

Changing Sea Ice Conditions in Hudson Bay, 1980–2005

K. Hochheim, D.G. Barber, and J.V. Lukovich

Abstract We present an overview of changes in Hudson Bay sea ice in the context of thermodynamic forcing due to increased surface air temperatures and dynamic wind and current forcing mechanisms. Examined in particular is the correspondence between sea ice extent, surface air temperatures, and atmospheric indices during spring and fall from 1980 to 2005. Changes in the timing of freeze-up and break-up over the last several decades were significant. In the spring, temperature trends were consistently positive with temperature increases of $0.23^{\circ}\text{C}/\text{decade}$ from 1950 to 2005. With increasing temperatures in the Hudson Bay region, sea ice concentrations and sea ice extents have decreased significantly as well. Warmer surface air temperatures have also shifted the mean freeze-up and break-up dates by 0.8–1.6 weeks in each of the seasons. Dynamic forcing of sea ice is further explored using the concept of relative vorticity, or the tendency for sea ice to rotate clockwise (or counterclockwise) within Hudson Bay in response to changes in atmospheric circulation. Surface air temperatures and hence ice extent showed cyclical patterns over the time period studied and appear to be driven by large scale atmospheric circulation patterns. This cyclical behaviour has been previously associated with various hemispheric indices including the North Atlantic Oscillation. The implications of changing ice conditions in Hudson Bay for marine mammal habitat are discussed.

Keywords Atmosphere • Circulation • Freeze-up • Break-up • Forcing • Rotation • Ice phenology • Hemispheric indices • Surface air temperature

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Introduction

Sea ice forms an integral part of the marine ecosystem at high latitudes. Marine mammals and sea birds are affected directly through change in sea ice-related habitats or indirectly through changing marine productivity processes, food web energetics and caloric transfer (Hoover this volume). In general, changes in sea ice growth, decay, and the spatial and temporal variability of these processes all affect the marine cryosphere and associated physical–biological coupling, ultimately impacting higher trophic level biota. Changes in dynamic processes (i.e., ice motion) affect habitat suitability through the formation of open water in winter, sea ice ridging, rubbing, and movement of ice over preferred feeding areas (e.g., walrus). Changes in thermodynamic processes can affect access to preferred habitats, destruction of habitats in the early spring (e.g., rainfall effect on snow lairs) and the timing of critical habitat formation (e.g., ice formation suitable for polar bears in the fall).

Changes in sea ice and its associated snow cover (hereinafter referred to as the marine cryosphere) have impacts on all aspects of the Arctic marine system due to the control which sea ice has on transmission of light, heat and momentum across the ocean–sea ice–atmosphere (OSA) interface (Carmack et al. 2006). Changes in the light environment result principally from changes in the snow cover on sea ice, due to the higher extinction of photosynthetically active radiation (PAR) in snow relative to sea ice. These changes have a direct connection to primary production both beneath the sea ice in spring (Mundy et al. 2009) and in the summer open water (Arrigo et al. 2008). Control of heat fluxes between the atmosphere and ocean are dominated by the presence and timing of sea ice formation (and are a consequence of these fluxes). The rate of sea ice formation is important to marine mammals and birds due to the relationship between fall storms and sea ice dynamic processes. For example, sea ice which tends to form later in the season tends to rubble and ridge more easily. Momentum exchanges across the OSA interface influence the presence and distribution of snow on sea ice, which both feedback into radiative transfer and heat exchanges. These processes can also have a strong impact on habitats for marine mammals, particularly in the formation of ringed seal lairs (Furgal et al. 1996; Chambellant this volume). Momentum exchange can also control upwelling of nutrients into the euphotic zone thereby feeding back directly into ecosystem productivity (Kuzyk et al. in press). This is true both of surface melt water stabilizing the ocean surface mixed layer and for upwelling at ice edges (Mundy et al. 2009).

In this chapter we review the general nature of sea ice from the perspective of a climatic analysis spanning the last 30 years. We examine whether the trends in sea ice extent and concentration are linear or periodic (cyclic) over this period. This will then shed light on how marine mammals and sea birds may evolve in the changing marine cryosphere of Hudson Bay.

