A Step-Change in the Date of Sea-Ice Breakup in Western Hudson Bay

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ABSTRACT. Over the last four decades there has been a trend to earlier summer breakup of the sea ice in western Hudson Bay, Canada. As this sea ice is critical for the polar bears that use it for hunting, the earlier breakup is believed to be a factor in the declining health of the regional polar bear population. Analysis of the change to earlier breakup using passive microwave satellite data is problematic because of currently unquantifiable systematic errors between different satellites. Analysis using Canadian sea-ice charts from 1971 to 2008 shows that the change to earlier breakup is best represented by a 12-day step. This step occurs from 1988 to 1989 with no significant trend before or after the step. Although not as great as the three-week gradual change suggested by previous studies, this change is still significant. An increase in regional southwesterly winds during the first three weeks of June and a corresponding increase in surface temperature are shown to be likely contributing factors to this earlier breakup. It remains to be seen whether these changes in atmospheric circulation might be ascribed to human actions or simply to natural climate variability.

Key words: sea ice, breakup, Hudson Bay, climate change, polar bear

RÉSUMÉ. Ces quatre dernières décennies, la débâcle de la glace de mer d'été a eu tendance à se faire plus tôt que d'habitude dans l'ouest de la baie d'Hudson, au Canada. Puisque cette glace de mer revêt une importance primordiale chez les ours polaires qui s'en servent pour la chasse, cette débâcle plus hâtive pourrait jouer un rôle dans le déclin de la population régionale d'ours polaires. L'analyse du changement en matière de débâcle hâtive effectuée au moyen de données satellitaires passives en hyperfréquences est problématique en raison des erreurs systématiques non quantifiables qui existent entre différents satellites. L'analyse réalisée à l'aide des données sur la glace de mer prélevées au Canada de 1971 à 2008 indiquent que la débâcle plus hâtive est mieux représentée à l'aide d'une phase de 12 jours. Cette phase s'est produite de 1988 à 1989 sans qu'une tendance remarquable n'ait été enregistrée avant ou après la phase. Bien que ce changement ne soit pas aussi grand que le changement graduel sur trois semaines qui avait été suggéré par des études antérieures, ce changement est tout de même important. L'intensification des vents régionaux du sud-ouest pendant les trois premières semaines de juin de même que l'augmentation correspondante de la température de surface seraient des facteurs ayant vraisemblablement contribué à cette débâcle plus hâtive. Reste à voir si ces changements en matière de circulation atmosphérique pourraient être attribuables aux actes de l'être humain ou simplement à une variabilité climatique naturelle.

Mots clés : glace de mer, débâcle, baie d'Hudson, changement climatique, ours polaire

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INTRODUCTION

During the winter and spring, Hudson Bay (Fig. 1) is almost totally ice covered. The sea ice breaks up in late spring and summer and the sea is mostly ice free from August to November. The sea ice is the primary hunting ground for polar bears (*Ursus maritimus*), and in its absence the bears become inactive and do not eat for up to several months (Stirling et al., 1999).

The duration of this ice cover has changed. From analysis of Canadian Ice Service (CIS) charts, Gagnon and Gough (2005) found that the greatest change has been the shift to earlier breakup in the western area of Hudson Bay. They stated that for the period 1971–2003, there was "a trend of more than 0.8 days per year" and that "by 2003, breakup was occurring approximately 26 ± 7 days earlier than in 1971" (Gagnon and Gough, 2005:376). Stirling and Parkinson (2006) measured the sea-ice breakup in five different regions that are considered important for polar bear populations. They used satellite passive microwave data from 1979 to 2004. They also found that the greatest trend to earlier breakup, at 0.75 ± 0.25 days per year, was in western Hudson Bay and stated that "on average, breakup has been occurring about 7–8 days earlier per decade" (Stirling and Parkinson, 2006:265).

This trend to earlier breakup has had several consequences for polar bears. Stirling et al. (1999) found a strong correlation from 1991 to 1998 between the time of breakup and the date the Western Hudson Bay polar bears came ashore. A decline in the body mass of adult female polar
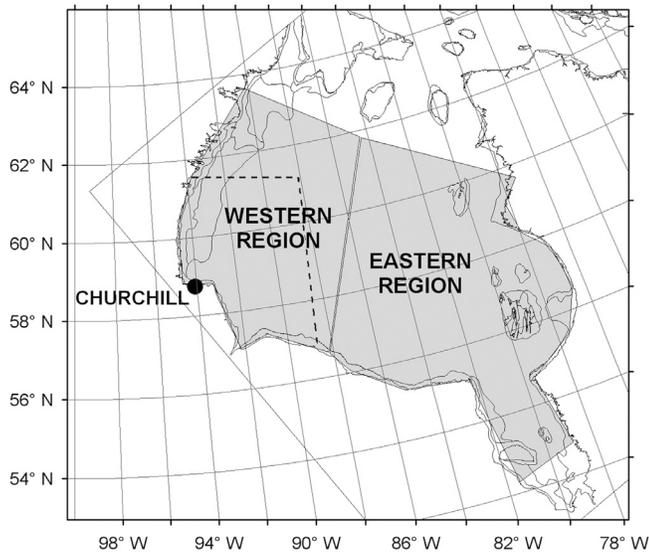

