases in both evaporation and precipitation (Cohen et al. 1994; Maxwell 1997). They predict warming over much of western and northern Canada, but sometimes disagree on the location and magnitude of areas of surface temperature or precipitation change, particularly in eastern Canada. Warming is predicted to be greater over land than sea.

One weakness in GCMs is that few consider the effects of changes in atmospheric aerosol content (Maxwell 1997). Aerosols from atmospheric pollution can affect incoming solar radiation directly by scattering light back into space, and indirectly by promoting cloud formation and altering the chemical, thermodynamic, and optical properties of clouds. Studies are underway at Churchill, and across Canada, to gather data on spatio-temporal changes in Arctic aerosols to improve understanding of how they influence global climate and to improve the predictive ability of future climate models (Bokoye et al. 2002).

Another important weakness of climate models is their limited ability to simulate oceanographic processes, particularly those related to spatial variations in temperature and salinity (Schmitt 2000; Curry et al. 2003; Gagosian 2003). Like atmospheric winds, ocean currents circulate around the globe distributing heat. Changes to either circulation can have far-reaching climatic effects. The ocean currents move slowly but have a much greater heat capacity than the atmosphere (e.g., El Nino). When the saline surface water in the North Atlantic flows northward it loses heat to the atmosphere and cools until it can become dense enough to sink to the bottom. This makes room for more warm water to move north for cooling. If too much fresh water were to enter the North Atlantic its surface waters would no longer sink when cooled, and the flow of warm water from the Gulf

Stream could slow and perhaps stop (Aagaard and Carmack 1989; Curry et al. 2003). This might elicit a non-linear threshold response and cause an abrupt (< 10 y) climate change that would disrupt the hydrological cyle and partially or totally offset the effects of global warming in the North Atlantic region, a concern that has been identified for urgent study (e.g., Schmitt 2000; Curry et al. 2003; Gagosian 2003; Curry 2004). Whether, or how, this might affect the Hudson Bay marine ecosystem is unknown.

Climate models are not infallible. They are a respository for what we think we know (Schmitt 2000), and their response to different change scenarios relies on the judicious choice of model parameters. Gough (2001) demonstrated this in a study of the effects of climate change on sea ice in Hudson Bay. The model he used would reproduce the current climatology of the sea ice using many different pairs of values for the thermal conductivity of sea ice and thermal diffusivity of water. However, the ice thickness it predicted under a 3°C warming scenario varied widely for the different pairs, illustrating the precarious nature of modelling the climate system. The same is true of the choice of models. Gough and Wolfe (2001) compared the predicted impacts of doubling CO_2 on the Hudson Bay region, using a second generation of the Canadian general circulation model (GCMII) and the Canadian first-generation coupled general circulation model (CGCM I). The former represented the ocean as a simple two-layer slab ocean 50 m thick and predicted that the ice platform would remain in Hudson Bay; the latter used an ocean general circulation model and predicted its virtual disappearance. Clearly, the results of these models must be used with caution when their parameters produce such strikingly different results for an aspect of the marine ecosystem as vital as sea ice.

Work is under way to improve the predictive ability of these climate models for Hudson Bay (Wang et al. 1994a+b; Gachon et al. 2002, 2003; Senneville et al. 2002; Gachon and Saucier 2003; Saucier et al. 2004). It includes in particular the development of a model that more accurately represents the regional oceanography year-round. Embedding such a model into a larger scale climate model should improve predictive ability. However, improvements are also needed to the atmospheric model, particularly with respect to low-level atmospheric fields (e.g., lower winds and higher temperature) (Senneville et al. 2002). Because models are only as good as the information upon which they are based, a great deal of basic research is needed to improve understanding of the regional oceanography. Validation data sets are crucial, and coherent time series must be collected for a variety of locations.

17.2.1 Temperature

The global climate model (GCM) developed by the Canadian Centre for Climate Modelling and Analysis (CCC92) predicts a winter warming of up to 10°C and summer warming of 1-2°C by 2100 in central Hudson Bay (Maxwell 1997; Figure 17-12). Along the coasts, this increase is greater in winter (6-9°C) and than in summer (2-5°C). These warmer temperatures will melt permafrost and sea ice.

Various models predict that the area of discontinuous permafrost will eventually be halved and the boundary between continuous and discontinuous permafrost will shift hundreds of kilometres northward (Figure 17-13) (Woo et al. 1992; Maxwell 1997; Gough and Leung 2002). The timeframe for this change is uncertain but permafrost melting will lag behind surface air temperature changes (Smith 1989). Vegetation cover, soil properties, and snow cover will affect the rate and extent of changes in the permafrost. In the discontinuous zone, the depth of the active layer of soil may double. This may increase coastal erosion and the frequency of landslides and lead to pronounced thermocarst topography.

Soil processes will be affected strongly by the predicted increases in temperature and moisture (Maxwell 1997). The depth of the active layer will increase as permafrost thaws and nutrient availability should increase as the conditions for microbial decomposition of organic matter improve. Arctic tundra communities will respond with a shift toward larger shrub species that are more tolerant of moisture, and away from non-vascular plants and soil-insulating mosses (Figure 17-14). This will eventually lead to a northward shift of the treeline--which is closely related to the position of the 10°C mean July isotherm (see also Timoney et al. 1992), by up to 750 km in Kivalliq.