Background

Our best knowledge of sea ice conditions is based on satellite data that has been acquired on a regular basis since 1979. These data show that trends in sea ice concentration during the 1979–1996 period were relatively small throughout the Arctic, -2.2% and $-3.0\%/decade$, in contrast to the 1997–2007 period which showed that declines in sea ice concentration accelerated to -10.1% and $-10.7\%/decade$ (Comiso et al. 2008). We also note that trends in sea ice concentration in ice marginal zones within the polar seas during early part of the satellite record (1979–1993) varied geographically (Deser and Teng 2008). In particular during the winter, Eastern Canada (Labrador Sea) and Bering Sea had large positive trends in sea ice concentration (indicating more ice), while the Greenland and Barents seas and the Sea of Okhotsk had large negative trends (less ice). In 1993–2007 sea ice concentration trends were consistently negative throughout all of the Arctic and sub-arctic seas indicating a more general global warming trend. Geographic variations in sea ice concentration within the Arctic are also evident for the summer melt period during the early part of the satellite record while more recent trends in sea ice concentration are dominated by negative trends throughout the Arctic.

In Hudson Bay, Parkinson et al. (1999) noted that only very slight negative trends in sea ice extent existed within the Hudson Bay Region (HBR) (including Foxe Basin) from 1979 to 1996, and that these trends were statistically non-significant. Based on data from Environment Canada, Gagnon and Gough (2006) showed that temperature trends from 1960 to 1990 were predominately negative (cooling) and ice thickness trends were positive (thickening) during the fall and winter periods thus supporting the satellite observations showing increased sea ice concentrations in Eastern Canada from 1979 to 1993 (Deser and Teng 2008). Freeze-up and break-up of sea ice in Hudson Bay showed statistically significant trends with freeze-up dates occurring later in northern and northeastern HBR of $0.32\text{--}0.55$ days/year, 1971–2003 (Gagnon and Gough 2005). During the spring melt period, Gagnon and Gough (2005) noted that break-up was occurring earlier, with magnitude ranging from -0.49 to -1.25 days/year. These trends were typically occurring in James Bay, along the southern shore of Hudson Bay and in the western half of Hudson Bay. Parkinson and Cavalieri (2008) also noted significant negative trends in sea ice extent (less ice) in the HBR using satellite passive microwave data for years 1979–2006. Changes in sea ice extent during the fall were estimated at $-8.5 \times 10^3 \text{ km}^2/\text{year} \pm 1.9$. Spring trends in sea ice extent were estimated at $-3.4 \times 10^3 \text{ km}^2/\text{year} \pm 0.8$ and these were all significant at 99% probability. Also using satellite passive microwave data, Markus et al. (2009) examined trends in the time of melt onset and freeze-up for ten different Arctic regions. In all regions except one (Sea of Okhotsk) trends in melt onset were negative (toward earlier melt) ranging from -1 to -7.3 days/decade, while the trend for the HBR was -5.3 days/decade and significant at the 99% level. Trends in freeze onset were consistently positive throughout the regions, ranging from 1.0 to 7.0 days/decade (indicating later

freeze-up), with Hudson Bay having one of the larger trends at 5.4 days/decade. Hochheim and Barber (2010) show sea ice concentration and their spatial distribution within the HBR, linking both sea ice concentrations and sea ice extent to interannual variations in surface air temperatures and hemispheric indices; some of these results are highlighted below.

In the sections below, we use various data sources to better appreciate recent changes in the sea ice regime in the HBR by: (1) showing mean surface air temperature trends surrounding Hudson Bay (1950–2005); (2) producing maps showing trends in sea ice concentration to gain a better understanding of the spatial distribution and extent of changes in sea ice; and (3) linking the observed ice trends to surface air temperature and dynamic forcing.

Methods

Surface air temperature anomaly trends for the HBR were computed using CANGRID data developed for climate change studies by the Climate Research Division of Environment Canada. The bounds used to compute the mean HBR regional temperature anomalies (per month per year) were 50–65°N and 72.5–100°W. The use of temperature anomalies in gridding data has the advantage of removing location, physiographic, and elevation effects. Monthly temperature anomalies were computed for each month per year relative to the 1980–2005 mean to match the normals computed for sea ice data. A three month running mean was applied to the monthly surface air temperature anomaly data ending on (including) the month of interest; the intent here was to incorporate lead-up surface air temperatures to obtain a (moving) seasonal temperature index (anomaly) value.