FIG. 1. Map of Hudson Bay, Canada. The background is the coastline and sea ice areas from the Canadian Ice Service (CIS) chart from 15 May 2004. The grey shaded regions are the western and eastern Hudson Bay masks used in the analysis of the CIS data. The southwest section of the western Hudson Bay area, used for closer comparison with the analysis of Gagnon and Gough (2005), is delineated with a dashed line.

bears from 1980 to 2004 was also linked to the progressively earlier breakup dates (Stirling and Parkinson, 2006). The breakup date each year was found to have such a close correlation to the survival of young polar bears, aged 0–4, and senescent bears, aged over 20 years (Regehr et al., 2007), that it appears unlikely that any other environmental changes during these years, including hunting, seal population, or human contact, could be as significant as the ice breakup date for the survival of these groups. There appears to be a downward trend in the total population size of the Western Hudson Bay bears; however, the trend expressed within the 95% confidence limits is not yet significantly different from zero (Regehr et al., 2007).

The trend to earlier sea-ice breakup has been linked to the long-term effect of warming in the region (Stirling et al., 1999; Gagnon and Gough, 2005). The existence of a sufficiently long-term regional warming trend was disputed by Dyck et al. (2007), but they acknowledged an increase in late spring (April–June) temperatures at Churchill, Manitoba (Fig. 1), over the period 1981–99.

Here we take a new look at the breakup of the sea ice in western Hudson Bay. We discuss the merits and drawbacks of the two data sets (passive microwave and sea-ice charts) used for measuring the sea-ice breakup. We run a new analysis on both of these data sets, bringing the time series up to date. We look at the temperature trends in the area around the time of breakup in more detail than was found in previous studies (e.g., Stirling et al., 1999; Gagnon and Gough, 2005; Dyck et al., 2007), which have generally discussed trends in the monthly (or even three-monthly) average temperatures. Finally, we examine changes in atmospheric circulation patterns that may be driving any related changes in temperature and sea-ice breakup.

BACKGROUND: MEASURING SEA-ICE BREAKUP

Passive Microwave Data

Stirling and Parkinson (2006) employed passive microwave data (Cavalieri et al., 1999) to examine trends in sea-ice breakup for five regions from 1979 to 2004. Sea-ice breakup was defined as the date at which the ice cover (surface area) fell to 50% or below. The greatest trend to earlier sea-ice breakup was found to occur in western Hudson Bay, with lesser trends in Foxe Basin and Baffin Bay. One immediately striking aspect of the data for western Hudson Bay was a step-change to earlier breakup occurring from 1988 to 1989 (Stirling and Parkinson, 2006: Fig. 2), masked by a late breakup date in 1992, which the authors attributed to a cold year following the 1991 eruption of Mt. Pinatubo (cf. Kirchner et al., 1999; Stirling and Parkinson, 2006). This step from 1988 to 1989 was not noted in the analysis by Stirling and Parkinson (2006). A similar but smaller change can be noted for Foxe Basin, but occurring from 1992 to 1993.

The passive microwave sea-ice concentration data set started in 1978 with the launch of the Scanning Multichannel Microwave Radiometer (SMMR) onboard the Nimbus 7 satellite and continued with a series of three Special Sensor Microwave/Imager (SSM/I) instruments onboard the Defense Meteorological Satellite Program (DMSP) satellites from 1987 onward (Cavalieri et al., 1999). Sea-ice concentration data derived via the NASA Team Algorithm are available on a grid with an individual pixel size of 25 km × 25 km (Cavalieri et al., 2008). The accuracy of the concentration data is stated to be at its worst, at ± 15% of the actual sea-ice concentration (Cavalieri et al., 1992), during summer in the Arctic, which unfortunately corresponds to the time of breakup we are interested in. This low accuracy is largely due to the effects of surface melt ponds on the sea ice, which can to lead to underestimation of the sea-ice concentration. In addition, at the ice margins and areas of ice breakup, the many different concentrations that can exist within one pixel will be smoothed to an average figure. Several studies have shown that because of the surface melt, in particular, the passive microwave–derived data tend to systematically underestimate ice concentration (e.g., Agnew and Howell, 2003; Shokr and Markus, 2006). When compared to sea-ice charts, the passive microwave sea-ice concentrations derived from the NASA Team algorithm were found to underestimate concentration during summer melt by 20.4% to 33.5%. The improved NASA Team 2 algorithm has been shown to underestimate concentration by 18.35% on average, with a standard deviation of 16.8% (Shokr and Markus, 2006). These studies suggest that although a random error of around 15% is still reasonable, there will be a systematic underestimation of ice concentration in the passive microwave concentration data set.