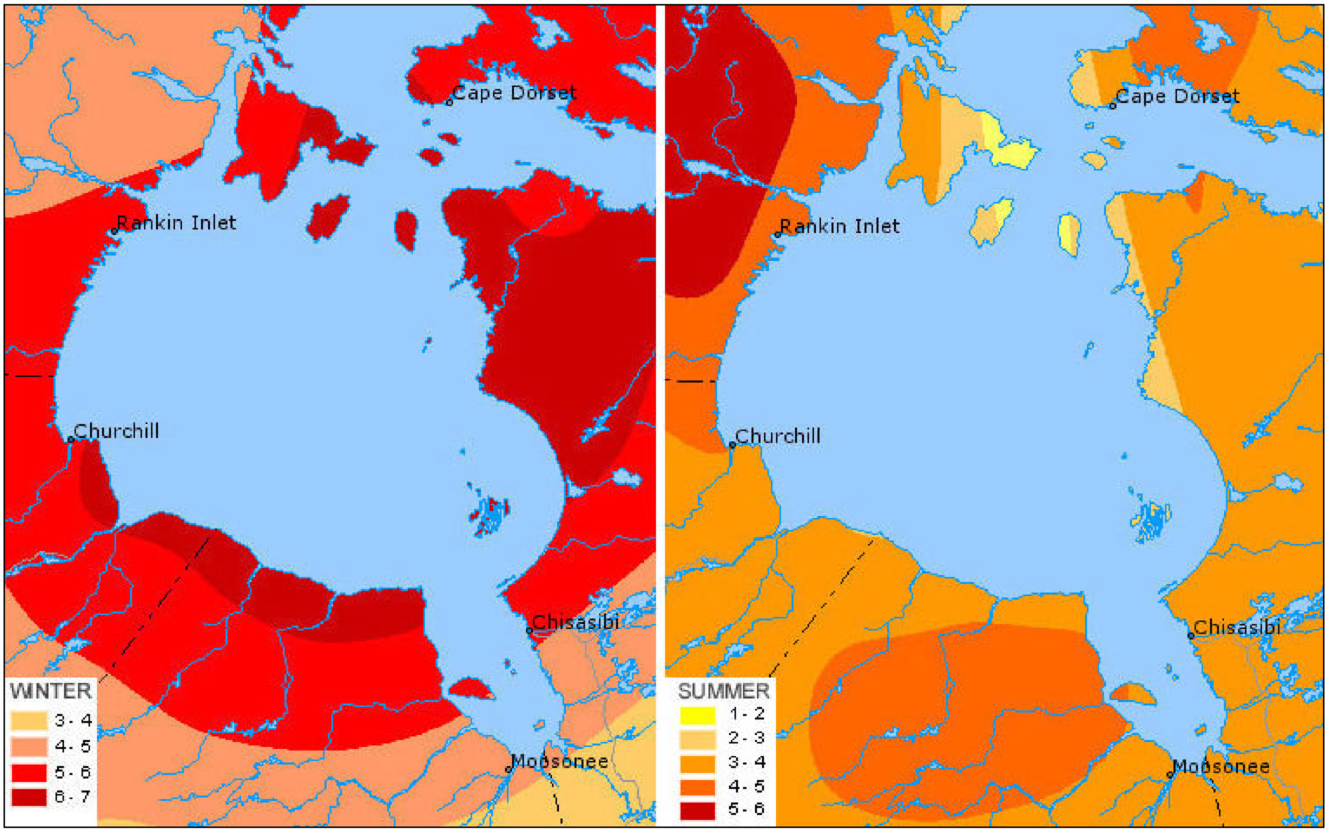

Figure 17-12. Change (°C) projected by the CCCma model in winter (December-February) and summer (June-August) air temperature from the reference period (1961-1990) to the middle of the current century (2040-2064) (from National Atlas of Canada 6th edn 2003c).

The Arctic Tundra biome may shrink until it is confined largely to the Arctic Islands. And, infilling by the taiga biome may not keep pace with the very rapid speed at which climatic warming is expected to occur. Within the existing treeline, the species composition of the forests is likely to change. Entire forest types may disappear, leading to new assemblages of species and ecosystems. The incidence of forest fires may increase and insect pests may move northward, reducing the yield of northern forests (Maxwell 1997). Timoney et al. (1992) provide a useful baseline for the location and composition of the treeline in Nunavut and the Northwest Territories against which change can be measured.

The subarctic peatlands south of Hudson Bay require a high, stable water table. They may be extremely vulnerable to climate change if warmer temperatures thaw the permafrost and affect their hydrology through changes in surface elevation, drainage, or flooding (Maxwell 1997).

Recent studies suggest that ice cover in Hudson Bay and James Bay will be reduced by climate warming but do not agree on the extent of the reduction. Global Climate Model results vary widely depending upon modelling parameters; some suggest that Hudson Bay may become ice free in winter (Cohen et al. 1994; Gough and Wolfe 2001). A three-dimensional coupled ice-ocean model also shows large reductions in the winter ice volume with climate warming (Saucier and Dionne 1998). It suggests that a simple 2°C increase in air temperature might reduce the sea ice produced in Hudson Bay by 20%, increase summer sea surface temperature by 4°C, and cause a two-week advance of breakup and delay of freezup. A comparison of sea ice concentration to melting degree day data suggests that warming of 1°C could advance ice break-up as much as two weeks in parts of the Bay (Etkin 1991). Because melting sea ice contributes more fresh water to Hudson Bay than does runoff, any change in ice cover will alter the freshwater budget (see Section 4.3), with wide ranging effects on the oceanography and ecology (see also Chapter 5 and Section 15.1).

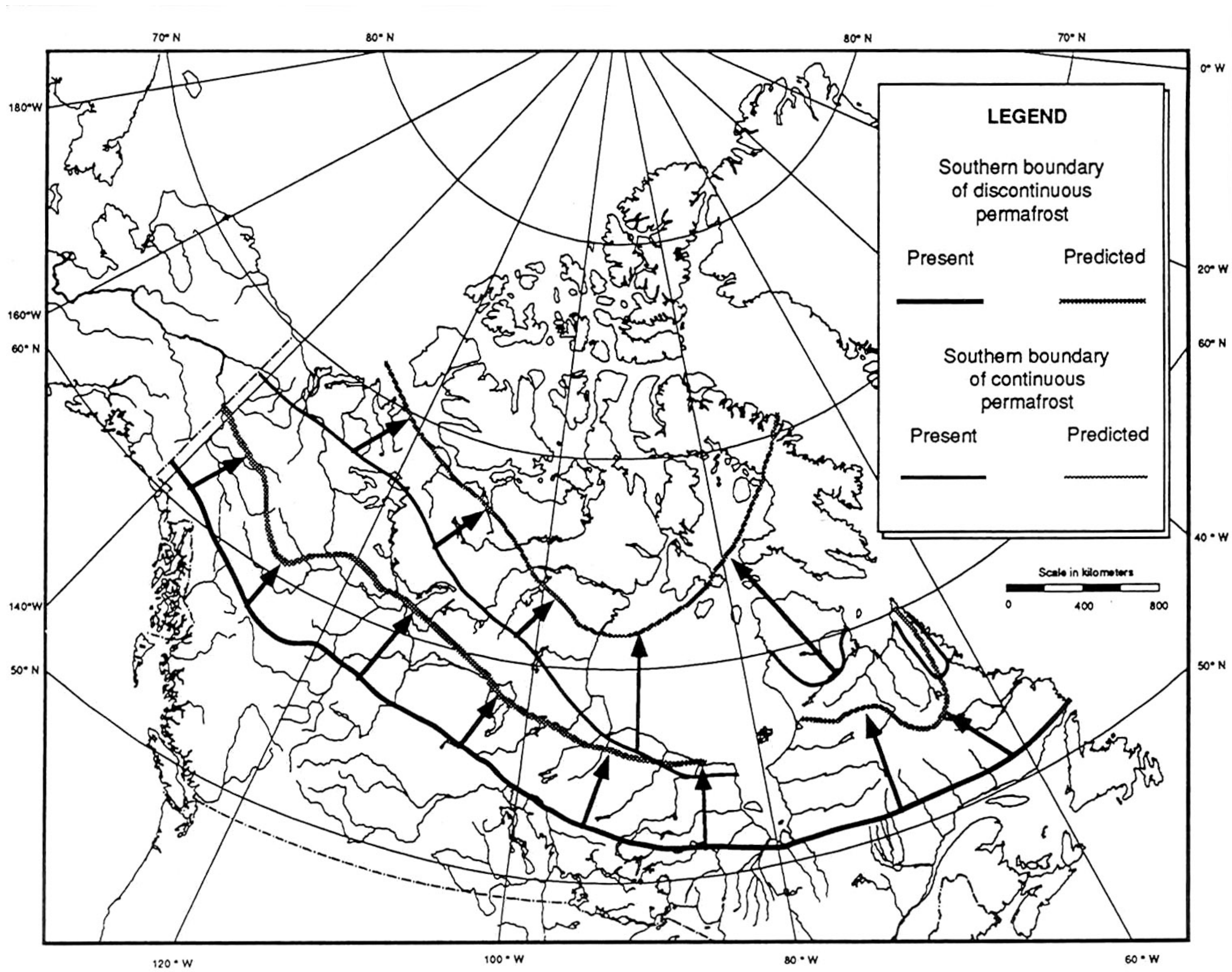

Figure 17-13. Projected shift in the boundaries of discontinuous and continuous permafrost resulting from a surface temperature change of 4-5°C (from Woo et al. 1992:298). New boundaries are equilibrium positions assuming no change in other climatic factors or vegetation: it will take decades to centuries to reach equilibrium.