The sea ice concentration trends and sea ice extent data were generated based on Canadian Ice Service digital ice charts (Environment Canada, Canadian Ice Service). Although the Canadian Ice Service data goes back to 1970, the charts produced since the early 1980s are of more consistent quality due to improvements in earth observation technology. To determine trends in sea ice concentration anomalies, a least squares linear regression was calculated for each grid point over the 26 year period where the slope of the regression indicated the trend per year, following an approach established by Parkinson et al. (1999), Parkinson and Cavalieri (2008), and Galley et al. (2008).

In order to monitor sea ice dynamics, ice relative vorticity, or tendency for ice to move clockwise (or counterclockwise) within Hudson Bay was computed using weekly sea ice motion vectors from the NSIDC data set for the Hudson Bay region, and spatially averaged over the region extending from 55°N to 64°N, and from 77°W to 95°W. The analysis was computing using vorticity was computed using a numerical finite-differencing scheme on the zonal and meridional ice motion components, as in Lukovich and Barber (2006). This analysis was used to explain in part the spatial distribution of positive and negative sea ice concentration anomalies in Hudson Bay.

Below we present a short overview of changes in freeze-up and break-up dates in Hudson Bay. The threshold used to determine freeze onset and break-up was 50%

sea ice concentration. Instead of computing linear trends over the 26 year period we compared mean differences in dates between two periods, 1980–1995 versus 1996–2005; the former being representative of the cooler temperature regime, the latter being representative of a significantly warmer temperature regime.

Air Temperature Trends

Based on gridded, historically-adjusted temperature data from Environment Canada using 3 month running means ending on the month of interest, temperature trends surrounding Hudson Bay during the fall were positive indicating a warming of 0.2–1.8°C/decade depending on month and location (Hochheim and Barber 2010). In general the largest increases were on the eastern half of Hudson Bay and the lowest were along the southwestern coast of Hudson Bay between the Nelson River Estuary and James Bay. During spring, temperature trends were positive (warming) but generally weaker, ranging from 0.2°C to 1.0°C/decade with the greatest warming occurring in the northeast and northern portions of Hudson Bay (June), and northwestern and eastern Hudson Bay during June–August. The lowest (but positive) temperature trends in the spring were also observed along the southwestern shore of the Bay.

Overall mean regional surface air temperature trends surrounding Hudson Bay are shown in Fig. 1 for both spring and fall. The graphs suggest that: (1) surface air temperature anomalies for a given month vary interannually; (2) the temperature fluctuations have a cyclical nature (smoothing spline fit $\lambda = 0.0957$ (minimal smoothing)); and (3) temperatures in the past have been relatively cooler. During the fall period the 1950s to the early 1990s were relatively cooler: temperature trends during this period were negative (cooling) from -0.12°C to $-0.28^\circ\text{C}/\text{decade}$ (for November and December, respectively), although none of these trends were statistically significant. Since 1989 surface air temperatures have increased dramatically from 1.8°C and 2.3°C/decade for November and December, respectively (Hochheim and Barber 2010). Interestingly, warming trends from 1950 to 2005 for both November and December were statistically non-significant, owing to large interannual variations in temperature and the more semi-curvilinear temperature trend.

Comparing semi-decadal mean surface air temperature anomalies between 1980–1995 and 1996–2005 for October and November, mean surface air temperatures were significantly higher for the latter period (0.99°C and 1.44°C respectively). In December, 1996–2005 was identified as statistically different from the two preceding periods; 1.94°C warmer than 1970–1979 and 1.85°C warmer than 1980–1995.

During the spring and summer break-up period (June–August) negative surface air temperature anomalies occurred in the mid 1950s to early 1970 in contrast to the fall period where negative anomalies were observed from the 1970s to early 1990s. Mean 3 month surface air temperatures ending in June showed warming trends on the order of 0.23°C/decade ($p = 0.0436$) from 1950 to 2005 (Hochheim et al. 2010). Similar trends are observed for July and August (Fig. 1).