The NASA Team algorithm used to calculate the concentration was tuned to minimize differences in ice extent, not ice concentration, between the different sensors
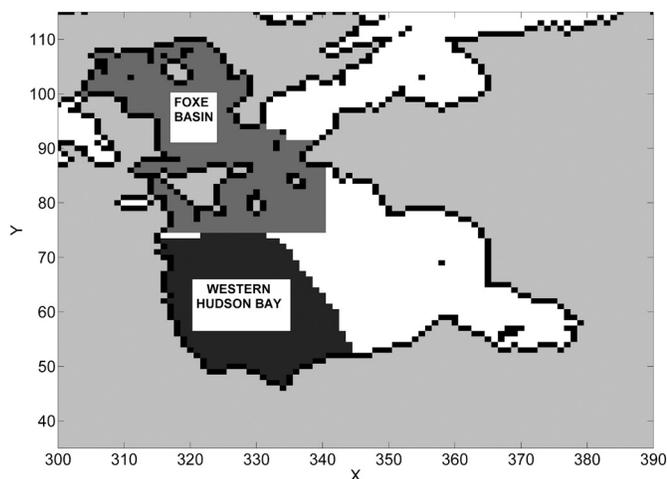
FIG. 2. Areas of analysis for sea ice concentrations from passive microwave data. Axes define the polar stereographic grid (approximately 25 km resolution) for which data are available (Cavalieri et al., 1996). Light grey denotes land, white is sea and the regions of analysis are shaded darker grey.

(documentation from Cavalieri et al., 2008). There was only a six-week overlap in the operation of the SMMR and SSM/I instruments, and only 22 days of common coverage from 9 July 1987 to 20 August 1987. Cross-calibration of the sensors has therefore been difficult (Cavalieri et al., 1999). One difference between the SMMR and SSM/I sensors, which does not affect the transition between the different SSM/I sensors to the same extent, is the time when the satellite passes overhead. This is dependent on the latitude of the region and the orbital characteristics of the satellite. A correction for the difference in the detection of melt areas by SMMR and SSM/I in Antarctica was found not to be possible for every region (Picard and Fily, 2006). One example given is the Amery Basin region of Antarctica, where the SMMR sensor passed over at midday and midnight, while the SSM/I sensors pass in the early morning and late evening. As a result, the SMMR sensor was far more likely to detect a midday melt event for this area (Picard and Fily, 2006). Such issues are of concern when analyzing summer breakup trends, particularly over a period spanning the two different sensor types. Another effect on the sea-ice concentration values is "land contamination," which can be different for the SMMR and SSM/I sensors because of changes in footprint size and the timing of the overhead passes (Cavalieri et al., 1999). A sea area such as western Hudson Bay has a large number of pixels adjacent to land. It is of note that the major change in breakup times for western Hudson Bay (1988–89) occurs at a very similar time to the change in passive microwave sensors.

Canadian Ice Service Charts

There is some evidence that CIS charts are more accurate than passive microwave data for estimates of ice concentration, particularly in the presence of surface melt (documentation from Fetterer et al., 2008; Agnew and Howell, 2002). The CIS state that they rarely use passive microwave data

for their charts. Therefore, changes in sensor from SMMR to SSM/I in 1987 are unlikely to affect them. However, there have been several changes in the techniques used to compile the charts (CIS, 2000). These include a change to computer-based analysis, allowing the incorporation of more satellite data, in 1987. A change to airborne Synthetic Aperture Radar (SAR) in 1990, which allowed a much greater resolution, was followed by the use of satellite SAR data from 1992 onwards. The resultant map of breakup is fairly complex and patchy. Each chart is compiled by an individual interpreter, and the emphasis is on getting timely data out for shipping operations rather than keeping a consistent, long-term record. Changes in the resolution are likely to affect the results, but it is not possible to quantify this.

Gagnon and Gough (2005) analyzed trends in breakup date from 1971 to 2003, using sea-ice concentrations from the CIS charts at 36 points across Hudson Bay. They defined the breakup date as the day on which the ice concentration for an individual point reached 50% or less, following the methodology of Etkin (1991). They also used points spaced 1° apart in latitude and longitude and averaged the concentration values at all of the points in the region. They stated that the error in determining breakup date is ± 7 days because the charts were generally published weekly. Another factor to consider is that since the charts give concentrations in tenths, the 50% breakup concentration would be reached sometime between the date where the concentration at a particular point was specified as 6/10 and the date where it was given as 4/10, assuming the charts were accurate to the nearest tenth, with an even distribution within this time. These errors are not used in the analysis of the statistical significance by Gagnon and Gough (2005).