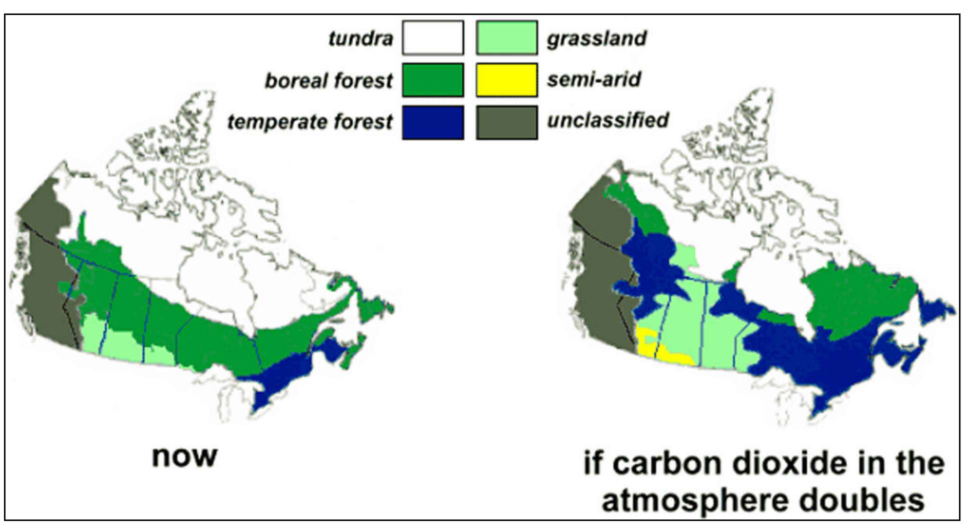

Figure 17-14. Predicted changes in vegetation if carbon dioxide in the atmosphere doubles (from Rizzo pers. comm. <u>in</u> Hengeveld 1995).

Glacial melting and thermal expansion of the world's oceans caused by climate warming may slow, halt, or even reverse the rate of coastal emergence in Hudson Bay and James Bay by offsetting the effects of isostatic rebound (Egginton and Andrews 1989; IPCC 1995 cited in Maxwell 1997; Gough 1998; Shaw et al. 1998). Three main factors cause the sea level to vary: changes in the earth's crust; changes in the amount of water stored on land as ice; and the thermal expansion or contraction of the World's oceans. Isostatic rebound is the main source of change in the earth's crust affecting the Hudson Bay marine ecosystem. It is causing the land to rise relative to the sea at a rate of 0.7 to 1.3 m per century (Andrews 1970 cited in Barr 1979; Hunter 1970; Webber et al. 1970; Hillaire-Marcel and Fairbridge 1978; Vincent 1989). Land-based glaciers and ice caps are a vast reservoir of water that, if melted, would enter the world's oceans. The net effect of climate warming on the largest of these, the Antarctic and Greenland ice sheets, is uncertain. Indeed, warming scenarios suggest that they may actually accumulate more water as a result of changes in precipitation than they might lose due to melting. Warming will also increase the volume of the world's oceans directly, since saline water expands when warmed. These increases in volume will cause the sea level around the world to rise. In the Hudson Bay marine ecosystem, results of 3-dimensional modelling analyses suggest that global sea-level rise will decrease the relative rate of local coastal rise due to isostatic rebound by at least 75% for a 3°C warming of the earth's surface (Gough 1998). The physical impact of this change would be least along low-lying coastal sections of James Bay and southern Hudson Bay, where the fastest isostatic rebound is occurring, but the biological impact in these areas could be severe if coastal salt marshes are adversely affected.

17.2.2 Precipitation and Hydrology

Precipitation scenarios from the CC92 GCM suggest a general increase in precipitation in the Hudson Bay region of between 0 and 30% for a doubling of atmospheric carbon dioxide, with the main increases in summer and autumn (Maxwell 1997). In winter and spring, northwestern Hudson Bay may receive less precipitation than at present (Figure 17-15). While this overall increase suggests that more water will be available for runoff, the water storage capacity of the land may increase substantially as permafrost melts--depending upon its ice content. More water may be stored underground and runoff may decrease (Soulis et al. 1994; Maxwell 1997). This could change the flow regime such that rainfall events rather than smowmelt dominate (Woo et al. 1992).

By 2050, ice may melt up to a month earlier in large rivers and up to 2 weeks earlier in large lakes (Maxwell 1997). The longer open water period and warmer conditions will increase evaporative loss from lakes, ponds and wetlands (Woo 1990; Boudreau and Rouse 1995; Schindler 2001) and affect their chemical, mineral, and nutrient status (Rouse et al. 1997). Changes in the precipitation regime may have a greater impact on the evapotranspiration of subarctic wetlands than the increase in air temperature (Eaton and Rouse 2001). Changes in vegetation cover will also modify evaporative losses over land. Coupled with permafrost degradation, these evaporative changes may alter the water balance such that some wetlands and shallow lakes disappear. The magnitude of the change in water balance will differ among terrains depending upon their evapotranspiration, runoff, and water storage characteristics (Boudreau and Rouse 1995; Eaton et al. 2001). Lakes with the smallest ratios of lake volume to catchment area are likely to be most affected (Rouse et al. 1997).

The effects of climate change on stream flow into Hudson Bay are not easy to predict because the pattern of change in temperature and precipitation will not be consistent across the region in time or space (Gagnon and Gough 2002). But, climate change will alter the volume of water available, the relative contributions of snowmelt and rainfall, and spatial and temporal flow patterns (Woo and McCann 1994; Schindler 2001). It may also alter the relationships between sediment and streamflow, and the runoff chemistry.

17.2.3 Wind

Reductions in the extent and/or duration of seasonal ice cover of Hudson Bay and James Bay will prolong the exposure of their surface waters to wind forcing. This may alter the wave climate and could increase the frequency of storm surges.