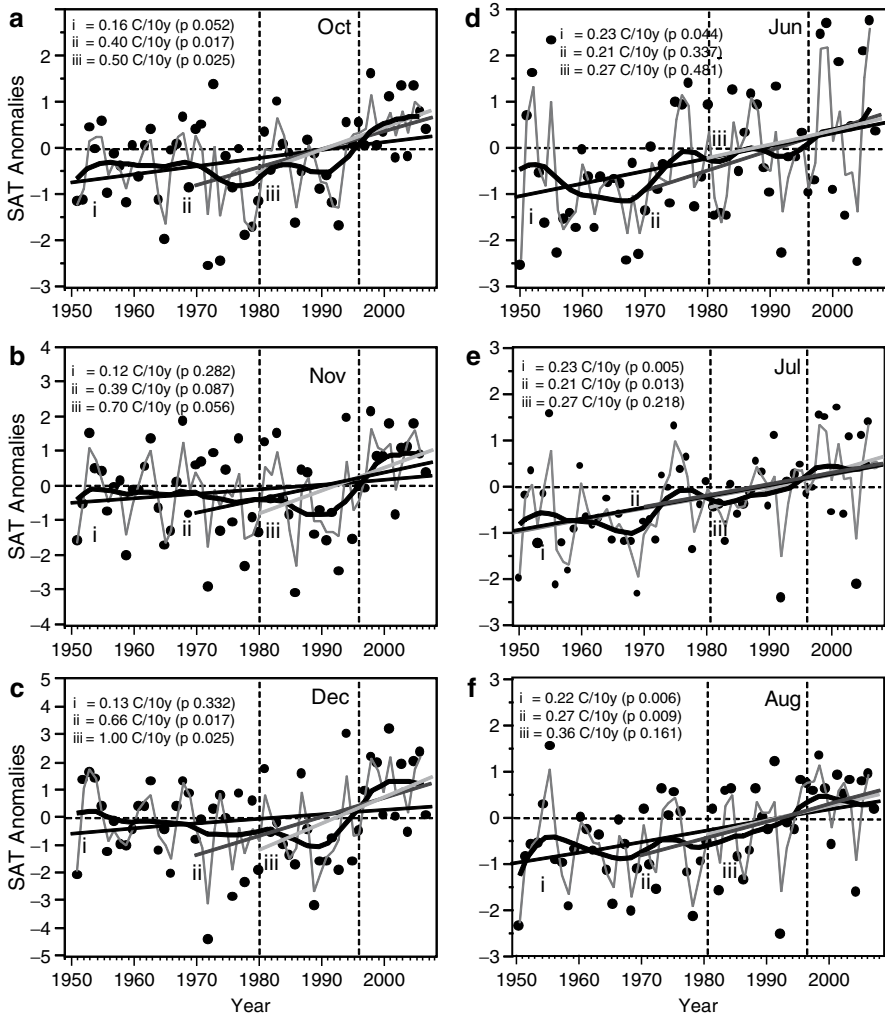


Fig. 1 Mean surface air temperature (SAT) anomalies based on seasonal 3 month running means ending for the freeze-up period from October to November (a–c) and for the break-up period from June to August (d–f). Two spline fits are added to show the higher frequency cyclical patterns surface air temperature anomalies ($\lambda = 0.0957$) and the longer pattern ($\lambda = 100$) of SAT anomalies. Three linear trends are shown, (i) 1950–2005, (ii) 1970–2005, (iii) 1980–2005

Sea Ice Freeze-up and Break-up Patterns

Freeze-up starts in the northern portion of the Hudson Bay around the shores of Southampton Island and along the northwestern coast of Hudson Bay. The ice then extends southward over Hudson Bay and along the coast to the Nelson Estuary and in a narrow band along the southwestern coast towards James Bay. The nearshore