METHODS

Passive Microwave Data

To obtain breakup dates for the period 1979–2007, the sea-ice concentration data (Cavalieri et al., 2008) for western Hudson Bay were re-analyzed, using methods similar to those of Stirling and Parkinson (2006) and approximately the area defined by those authors (Fig. 2). Another reason for choosing this area is that it covers the range of bear movements within the Western Hudson Bay population (Stirling et al., 1999). The total area of sea ice was calculated by multiplying the concentration of ice in each pixel by the pixel area, and the percentage cover of sea ice in the region was calculated for each day. Where data were only available every other day, during the SMMR measurement period, the concentration was linearly interpolated to give daily concentrations. The breakup date was defined as the date at which cover fell to 50% or less. However, we take into account the ± 15% uncertainty in the concentration specified by Cavalieri et al. (1992). Therefore the results are presented as the midpoint day between the 65% and 35% concentrations, along with error bars spanning the period

between the 65% and 35% concentration dates. It is possible that this is an overcautious random error, because it assumes all pixels will exhibit the same error on any given date. It is preferable to be overcautious in case the error is largely due to changes in atmospheric conditions or sea-ice conditions, which could be similar over a large area. There is also likely to be a systematic underestimation of concentration that is greater than this error (e.g., Agnew and Howell, 2003; Shokr and Markus, 2006) but this will not affect the overall trend unless there is a change in this systematic error between sensors.

Canadian Ice Service Charts

The sea-ice concentration and extent data were available from the CIS in E00 format, which can be read by standard Geographical Information System (GIS) software. The 15 May to 15 August data for the Hudson Bay region for the years 1971 to 2008 inclusive were converted into the Arc-GIS (ESRI, 2008) shapefile format. Each area of ice was assigned a polygon with attributes such as concentration, ice type, and thickness associated with it. Using the masks shown in Figure 1, Hudson Bay was then separated into western and eastern areas that closely match the areas analyzed using the passive microwave data (Stirling and Parkinson, 2006). With the ArcGIS toolboxes, it was possible to separate all sections of ice area polygons falling within western Hudson Bay from those within eastern Hudson Bay and to do an area calculation on each ice area polygon. These areas were multiplied by the concentration associated with them and then summed to give total ice areas (expressed as a percentage of ice cover) for the eastern and western regions. The breakup was calculated as the date at which the total ice concentration reached 50% or less. Since the CIS charts are published weekly, we again used linear interpolation to give daily concentrations. The fact that concentrations for individual areas are specified only to the nearest tenth may be a source of inaccuracy; however, since there are many ice patches around the time of breakup, it is assumed that such errors will to some extent cancel each other. Nevertheless, it is reasonable to be conservative and still assume an error of ± 7 days. The important benefit of this technique is that it uses the actual areas of the polygons drawn on the charts rather than extrapolations from points within those areas, as was done in the previous analysis by Gagnon and Gough (2005).

RESULTS

Passive Microwave Data

The results of the passive microwave concentration analysis are presented in Figure 3. Using a least squares fit for these results gives a trend to earlier breakup of −0.6 ± 0.2 days per year for the period 1979–2007. The error given in the trend is the 95% confidence limit, which was calculated
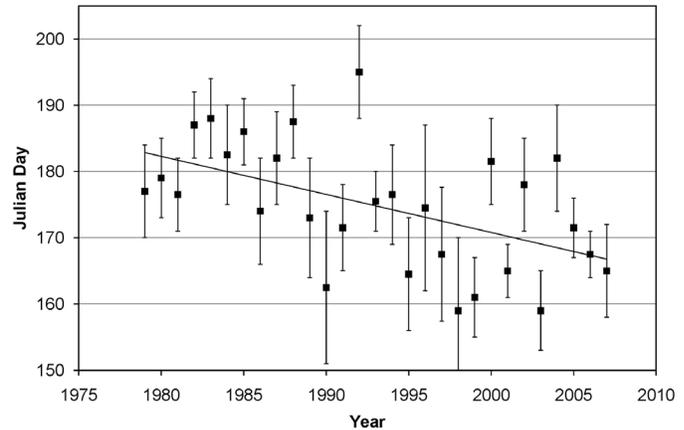

FIG. 3. Breakup dates, defined as the midpoint between 65% and 35% ice concentrations (± 15% error bars), for western Hudson Bay (as shown in Fig. 2). Data are derived from passive microwave records (Cavalieri et al., 2008).

by taking the individual data point errors and allowing the values to vary randomly within these errors, repeatedly fitting the trend line by least squares regression. For easier comparison with Stirling and Parkinson (2006), we defined breakup day as the first time the concentration reaches 50% for the years 1979 to 2004, which gives −0.7 ± 0.2 days per year. An error-based analysis of the data is probably the best way of assessing the importance of the trend toward earlier breakup because an analysis of statistical significance gives no information on the size of the uncertainty.