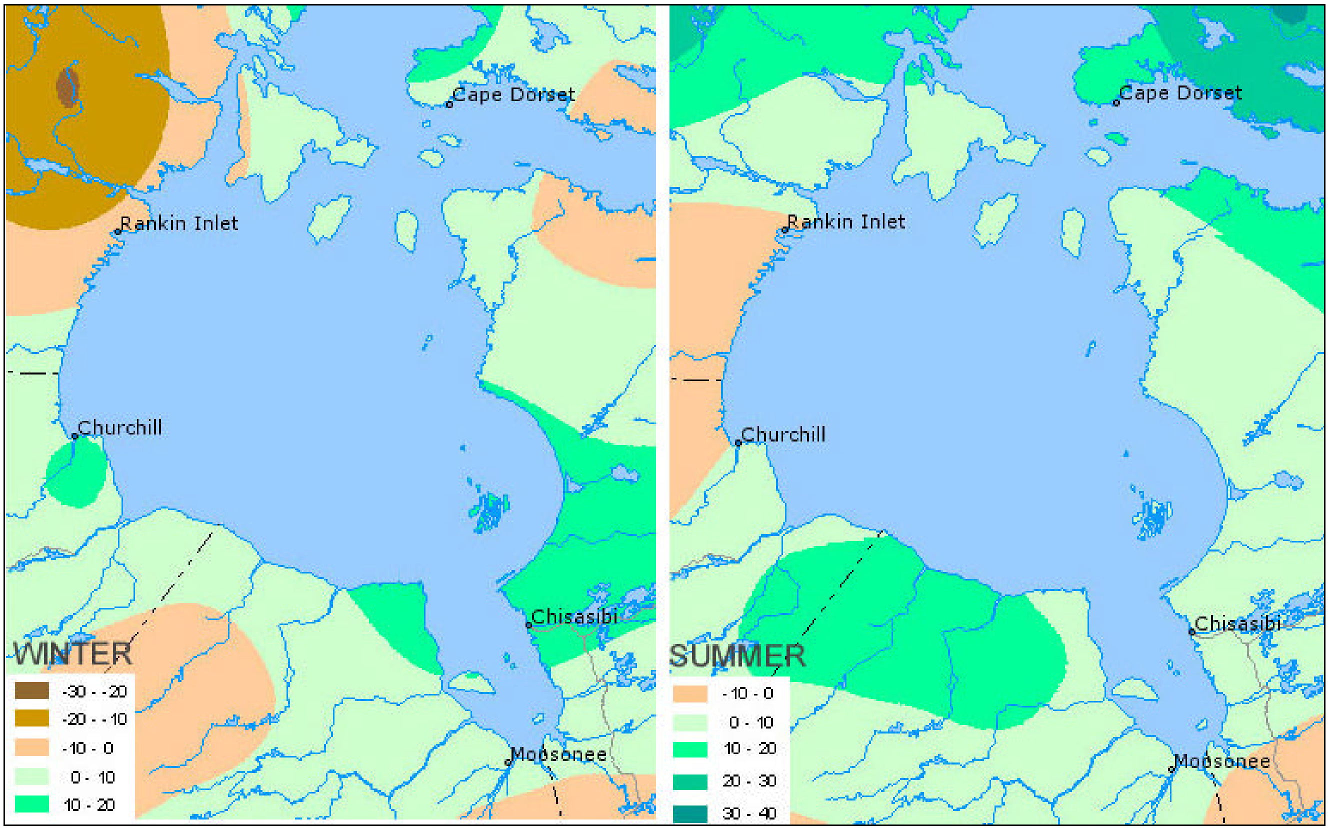

Figure 17-15. Change (%) projected by the CCCma model in winter (December-February) and summer (June-August) precipitation from the reference period (1961-1990) to the middle of the current century (2040-2064) (from National Atlas of Canada 6th edn 2003c).

17.3 POTENTIAL IMPACTS OF CLIMATE CHANGE

Residents of the Hudson Bay region are accustomed to dealing with seasonal and geographical variations in climate, so too are the vegetation and wildlife upon which they depend (Maxwell 1997; Hansell et al. 1998). The effects of these variations are reflected in all aspects of life and the environment. Plant communities are adapted to the local water, soil, and weather conditions; marine communities to seasonal ice cover; harvesters and tourists to the presence of plants and animals at a particular time and place; communities are designed to be compatible with permafrost; and ships are built to withstand expected wave heights and sea ice conditions. These and many more adaptations are ongoing in response to climate change. Two vital questions remain. Are plants and animals in the Hudson Bay marine ecosystem capable of adapting to the speed and magnitude of climate change that has been predicted? And, how might society best adapt? The following sections outline what may be some key impacts of climate change on the Hudson Bay marine ecosystem, to assist with future planning initiatives.

The strong climatic linkages between Hudson Bay and its surroundings mean that coastal environments may be doubly impacted by climate change (Rouse 1991). They will be warmed more by overall global temperature warming and cooled less during the growing season by air originating over Hudson Bay. This will increase evapotranspiration from the wetlands; causing them to dry and reducing water yield for stream flow. It will cause permfrost degradation and favour northward movement of vegetation zones. Warmer drier soil conditions may cause the peat soils of wetland tundra to release rather than accumulate carbon dioxide from the atmosphere (Burton *et* al. 1996). The natural incidence of forest fires may increase. Climate change may simply cause a spatial shift of an ecozone or climate region (i.e., northward), or it may create a new type not previously observed (Whitfield et al. 2002).

17.3.1 Oceanography

While the satellite sea ice data show changes in the sea ice, they do not explain their causes or predict future changes (Parkinson and Cavalieri 2002). If the observed changes are tied most closely to Arctic warming (Martin et al. 1997; Serreze et al. 2000) that continues, then the ice cover should continue to decrease; but, if the sea-ice changes are tied more closely to oscillatory changes in the climate system, such as the North Atlantic Oscillation and the Arctic Oscillation (Deser et al. 2000; Morison et al. 2000; Parkinson 2000), then sea ice cover will likely fluctuate (Parkinson and Cavalieri 2002). This uncertainty means that extrapolations of decreases seen in the sea ice cover in the 1990's should be done with caution (Parkinson 2000a).

Changes in the ice cover have major implications for the Hudson Bay marine ecosystem. The reduction or loss of seasonal ice cover would reduce or eliminate the most important component of the freshwater budget of the bay (i.e., sea ice melt) and threaten existing ecosystems (Cohen et al. 1994; Ingram et al. 1996; Ingram and Prinsenberg 1998; Carmack and Macdonald 2002; Macdonald et al. 2003b). How changes in the ice environment affect each species will depend very much on the exact way in which the animal or plant uses ice, and on the plasticity of that use.

A reduction or elimination of seasonal ice cover would:

- initially increase and eventually reduce or eliminate polynya and ice edge habitats that are important areas for the exchange of energy between ecosystems;
- alter seasonal tidal spectrums by reducing or eliminating the damping effects of ice cover;
- reduce or eliminate coastal ice scour and the redistribution of sediment and other material trapped within the ice or carried on its upper or lower surface;
- increase surface salinity by reducing or eliminating the release of fresh water at the surface by melting sea ice. With a thinner layer of low salinity water at the surface, and longer open water period, wind mixing should make more nutrients available to primary producers in the upper water column (Dunbar 1993).
- make more light available to primary producers;
- increase surface water temperature and reduce or eliminate freezing of macrophytes;
- reduce or eliminate ice habitats, their associated biota and seasonal biological production; and
- trigger trophic changes, from the bottom up and top down (Macdonald et al. 2003b).