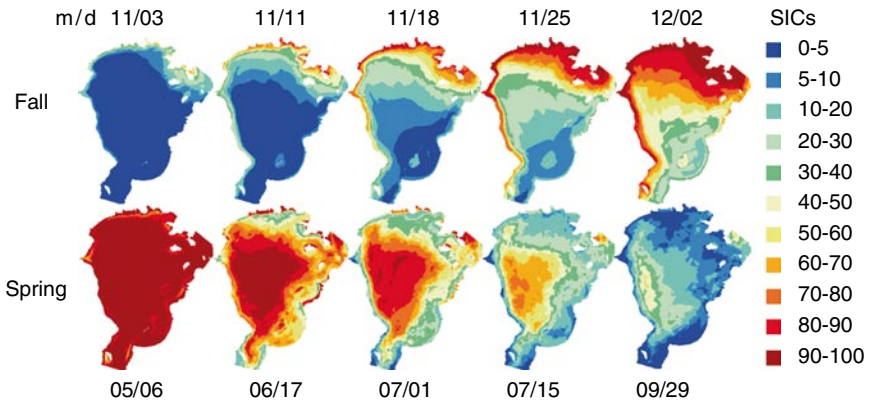


Fig. 2 Fall freeze-up and spring break-up sequences for Hudson Bay based on Canadian Ice Service data using mean sea ice concentrations computed over 1980–2005

waters are typically shallow (≤ 40 m) and less saline due to riverine inputs and therefore subject to early freezing. By 2 December the coastal areas along the southwestern portion of Hudson Bay are consolidated. The southeastern portion of the Bay including James Bay is typically the last to freeze (Fig. 2).

During the winter months the sea ice is consolidated $\geq 90\%$ and typically consists of very large floes. The ice tends to slowly circulate in a counterclockwise fashion in response to currents and prevailing winds and thus has a positive vorticity.

During the spring, break-up occurs along the northern and northwestern portions of the Hudson Bay and along the east coast. Currents and winds tend to keep sea ice concentration highest in the central and southwestern portions. The last remnants of ice typically occur along the southwestern coast and the Bay is typically ice free following the second week of August.

The mean sea ice concentration map ending 6 May shows typical late season latent heat polynyas in Hudson Bay. Latent heat polynyas are areas of open water (or low sea ice concentration) which are created by prevailing winds. These areas are biologically productive and thus are loci for organisms at higher trophic levels. The largest polynya is located along the northwestern coast of Hudson Bay including Southampton Island, while other polynyas are located southwest of Cape Churchill towards the Nelson River Estuary, along the east and west shores of James Bay, the Belcher islands, and Coates and Mansel islands and off the west coast of Québec (Barber and Massom 2007).

Sea Ice Concentration Trends, 1980–2005

Trends in sea ice concentration anomalies were computed for weeks ending 3 October to 2 December for the fall period, and weeks ending 24 June to 24 July using the CIS data (Fig. 3). The sea ice concentration anomaly trends were

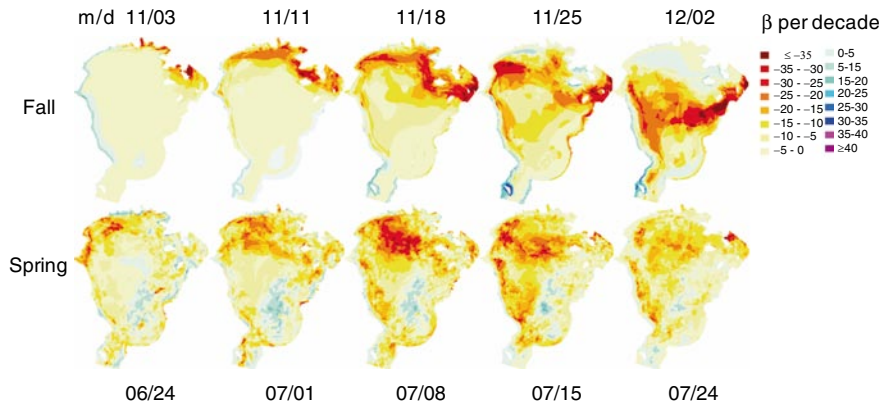


Fig. 3 Linear trends (β) in sea ice concentration anomalies using Canadian Ice Service data (1980–2005) for the fall and spring period

predominantly negative indicating reduction in sea ice concentration (note: near-shore positive anomalies are attributed to improved detection capabilities in sea ice due to RADARSAT-1 introduced in 1996). During the fall period, significant trends were found suggesting reductions in sea ice concentration of -23.3% to -26.9% /decade. During the week ending 2 December the most significant trends in ice reduction occurred off the southwestern and northeastern coasts of Hudson Bay.