As mentioned above, the graph shows a step to earlier breakup between 1988 and 1989 (Fig. 3) with much less long-term change on either side of that step. To confirm that a step is present in the data we employed an automated process following the methodology of Lund and Reeves (2002). This method uses a two-phase regression model with an F test for the significance of any change points, such as discontinuities, detected in the climatic data series. The year 1992 is exceptional because of a summer (June–August) cooling anomaly over Hudson Bay caused by the eruption of Mount Pinatubo (Kirchner et al., 1999). When this anomalous year is removed, a clear step is detected from 1988 to 1989. However, because the time series examined is relatively short and interannual variability is high, the step is not statistically significant and could therefore be due to coincidence. Nonetheless we note that it is significant below the 5% level using the less robust but commonly used method employed by Vincent (1998). The sum of the residuals between the fitted model and the data is less for a flat step than for a linear trend. Analysis of other data sets (described later) for step-changes found similarly equivalent results.

As this step occurs at a similar time to the change in satellite instruments, it is important to assess the effect of the transition from SMMR to SSM/I data, which could introduce a change in the systematic errors, as noted above. Unfortunately the first overlap day occurs on 9 July 1987, which was four days after the 50% concentration date for western Hudson Bay. Since the change in the concentration

TABLE 1. A pixel-by-pixel comparison of SMMR and SSM/I concentrations for the two days closest to breakup (50% total ice concentration) in western Hudson Bay.

SMMR Concentration	Average Concentration Measured by SSM/I Compared to SMMR	Number of Pixels Compared
2% to 40%	-1.8%	661
40% to 50%	- 3.8%	227
Greater than 50%	-19.8%	47
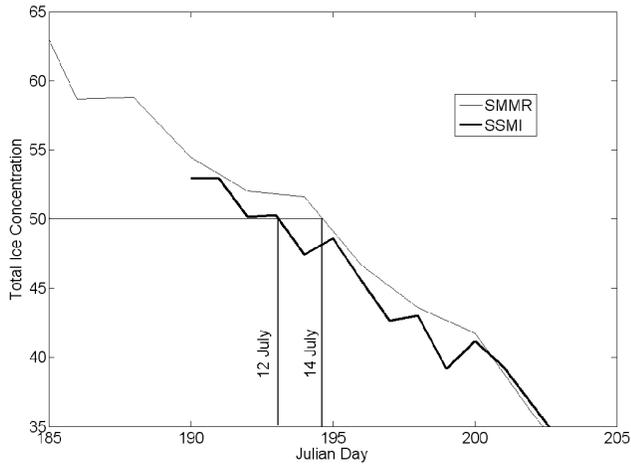
FIG. 4. A comparison of 1987 sea ice concentrations from SMMR and SSM/I for Foxe Basin (as shown in Fig. 2). Passive microwave data are from Cavalieri et al. (2008).
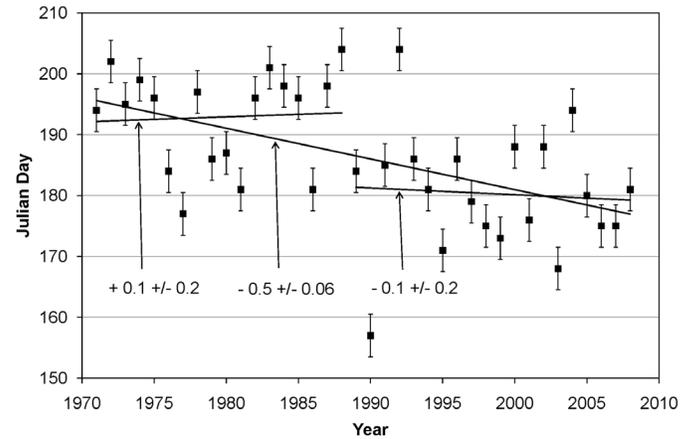

FIG. 5. Breakup dates, defined as the day total ice concentration reaches 50%, for western Hudson Bay (as shown in Fig. 1). Data are derived from Canadian Ice Service regional charts. Bars represent ± 15% error.

around breakup is rapid, it is difficult to get an impression of what the differences over the whole breakup period would be. Comparing the concentrations for each pixel on the two days closest to the breakup (9 July and 11 July) gives some interesting results (Table 1). For both of these days, the SSM/I data give a lower concentration. This difference is particularly pronounced for pixels with higher total concentrations. Given that there would be more high-concentration pixels earlier in the breakup, this effect can be expected to vary from day to day and from year to year. Therefore it is not easy to see how a robust correction to the mismatch between the two sensors could be derived. It is useful to analyze other regions although, as stated earlier, differences between the sensors are dependent on region.