A shorter duration of ice cover when coupled with stronger winds may:

- increase re-working of coastal habitats by wave action, leading to increases in longshore sediment transport and changes in spit and delta formation [Note: because much of the coastline is low-lying or rocky, these changes are unlikely to be severe as in areas with steep, unconsolidated shorelines such as the Beaufort Sea.];
- increase winter mixing and upwelling, and thereby the nutrients available to phytoplankton (Carmack and Macdonald 2002);
- favour more severe wave development and more frequent storm surges; and

- lead to warmer temperatures and earlier melt in coastal areas. The rate of evapotranspiration would increase and could lead to drying of wetlands and lengthening of the growing season.

These changes are not necessarily linear and there may be a few threshold responses and non-linear surprises. There may also be unexpected cumulative effects when impacts of climate change interact with those from other environmental stressors, such as hydroelectric development (see also Section 15.1).

17.3.2 Plants

If ice does not form, primary production by ice algae would be eliminated. However, the effects of decreasing ice cover are less certain, as changes in light and nutrient availability related to the depth of snow cover, ice thickness, extent of ice cover, and timing of breakup relative to the incoming solar radiation are complex. In either case, elimination or reduction, the timing, location, and magnitude of primary production are likely to change and to affect animal populations and their ability to adapt to other environmental change. Reduction or elimination of seasonal ice formation would permit the establishment of richer benthic macrophyte communities. Plants would no longer be subject to freezing, ice scour, or seasonal light deprivation to the same extent. These changes to planktonic and benthic plant communities may alter the quantity, quality, and distribution of food available to consumers and thereby trophic dynamics (Macdonald et al. 2003b).

Glacial meltwaters that offset isostatic rebound along low-lying coastal sections will effectively reduce the rate of coastal emergence, at least over the short term (several hundred years?). Tidal salt marshes are diverse and highly productive ecosystems that exist within a small elevation range relative to sea level and rely on a variety of processes for their continued existence. Altering the rate of coastal emergence may reduce the extent of these marshes, as inland vegetation will tend to encroach on the marsh and new marsh will not be created at the same rate on the seaward side. These effects might be partially offset by the reduction or elimination of erosion by shore ice and of freeze-thaw processes in intertidal sediments. This may alter the amount and composition of plant resources available to birds.

Reducing the ice cover and thickness should also reduce seasonal ice damage to eelgrass beds. Whether this will facilitate expansion of the beds and increase their biological productivity is unknown, as ice can also promote eelgrass growth by removing dead plant material. Perhaps, in the absence of ice, increased wave action may perform the same task.

17.3.3 Invertebrates

If ice no longer forms, secondary production by ice fauna will be eliminated. However, as with ice flora, the effects of more subtle changes in the ice cover on invertebrate ice fauna and production are hard to predict. Overall, warmer water and reduced ice cover should increase nutrient recycling and biological productivity (Dunbar 1993). The reduction or elimination of seasonal ice formation would enable the establishment of richer communities of molluscs and other invertebrates in the nearshore zone that is now subject to freezing and ice scour. Southern species may invade; some northern species may grow faster and larger. Changes in plant communities may alter the flow of food energy among epontic, pelagic, and benthic habitats and thereby alter invertebrate trophic dynamics (Macdonald et al. 2003b). Opportunities for the commercial harvest of marine invertebrates may improve over time.

Parasitic invertebrates may also be influenced by climate change (Marcogliese 2001). Depending upon how changes affect their hosts, some species may be extirpated locally and others introduced. Parasite transmission and possibly virulence may also be affected.

17.3.4 Fish

Fish in Hudson Bay and James Bay will be affected by changes in water temperature, ice cover, salinity, and nutrients. These changes will affect the quality and availability of ice edge and nearshore habitats, and of plant and invertebrate food resources. They will cause shifts in species distributions and in the biological productivity of fish species and communities (Shuter et al. 1998; Macdonald et al. 2003b). Indirect evidence from changes in the diet of seabirds suggests that climatic warming may cause Arctic cod and some benthic sculpins and zoarcids to become less abundant, while capelin and sand lance become more abundant (Gaston et al. 2003).

The IPCC (1995) has estimated that many species in lakes and streams are likely to shift northward by about 150 km for each 1°C increase in air temperature. This axiom may also be useful for estimating oceanic impacts, at a general level (Maxwell 1997). The northward expansion of freshwater fishes such as brook trout and northern pike may, for example, reduce or eliminate Arctic charr populations along the Hudson Bay coasts since the distributions of these species seldom overlap. The presence of Arctic waters in Foxe Basin and Hudson Strait may slow or prevent the invasion of some subarctic marine species.

Changes in the seasonality of streamflow may affect access of anadromous species moving between freshwater and marine environments in the spring and fall. It may also affect their access to headwater lakes for spawning. The productivity of other species that traditionally have been harvested from these lakes may also change, but the effects on overall fish productivity are uncertain (see Minns and Moore 1992; Reist 1994; Rouse et al. 1997; Shuter et al. 1998; Schindler 2001). Freshet timing and plume dynamics are also important determinants of the feeding success of marine fish larvae (e.g., Arctic cod and sand lance) (Fortier et al. 1996). The impact hydrological changes related to climate fluctuations, and/or hydroelectric developments, have on recruitment will likely depend upon what fraction of the larval dispersal area is affected by river plumes.

17.3.5 Marine Mammals

Climatic warming may favour some migratory marine mammals such as belugas, bowheads, harp seals, and hooded seals by improving seasonal access. The effects of changes in the availability of suitable prey species are less certain, with the exception of important ice-associated prey such as Arctic cod and sympagic (with ice) amphipods which are likely to become less abundant (Tynan and DeMaster 1997). The fact that belugas frequent warmer estuaries in southern Canada suggests that warming will not force them to vacate important estuarine habitats in Hudson Bay where they summer. However, the attractiveness of some estuaries may change if there are large changes in flow. Both the whales and seals may be subject to increased predation from killer whales and to competition from other whale and dolphin species that may invade from southern latitudes. Changes in sea ice concentrations in areas of the North Atlantic where harp and hooded seals breed may affect their populations and limit their need or ability to take greater advantage of a warmer Hudson Bay marine ecosystem.

Non-migratory harbour seals might also benefit from climatic warming, as they would be less vulnerable to harvest and predation in the winter when ice limits their movements in coastal estuaries and rivers. If more areas along the coast of Hudson Bay and James Bay, and in the lower reaches of their tributaries, remain open year-round the harbour seal population may disperse and increase. However, subsistence hunting pressure on harbour seals may increase if fewer ringed and bearded seals are available.

Partial or total loss of the seasonal snow or ice cover may be disasterous for resident, ice-adapted species such as ringed and bearded seals, and the polar bear (Stirling and Derocher 1993; Stirling and Lunn 1996; Stirling et al. 1999; Stirling and Smith 2004). Each of these species has particular requirements for the duration and quality of ice cover and for its distribution relative to feeding resources. Ringed seals build birthing lairs on the ice to provide shelter from the time they give birth until the pups are ready to enter the water. If the snow cover deteriorates too early in the season the lairs collapse, killing or exposing the pups; if the ice melts before they are ready to enter the water the pups die. Seals also haul out on the ice to keep dry and warm during moult. The question of how they may respond if the period of ice cover shortens and/or the quality of that cover deteriorates for breeding purposes is vitally important to seals, Inuit, and polar bears. An Inuit elder has suggested that ringed seals may move ashore to pup if ice is not available during the pupping season, and thereby become more vulnerable to predation by polar bears (Cleator 2001:18). Alternatively, the seals may adjust their pupping dates to correspond to changing ice conditions and snow cover, or simply disappear from the region. The ability of seals to adapt to changes in the fish and invertebrate communities, particularly to any decline in the availability of key prey species (e.g., Arctic cod for ringed seal), is unknown. Any decline in the polar bear populations should have a positive effect on seal survival.