During spring the largest negative trends in sea ice concentration were observed in western and northwestern Hudson Bay (Fig. 3). The statistically significant trends in sea ice concentration ranged from -15.1% to 20.4% /decade. Weak positive sea ice concentration trends (i.e., more ice) occurred in the eastern half of Hudson Bay, although these trends were statistically non-significant. The positive anomalies are, in part, explained by dynamic forcing resulting from changes in atmospheric circulation in the HBR (Hochheim et al. 2010).

Air Temperatures and Teleconnections

Hudson Bay is a relatively shallow sea (≤ 150 m) and more enclosed relative to other Arctic seas, in that it is more isolated from the effects of open-ocean circulation, which affects warm water intrusions and sea ice export (Wang et al. 1994). Thus unlike some other Arctic seas, variations in sea ice concentration and sea ice extent in Hudson Bay are more a function of atmospheric forcing, specifically changes in air temperature and wind circulation.

The cyclical nature of interannual variations in surface air temperature in Hudson Bay have largely been attributed to a number of standardized hemispheric indices (oscillations) which are associated with characteristic wind, temperature

and precipitation patterns. These oscillations operate at various scales ranging from 2 to 7 years to decadal scales of 20–50 years. In Hudson Bay, several indices have been linked to air temperature and include the North Atlantic Oscillation (NAO) (Prinsenberg et al. 1997; Kinnard et al. 2006; Qian et al. 2008) and the Southern Oscillation index (SOI) (Wang et al. 1994; Mysak et al. 1996). Positive NAOs predict cooler temperatures over Hudson Bay. A strong NAO is associated with more northerly winds and the negative NAO phase is associated with more southerly winds and warmer temperatures. When strong positive NAOs occur together with strong negative SOIs, Hudson Bay regional temperatures are exceptionally cold (Wang et al. 1994; Mysak et al. 1996).

More recently, evidence shows that the East Pacific/North Pacific (EP/NP) predicts fall (September–November) surface air temperatures surrounding Hudson Bay. About 62% of the variance in surface air temperature surrounding Hudson Bay was explained by the EP/NP index over 1951–2005, and 79% explained over 1980–2005 (Hochheim and Barber 2010). Although most atmospheric indices are generally poorly correlated with spring surface air temperature anomalies, recent results suggest that both the EP/NP index West Pacific (WP) and Arctic Oscillation (AO) together can explain up to 68% of the variation in interannual surface air temperatures for July and August in the HBR (Hochheim et al. 2010).

Air Temperature and Sea Ice Extent

During the fall period the seasonal surface air temperature anomalies surrounding Hudson Bay explain up to 62% ($p < 0.001$) of the interannual variation in sea ice extent for consolidated ice (sea ice concentration $\geq 80\%$) computed with CIS data. Results for the week ending 2 December (1980–2005), a period of maximum interannual variation for sea ice extent, show that for every 1°C increase in surface air temperature, the area of consolidated ice decreased by 116,600 km^2 . Similar results were obtained in spring. Using sea ice extent $\geq 60\%$ in the spring for the week ending 15 July ($R^2 = 0.62$; $p < 0.0001$), for every 1°C increase in temperature there was a reduction in sea ice extent of 118,000 km^2 . Using multiple regression and integrating both spring and fall surface air temperatures (ending November) consistently improved the capability of predicting weekly spring sea ice extents; coefficients of determination (R^2) were as high as 74% (Hochheim et al. 2010).

Relative Vorticity

The strong negative trends in sea ice concentration in the western portion of Hudson Bay and the positive trends in the eastern portion of Hudson Bay during the spring (Fig. 3) were partially explained by large-scale dynamic forcing due to changes in atmospheric circulation patterns that affect the distribution of late season (mobile) ice within Hudson Bay (Hochheim et al. 2010). Since 1990 the

sea ice has had a predominantly positive vorticity (a counterclockwise rotation) causing ice to circulate eastward as a result of prevailing winds, thus enhancing negative sea ice concentration trends in western Hudson Bay, while creating positive trends in eastern Hudson Bay (Fig. 4). During 1983–1989, the vorticity was strongly negative (sea ice circulating clockwise), thus contributing to heavier ice conditions in the west during the early part of the satellite record and relatively lower sea ice concentrations in the eastern portion of Hudson Bay. Wind composites for negative and positive sea ice relative vorticity regimes (clockwise and counterclockwise circulation, respectively) highlight correspondence between late-season sea ice and atmospheric dynamic variability, with implications for marine ecosystems.