The closest region where a similar trend in breakup was observed is Foxe Basin (Fig. 2). The later breakup of ice in Foxe Basin means that the two sensors overlap just around the 50% concentration point (Fig. 4); however, the SMMR data give a breakup date of 14 July, while the SSM/I data give a breakup date of 12 July, two days earlier. With a shift of just 0.2% in total concentration, the SSM/I data would give a breakup day of three days earlier. Even with this result, a pixel-by-pixel comparison for Foxe Basin does not give as great a difference as for western Hudson Bay.

While it is not possible to extrapolate these limited results to other years, the comparisons outlined here suggest that the SMMR data give a later breakup date than the SSM/I data. Correcting for this difference decreases the overall trend to earlier breakup, although the trend is large enough that any correction would be unlikely to remove it altogether. Applying a correction for western Hudson Bay of two days, as indicated by the one year's coincident data available from Foxe Basin, would reduce the western Hudson Bay trend to -0.5 ± 0.2 days per year.

Canadian Ice Service Charts

The results of this analysis are displayed in Figure 5. The least squares fit to the data gives a trend of -0.50 ± 0.06 days per year for the period 1971 – 2008, or five days per decade. In fact a close look at the data shows that, as with the trend shown in the passive microwave data, there appears to be a step to earlier breakup dates from around 1988 to 1989 and not really a continuous trend at all. Using the same method described previously, a step to earlier breakup of 12 days was detected occurring between 1988 and 1989. Fitting a linear trend separately to the first 18 years of data (1971 – 88) gives $+0.1 \pm 0.2$ days per year and to the last 20 years (1989 – 2008) gives -0.1 ± 0.2 days per year. In summary, the trend before and after this step, for time periods of around two decades, is below data-error levels. Along with the fact that there is a marked step-change between 1988 and 1989, this means that describing the change as a progressive trend over the whole period is misleading.

For closer comparison with the area analyzed by Gagnon and Gough (2005), the breakup in the smaller area of southwestern Hudson Bay (Fig. 1) was analyzed separately. This analysis gives a similar step and significance levels, with no significant trend either before or after the step. However, the size of the step is increased from 12 to 14 days.
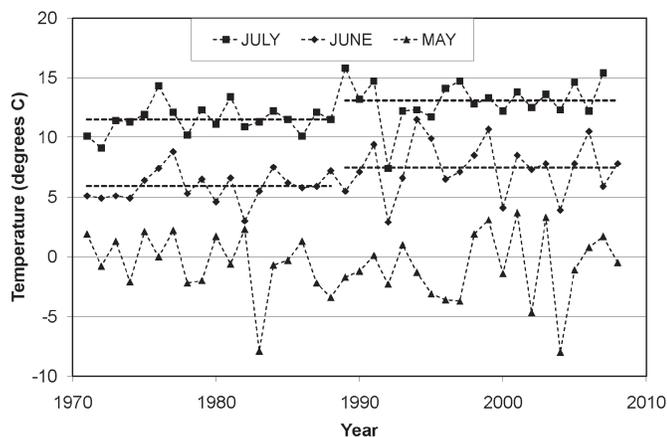
FIG. 6. Monthly average temperatures for Churchill, Manitoba, for May, June, and July. Dotted lines show average June and July temperatures for 1971–88 and 1989–2008.
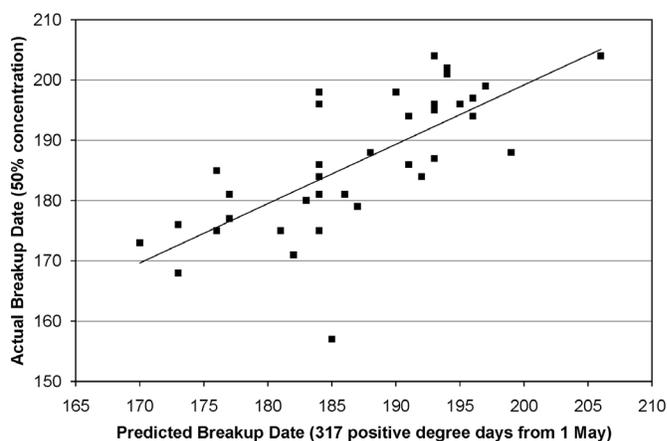

FIG. 7. Predicted breakup date (the day that the positive degree day total reaches 317) plotted against actual breakup date for western Hudson Bay, from CIS chart analysis.