Changes in the sea ice that decrease the availability of seals will have an important negative effect on polar bear populations. These changes may already be happening in western Hudson Bay (Stirling and Derocher 1993; Stirling et al. 1999). Breeding populations will be eliminated from western Hudson Bay if females are unable to build up enough fat reserves over the winter to sustain themselves and their offspring over the following summer. This is likely to occur well before seal populations are seriously affected by climate change and well before the seasonal ice cover is lost. In the short term, affected bears may move north or east to areas less affected by warming, and they may become more aggressive in their search for food around humans. Inuit in eastern Hudson Bay have observed both of these changes but cannot attribute them directly to climate change (McDonald et al. 1997). In the long term, depending upon the extent of ice loss, bear populations may disappear from part or all of Hudson Bay and James Bay. Permafrost melting and heavier spring rains may cause more earth dens to collapse, and thereby increase mortality and decrease reproductive success. Overheating could become a problem for bears summering along the coasts.

The effects of ice habitat loss on narwhals are uncertain (Stewart 2004a). While they frequent northern Hudson Bay in summer, when the ice cover is least, they have a great affinity for areas with seasonal ice cover. Whether they would continue to visit the Respulse Bay area in the absence of seasonal ice cover is unknown. Reduced ice coverage may make narwhals more susceptible to predation by killer whales.

The direct effects of climatic warming or cooling on walruses likely are limited, and not necessarily negative. Born et al. (2003) hypothesized that a decrease in the extent and duration of Arctic sea ice in response to warming might increase food availability for walruses by increasing bivalve production, and improve seasonal access to rich feeding habitat in shallow inshore waters. However, the positive effects of these changes are by no means certain, as there may be unforeseen energetic costs associated with foraging or other activities. Behavioural and physiological responses to changes in air temperature suggest that Pacific walrus calves can maintain their body temperature at an air temperature of 18°C in still air and shade or under equivalent conditions (Fay and Ray 1968; Ray and Fay 1968). Above this temperature they withdraw into the water to avoid over heating. Air temperatures at or above this level for an extended period might disrupt normal feeding, moulting, and calving schedules. Walrus breed on the ice and the males appear to require ice habitat in order to establish territories and control harems (R. Stewart, DFO, Winnipeg pers. comm. 2003). In the event of climate warming, a northward expansion of human populations could reduce the availability of suitable walrus habitat and increase harvesting pressures (Stewart 2004b).

17.3.6 Birds

Climate change may alter the routes and destinations of migratory birds. Their ability to adapt to potentially rapid changes in key staging areas may be of critical importance to their futures. Transient species passing through the Hudson Bay marine ecosystem require appropriate time and space linkages for successful passage (Morrison and Gaston 1986). Given the dependance of so many species on the timing of break-up and freeze-up, changes to either could have extremely wide-reaching effects. Likewise, any reduction in the size or quality of salt marsh habitats that breeding waterfowl depend upon for food would adversely affect breeding success. Changes in coastal vegetation and wildlife could also reduce breeding success and cause species that breed on the tundra to relocate northward.

Birds using the Hudson Bay marine ecosystem on a seasonal basis may also be impacted by the effects of climate change in areas outside the region, where they lay down the fat stores necessary for successful Arctic breeding (Diamond 1998). These changes could have a detrimental effect on the populations regardless of changes in the Arctic. Cliff-nesting seabirds would have earlier and longer access to marine resources.

Changes in the relative abundance of prey species may cause some species, such as the thick-billed murre, to alter their diets and may attract other species, such as razorbill, to colonize the area (Gaston et al. 2003). Changes in coastal habitats could attract southern bird species, and terrestrial invertebrate and mammal species, to invade. Their presence as competitors/parasites/predators could make coastal habitats less attractive to bird species that currently breed, feed, and moult along the region's coasts.

17.3.7 Biodiversity

Climate warming will selectively eliminate from the Hudson Bay marine ecosystem Arctic biota that cannot adapt or relocate to suitable habitats quickly enough to survive. Ice-adapted species will be the most affected; species that occur over a wide range of latitudes will be least affected (Ingram et al. 1996). Warming may increase the opportunity for north temperate species to invade Hudson Bay (Hansell et al. 1998). However, most will have to do so via Hudson Strait, which may remain unfavourably cold. Relict species that live in James Bay may invade Hudson Bay but most southern species must enter via Hudson Strait. The lag between Arctic species receding and temperate species invading will likely reduce the biodiversity of southern Hudson Bay for some time. Interspecific interactions between predators and prey, and among warm and cold adapted species of competitors, will likely change if warming modifies communities—marine, freshwater, or terrestrial.

17.3.8 Human Activities

Climate change may fundamentally alter the local environment and resource base of communities, such that traditional knowledge is no longer applicable (Maxwell 1997; McDonald et al. 1997; Thorpe et al. 2002; Duerden 2004). This will make the outcomes of important decisions related to the environment--especially to harvesting and travel, less certain and effect major changes in the life style, housing, harvesting, and health of people who live along the coasts of Hudson Bay and James Bay and use the resources of the marine ecosystem (Fast and Berkes 1998; Maxwell 1997; Hansell et al. 1998; Ford and Smit 2004). Communities that retain the strongest links to the land and enterprises that depend on local conditions will be most directly affected, and these effects may be most pronounced along the southern and western coasts. Key species for which harvesting rights have been guaranteed to Inuit and Cree under comprehensive land claims agreements may no longer sustain current harvest levels (Fenge 2001). This may force the people with the lowest cash income to pay more for food and result in dietary and epidemiological changes that affect the health of area residents (Fast and Berkes 1998; Furgal et al. 2002; Duerden 2004). Climate change is just one of the stressors acting on northern Inuit and Cree communities, the cumulative effects of which may be greater than the sum of their parts.

<u>*Harvesting*</u>

While the end result of warming that is significant enough to reduce the ice volume in Hudson Bay and James Bay is likely an increase in biological productivity (Dunbar 1993), the direction and degree of change at any time during the transition is impossible to predict given the complexity of the changes that may occur. Ultimately the fisheries harvest potential may increase but the transition is unlikely to be smooth, as the biological communities and their production will be in flux. Climate change may alter both the target species and their catchability in time and space. Belugas, brook trout, and blue mussels are species that may benefit from warming—the extent will depend upon a myriad of factors, while populations of other key species, such as Arctic charr, ringed and bearded seals, and narwhals, may be reduced or disappear from the region altogether.