When including 3 month average relative vorticity ending late June with fall (November) and spring surface air temperature, as much as 84% of the variation in sea ice extent for the spring period was explained during the break-up period (Hochheim et al. 2010).

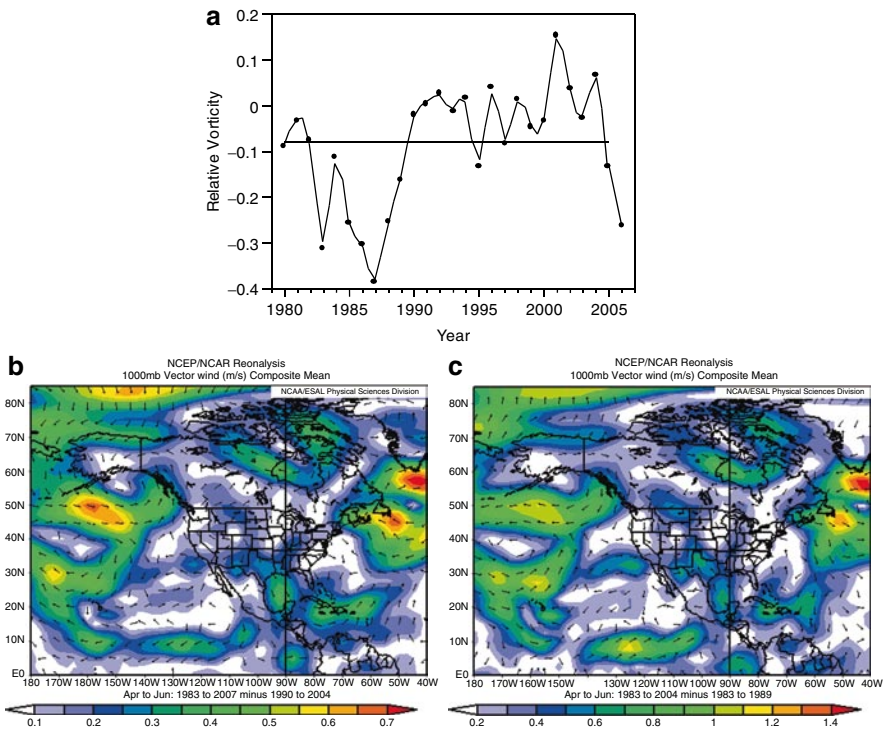


Fig. 4 (a) Sea ice relative vorticity for the Hudson Bay Region. Negative (positive) vorticity indicates a counterclockwise (clockwise) circulation of sea ice within Hudson Bay; the relative vorticity is averaged over a 3 month period ending June, (b) mean wind vectors over Hudson Bay associated with negative vorticity, (c) mean wind vectors over Hudson Bay associated with positive vorticity

Recent Changes in Freeze-up and Break-up Dates

Increasing regional surface air temperatures have led to later freeze-up dates (defined as sea ice concentrations $\geq 50\%$). Temporal shifts in mean freeze-up dates for the weeks ending 28 October–2 December (week of year 43–48) over 1980–1995 and 1996–2005 are depicted in Fig. 5a, b, with the change shown in Fig. 5c. During the fall period, freeze-up is 0.4–0.8 weeks earlier over 16% of Hudson Bay (or $1.35 \times 10^5 \text{ km}^2$), 0.8–1.2 weeks earlier over 25% of Hudson Bay (or $1.97 \times 10^5 \text{ km}^2$), and 1.2–1.6 weeks earlier over 38% of Hudson Bay (or $3.02 \times 10^5 \text{ km}^2$), and about 1.6–2.0 weeks earlier over about 10% of the Bay.

Similar shifts were observed for the spring period suggesting earlier break-up of sea ice. During the spring, 18% of the Hudson Bay area exhibited a 0.4–0.8 week earlier break-up (or $1.48 \times 10^5 \text{ km}^2$), 30% of the Bay had break-up 0.8–1.2 weeks earlier ($2.42 \times 10^5 \text{ km}^2$), 28% of the Bay had break-up occur 1.2–1.6 weeks ($2.27 \times 10^5 \text{ km}^2$), and 10% of Hudson Bay had a 1.6–2.0 week earlier break-up in the spring (or $8.11 \times 10^4 \text{ km}^2$).