CLIMATE TRENDS

Temperature

The nearest accurate long-term measure of temperature for the southwestern Hudson Bay area is at Churchill, Manitoba (Fig. 1). Temperatures during breakup over the middle of the western Hudson Bay area (Fig. 1) are closely related to those at Churchill (cf. Etkin, 1991: Fig. 3). The correlation between temperatures at Churchill and those at 60° N, 90° W, a site representative of western Hudson Bay, was assessed using the European Centre for Medium Range Weather Forecasts (ECMWF) ERA-40 reanalysis product (Uppala et al., 2005). The two sets of temperatures are highly correlated, with temperatures at the WHB site point colder than those at Churchill by a mean of 6.1°C in June. Although the general trend from this site has been examined in other discussions on sea-ice breakup in western Hudson Bay (Stirling et al., 1999; Gagnon and Gough, 2005; Dyck et al., 2007) it is interesting to assess the data in more detail. Any evidence for a physical cause of the earlier breakup would give more confidence that the observed change was not simply due to the change in data collection method.

To this end historical daily weather records for Churchill were obtained from Environment Canada (2008). Monthly average temperatures for May, June, and July are plotted separately in Figure 6. An increase in temperature can be seen over this period for June and July but a slight decrease in May. July temperatures are generally higher after 1989 except in 1992, the year influenced by the eruption of Mt. Pinatubo. The average increase is 1.6°C warmer in July from 1989 onward, which becomes 2.0°C if 1992 is omitted. The increase in the average June temperature appears to occur around two years later. The average June temperature from 1989 onward is 1.0°C warmer than before. It is possible that the higher July temperatures, in particular, result from earlier disappearance of the sea ice, which allows more solar radiation to be absorbed, rather than being a direct cause of

the breakup. From the CIS analysis above, the average date for breakup (50% concentration) for western Hudson Bay is 11 July for 1971–88 and 29 June for 1989–2008.

One way of looking for a possible cause of the breakup is to examine variations in the regional positive degree days. For each day the average daily temperature is greater than 0°C, the temperature in degrees centigrade was given as the number of positive degree days. This calculation is done cumulatively: i.e., a day with an average temperature of 4°C followed by a day with an average temperature of 5°C counts as 9 positive degree days. The average number of positive degree days from 1 May to the date the ice concentration reaches 50%, according to the CIS data analysis above, is 317. A plot of the date when the total of positive degree days reaches this average against the actual breakup date (Fig. 7) demonstrates there is a clear positive relationship between the cumulative positive temperature and the breakup date, with a coefficient of explanation (r^2) of 0.52. If the one anomalous year (1990) with an exceptionally early breakup date is removed, the coefficient of explanation for the trend over the remaining 36 years is 0.61.

To look in more detail at when the warming occurs, plots of the average daily temperature for 1971–88 and for 1989–2007 are given in Figure 8. It can be seen that before 1 June (Julian Day 152), there is little difference in the average daily temperature between these two periods. In fact, in early May the later period (1989–2008) is on average slightly cooler. Note that average April temperatures are several degrees below freezing and unlikely to cause strong melting. However, from 1 June to 21 June (Julian Day 172), the average daily temperatures for 1989–2007 are up to four degrees higher than those for 1971–88. The largest difference occurs around 20 days prior to the average 50% concentration date for 1989–2008. At that time, the sea-ice concentration has not fallen far from its maximum and is still between 75% and 90%. For the ten-day period around the 1989 to 2008 breakup date there is again little difference in the temperatures between the two periods. The higher temperatures in the first three weeks of June could
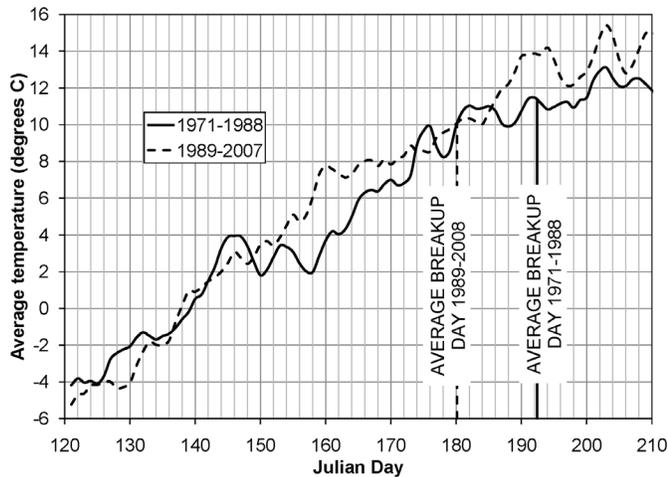
FIG. 8. Average daily temperature for the periods 1971–88 and 1989–2007. The temperatures have been smoothed by a three-day running mean.
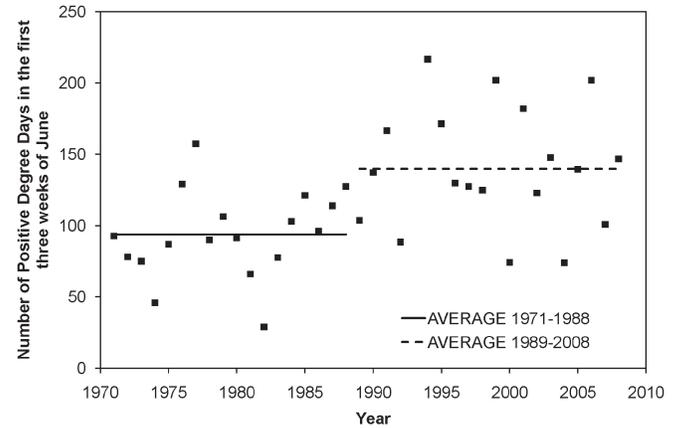