Traditional harvesters could face a very difficult transition as they adjust to changes in the physical environment and in species composition and availability. Initially, the migratory patterns of biota (e.g., anadromous Arctic charr) that have been available to generations of harvesters at a predictable time and location might change; eventually these species might be replaced by unfamiliar invaders (e.g., brook trout). Wholesale shifts in the focus of harvesting efforts may result--geographically, seasonally, and in terms of the target species (marine, freshwater, and terrestrial). The food value and economic value of commercial harvests may also fluctuate widely with changes in species availability and product demand until some future steady state is reached. Over the long term, a northward expansion of agriculture and forestry may occur, providing a more diverse renewable resource base for development.

Transportation

Northward expansion of agriculture, forestry, and mining activities may require the expansion of transportation networks. How this might affect development along the Hudson Bay and James Bay coasts is unknown. Permafrost melting likely will increase maintenance costs for existing runways and road and rail beds, at least in the short term (Maxwell 1997).

The impact of climate change on coastal travel between communities is uncertain. The reduction or elimination of landfast ice will reduce or eliminate coastal travel by snowmobile, Bombardier, and dog-team. This may be offset by a longer open water period that facilitates small craft travel between communities. Whether the overall effect is positive or negative will depend upon changes in the wave climate, susceptibility to superstructure icing, and many other factors. Warmer temperatures will shorten the period when winter roads can be used and may eliminate them in some areas.

The longer ice-free season would benefit floatplanes but this would be offset by reductions in ski-plane access. It may significantly lengthen the period wherein ships without hulls strengthened to withstand ice can visit ports and communities in the region (Maxwell 1997). This could increase ship traffic to and from the Port of Churchill in particular, and might alter the seasonal nature of community re-supply by ships from eastern Canada and shipping disturbances to marine mammals. Increased sediment transport may require more frequent surveys to monitor local shoaling and necessitate more frequent harbour dredging. Warmer, less dense air would reduce the lift available to aircraft and thereby their load-carrying capacity.

Increases in precipitation and in storm frequencies might increase the need for navigational aids and for search and rescue capabilities in the region (Maxwell 1997). It may also increase down time for air and watercraft. The effects of hydrological changes on boat traffic are uncertain but will likely vary among localities.

Oil and gas development

While climate change should ease the environmental conditions under which offshore oil and gas exploration and development are carried out; this may not be reflected in the cost of operations (Maxwell 1997). A longer open-water season would facilitate ship-borne drilling and testing operations for offshore oil and gas wells, enabling them to be completed in one season. These cost savings might be offset somewhat by stronger wave action. While decreases in the duration and thickness of ice cover would reduce the cost of production by reducing construction costs, the loss of seasonal ice cover would enable a switch to conventional offshore technology that could result in important cost savings. It would also reduce or eliminate the need to protect pipelines from ice scour by trenching and/or enable the use of tankers. Changes in the permafrost and in coastal conditions could have significant design and cost implications for onshore pipeline developments. Uncertainties in climate scenarios and the conservative nature of the industry are such that climate change may not cause an increase in operations in the Canadian Arctic, since the positive impacts of climate change cannot be incorporated into current designs and the negative impacts must be considered.

Building and construction

Increased air temperatures will reduce heating and insulation costs and lengthen the summer building season (Maxwell 1997). It may negatively effect heavy construction that takes advantage of ice or permafrost to support equipment or provide stability. In general, the main building and construction concerns are related to changes in permafrost. They include questions related to the stability of pipelines, pile foundations, and open pit mine walls, and on the release of contaminants sequestered in frozen tailings. The effects of changes in runoff, related to changes in precipitation and soil permeability, on bridges, pipeline river crossings, dykes and erosion protection structures, are difficult to assess.

Recreation and tourism

The effects of climate change on wind and visibility are not well known. These factors are important to tourism and lack of this knowledge hampers effects assessments (Maxwell 1997). Climate change would remove some or many of the Arctic features of the Hudson Bay environment--marine, freshwater, and terrestrial. This would fundamentally alter its attraction for tourists as a relatively accessible and cost effective location for viewing Arctic biota and experiencing the Arctic environment and seasons. Polar bears for example may no longer frequent Polar Bear Provincial Park in Ontario or Wapusk National Park in northern Manitoba. Depending upon the extent of the climate change, some aspects may remain, such as viewing opportunities for migratory birds and beluga whales. These negative effects might be offset somewhat by lengthening of the summer tourist season and improved access from the south. The impact of climate change on river recreation, particularly canoeing and kayaking, should be small and could be positive.

17.3.9 Contaminants

Climate change and variability could alter risk from contaminants in the Hudson Bay marine ecosystem by changing their transport to and from the ecosystem and bioaccumulation within the ecosystem (Macdonald et al. 2002, 2003c; see also Schindler 2001). The direction and extent of these changes are unpredictable, given the complexity of climate-driven changes to the marine ecosystem and its surroundings, and will likely vary over time and space. In the instance of mercury, for example, warming of permafrost-dominated terrains west of Hudson Bay may increase the erosion of particles, and the methylation and hence biological accumulation of mercury. Changes in temperature and hydrology can also alter the nature of scavenging of organic contaminants by rain and snow, and individual lipid dynamics which, coupled with changes in trophic structure (population size distribution, length of food chain), could alter the availability of contaminants to humans (Macdonald et al. 2002).

17.4 SUMMARY

The effects of climate change on the Hudson Bay marine ecosystem are difficult to predict and assess, but could be far-reaching. Changes have been observed in air temperature and precipitation, and are manifest in stream flow into Hudson Bay, sea ice, and biota. There is evidence of warming in western Hudson Bay and cooling in the east, and of increasing annual precipitation with trends toward greater precipitation in spring, summer, and autumn. River discharges are peaking earlier in the spring from Manitoba to Quebec, while total discharge has decreased in central Manitoba and increased in the Kazan River. Perhaps the most telling evidence of climate change is in the ice cover record derived from Satellite passive-microwave data. From 1979-96, the length of the sea ice season decreased in northwest Hudson Bay and along the southern coasts of Hudson Bay and James Bay, but increased in east central Hudson Bay and near the Belcher Islands and Akimiski Island. If these changes are tied most closely to Arctic warming that continues, then the ice cover should continue to decrease; but, if the sea-ice changes are tied more closely to oscillatory changes in the climate system, such as the North Atlantic Oscillation and the Arctic Oscillation, then sea ice cover will likely fluctuate. This uncertainty means that extrapolations of decreases seen in the sea ice cover in the 1990's should be done with caution.

Climate change may also be affecting the polar bears in western Hudson Bay. Their dependence on ice cover makes them very vulnerable to changes in its quality, distribution, and duration. Recent declines in body condition, reproductive rates and cub survival, and an increase in polar bear-human interactions, suggest that these bears are under increasing nutritional stress. These changes have been correlated with earlier breakup and later freeze-up that have increased the ice-free period, reducing feeding opportunities and prolonging their fast.

While many scientists agree that there is a high probability of global warming during the next century, they are less certain about its causative factors, rate, extent, and regional effects. The role played by the world's oceans in climate change is also poorly understood. Elaborate computer models have been developed to improve understanding of how the climate may respond to increases in greenhouse gas concentrations. These "general circulation models or GCMs" often simulate the type of climate that might exist if global concentrations of carbon dioxide were twice their pre-industrial levels. They use mathematical equations to represent physical processes of the climate system—particularly those involving radiation, heat and motion and the water cycle; and to calculate the interactions between these processes. Strictly speaking, they are not predictive models but rather a means of determining the sensitivity of the climate system to a change in one of its key elements.