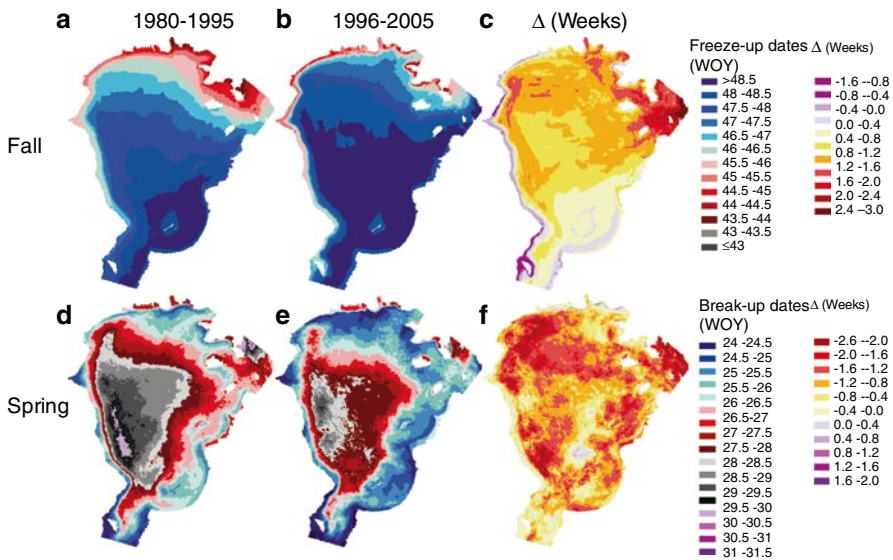


Fig. 5 Mean break-up dates based of 50% sea ice concentration for the fall period, 28 October–2 December (week of year 43–48) and the spring period 17 June–30 July (week of year 24–30). The shifts in freeze-up and break-up dates are computed for 1980–1995 which is representative of a cooler regime (a, d) and for 1996–2005 which is representative of the warmer regime (b, e). Difference maps show shifts in freeze-up (c) where positive values indicate shifts to later freeze-up dates (in weeks) and (f), where negative values indicate shifts to earlier break-up dates (in weeks)

Conclusions

Based on the CANGRID data, the HBR has recently undergone significant warming during the fall period, particularly since 1989. The largest differences in mean temperature before and after 1995 were in the month of December (1.85–1.94°C). In the spring, temperature trends were consistently positive estimating temperature increases of 0.23°C/decade from 1950 to 2005. With increasing temperatures in the HBR, sea ice concentrations and sea ice extents have decreased significantly as well. Warmer surface air temperatures have also shifted the mean freeze-up and break-up dates by 0.8–1.6 weeks in each of the seasons.

Surface air temperatures and hence ice extent are very cyclical and appear to be driven by large scale atmospheric circulation patterns. This cyclical behaviour has been associated previously with various hemispheric indices including the NAO, SOI, NP/EP and PDO, suggesting that Hudson Bay may become increasingly sensitive to hemispheric changes expected due to a warming planet. There is already ample evidence that the delay in sea ice formation is having an adverse effect on polar bears (*Ursus maritimus*) in Hudson Bay (Stirling et al. 1999) since the bears must extend their fasting period on land. Changes in sea ice phenology are also having a negative effect on thick-billed murres (*Uria lomvia*; Gaston et al. 2009). The late formation of sea ice can also be expected to increase the ridging and rubbing of sea ice which may in turn catch more of the fall snow thereby enhancing ringed seal habitats. We should expect that changes in the movement and phenology of formation and break-up of sea ice in Hudson Bay will have direct and strong impacts on all pagophilic species (Chambellant this volume; Mallory et al. this volume; Peacock et al. this volume). Moreover, with the possibility of increasing precipitation we can expect increasing snow depth on sea ice and this will have commensurate effects on various levels of the marine ecosystem due to control of light and heat across the ocean-sea ice-atmosphere interface (Hoover this volume).

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