Climate change scenarios derived from these models must be used with caution, as they are very sensitive to the choice of modeling parameters and different models can yield very different results. A model that more accurately represents the regional oceanography year round is being developed and will be embedded into a larger climate model to improve its predictive ability for Hudson Bay. Improvements are also needed to the atmospheric model, particularly with respect to low-level atmospheric fields (e.g., lower winds and higher temperature) and the effects of aerosols. As changes in temperature (first order) alter ice formation (second order), which affects sediment transport, primary production, foodweb dynamics, etc., (third order), a few threshold responses and non-linear surprises likely will be encountered (R. Macdonald, DFO, Sidney, BC pers. comm. 2004). Some of these thresholds, such as 0°C, will be more important than others when it comes to biological distributions. Consequently, better understanding of the regional oceanography and of threshold effects that might cause abrupt changes is needed to underpin these models.

The GCM developed by the Canadian Centre for Climate Modelling and Analysis (CCC92) predicts a winter warming of up to 10°C and summer warming of 1-2°C by 2100 in central Hudson Bay; smaller increases are predicted in winter (6-9°C) and greater increases in summer (2-5°C) along the coasts. Precipitation scenarios from this model suggest a general increase in precipitation in the Hudson Bay region of between 0 and 30% for a doubling of atmospheric carbon dioxide. Precipitation should increase throughout much of the region over most of the year, but mainly in summer and autumn. In winter and spring, northwestern Hudson Bay may receive less precipitation than at present. Glacial melting and thermal expansion of the world's oceans caused by climate warming may slow, halt, or even reverse the rate of coastal emergence in Hudson Bay and James Bay by offsetting the effects of isostatic rebound. Results of 3-dimensional modelling analyses suggest that this rise will decrease the rate of coastal emergence by at least 75% for a 3°C warming of the earth's surface. The physical impact of this change would be least along low-lying coastal sections of James Bay and southern Hudson Bay, where the fastest isostatic rebound is occurring.

The strong climatic linkages between Hudson Bay and its surroundings mean that coastal environments may be doubly impacted by climate change. They will be warmed more by overall global temperature warming and cooled less during the growing season by air originating over Hudson Bay. This will increase evapotranspiration from the wetlands; causing them to dry and reducing water yield for stream flow. It will cause permfrost degradation and favour northward movement of vegetation zones. The Arctic Tundra biome may shrink until it is confined largely to the Arctic Islands. Infilling by the taiga biome may not keep pace with the very rapid speed at which climatic warming is expected to occur. Within the existing treeline, the species composition of the forests is likely to change. More water may be stored underground and runoff may decrease. This could change the flow regime such that rainfall events rather than snowmelt dominate runoff. Warmer drier soil conditions may cause the peat soils of wetland tundra to release rather than accumulate carbon dioxide from the atmosphere. The natural incidence of forest fires may increase. Climate change may simply cause a spatial shift of an ecozone or climate region, or it may create a new type not previously observed.

Recent studies suggest that ice cover in Hudson Bay and James Bay will be reduced by climate warming but do not agree on the extent of the reduction. Some GCMs suggest that Hudson Bay may become ice free in winter. A three-dimensional coupled ice-ocean model suggests that a simple 2°C increase in air temperature might reduce volume of the sea ice produced in Hudson Bay by 20%, increase summer sea surface temperature by 4°C, and cause a two-week advance of breakup and delay of freezup. Because melting sea ice contributes more fresh water to Hudson Bay than does runoff, any change in ice cover will alter the freshwater budget.

The reduction or loss of seasonal ice cover has major oceanographic and ecological implications. A progressive loss of ice cover initially would increase, and eventually reduce or eliminate polynya and ice edge habitats that are important areas for the exchange of energy. It would increase surface salinity by reducing or eliminating the dilution of surface waters by freshwater released from melting sea ice. With a thinner layer of low salinity water at the surface, and longer open water period, wind mixing should make more nutrients available to primary producers in the upper water column. More of the light incident at the surface would be available to primary producers. Damage to plants and bottom habitats caused by freezing and ice scour would decrease, and ice habitats and their associated biota would be reduced or eliminated. More severe wave development would be favoured and storm surges could also become more frequent.

Climate change has the potential to affect the spatial distribution of biota in and around the Hudson Bay marine ecosystem. Species that cannot adapt to changes in habitat or food resources will be selectively eliminated. The effects on each species may depend in large part on how they use and interact with the ice environment, and on how plastic that use is. Ice-adapted species such as ice algae, sympagic amphipods, polar bears, and ringed and bearded seals, would likely be most affected by climatic warming. Breeding populations of polar bears could disappear from the region well before seals are affected seriously by changing ice cover. The effects of ice habitat loss on narwhals are uncertain, given their great affinity for areas with seasonal ice cover, while the direct effects on walruses may be limited and not necessarily negative. Warming may favour species such as belugas, bowheads, and harbour, harp and hooded seals by improving seasonal assess, but it could also alter their food resources and lead to increased predation by killer whales. Subarctic species may invade, although most aquatic species will have to do so via Hudson Strait, which may remain unfavourably cold. The lag between Arctic species receding and these species invading could reduce the biodiversity of southern Hudson Bay for some time.

While warming is likely to increase biological productivity over the long term, the direction and degree of change at any time during the transition is impossible to predict. Shifts may occur within and among communities and species, and the overall marine production will rise and fall until stability is regained. There will be more light and nutrients available for marine plant growth, and the reduction or elimination of ice scour and surface freezing will enable more plants and invertebrates to colonize the nearshore zone. Offsetting these changes will be the loss of production by ice algae and ice-adapted biota. Each consumer's share of the available production will depend on how well it adapts or is adapted to the environmental conditions. This will affect the sustainable harvest that individual species and particular locations can support. Scallops and mussels, for example, may grow faster and larger. Arctic charr may become more productive over the short term, in response to increased nearshore production, but over the long term may be replaced by other species, such as brook trout, that move northward to take advantage of increasingly favourable habitats.

Migratory birds visiting the Hudson Bay marine ecosystem rely on appropriate time and space linkages for successful passage. Given the dependance of so many species on the timing of break-up and freeze-up, changes to either could have extremely wide-reaching effects. Likewise, any reduction in the size or quality of salt marsh habitats that breeding waterfowl depend upon for food would adversely affect breeding success. Altering the rate of coastal emergence may reduce the extent of coastal salt marshes, as inland vegetation will tend to encroach on the marsh and new marsh will not be created at the same rate on the seaward side. Changes in coastal vegetation and wildlife could also reduce breeding success and cause species that breed and moult on the tundra to relocate northward. Cliff-nesting seabirds would have earlier and longer access to marine resources. Changes in the relative abundance of prey species may cause some species, such as the thick-billed murre, to alter their diets and may attract other species, such as razorbill, to colonize the area. Birds using the Hudson Bay marine ecosystem on a seasonal basis may also be impacted by the effects of climate change in areas outside the region, where they lay down the fat stores necessary for successful breeding.