FIG. 9. Number of positive degree days in the first three weeks of June from 1971 to 2008. Lines show averages for the periods 1971–88 and 1989–2008.

be one factor contributing to this earlier average breakup date from 1989 onward. To investigate whether there is a step-change in temperature around 1988 and 1989, we plotted the number of positive degree days for the first three weeks of June (Julian Day 152 to 172) for each year (Fig. 9). This figure shows a lot of interannual variability, but there is an increase in the number of positive degree days around 1988–89 with no significant trend before or after. Analyzing the step as before gives results similar to those observed in the passive microwave data. There is an average of 94 positive degree days for 1971–88 and an average of 140 positive degree days for 1989–2008: an increase of 50%.

Atmospheric Circulation

In order to relate the earlier breakup of sea ice in western Hudson Bay to atmospheric circulation changes, the mean Churchill temperature for the first three weeks of June (hereafter termed CTJ3) was correlated with gridded mean sea level pressure (mslp) data derived from a combination of the ERA-40 reanalysis product for 1971–2001 and the ECMWF operational product for 2002–08. Figure 10 shows the correlation for the entire 38-year period from 1971 to 2008. It indicates that warmer June temperatures at Churchill are associated with enhanced flow from the southwest. These offshore winds advect warmer air from the south into the region and push the ice offshore, and both actions accelerate ice breakup. Regions of both higher pressure to the southeast (centred on the north of James Bay) and lower pressure to the northwest (centred over northern Baffin Island) have a statistically significant relationship (< 5% level) with Churchill temperatures, with the region of significantly lower pressure having a much greater spatial extent.

We note that the basic dipole structure with higher pressure to the south and lower pressure to the north is similar to the positive phase of the broad-scale summer Northern Annular Mode (NAM) circulation pattern as shown, for example, by Figure 2d of Ogi et al. (2004). Indeed, the correlation between CTJ3 and the June values of the NAM (Climate Prediction Center, 2009) of 0.41 for 1971–2008 is statistically significant (< 5% level), indicating that NAM variability explains approximately 17% of changes in CTJ3. Mesquita et al. (2008) showed quantitatively that a positive summer NAM was associated with stronger cyclogenesis and consequent storm activity in the Hudson Bay area. These processes act to promote a positive feedback whereby earlier ice breakup allows greater seasonal ocean-air fluxes of heat and moisture to drive the cyclogenesis, which in turn is likely to cause further regional sea-ice breakup. Furthermore, Ogi et al. (2004) demonstrated that 850 hPa summer temperatures at Churchill are ~4°C higher for strongly positive versus strongly negative NAM. Thus broad-scale changes in circulation variability over North America are playing a role in driving the regional-scale changes in climate observed in the western Hudson Bay area.

Given that CTJ3 is highly correlated with airflow from the southwest, measurements of the near-surface wind at Churchill were examined to see whether any marked difference in wind regime existed at the site before and after the step-change in breakup date in 1988. The data reveal that while a wind from the northeast (i.e., onshore flow) is the most frequent direction during both periods, there was a 20% increase in the proportion of winds from the southwest quadrant for the first three weeks of June in the latter period. This increase provides further evidence indicating the importance of the frequency of southwesterly winds across western Hudson Bay in determining the date of regional sea-ice breakup.

The difference in mean June sea level pressure before and after the step-change (1989–2008 minus 1971–88) is shown in Figure 11. The figure reveals that there has been a statistically significant increase in pressure across northern North America (< 10% level), including a 1 hPa rise over much of the region where there is a significant positive relationship with CTJ3 (cf. Fig. 10). There has also been a decrease in pressure of similar magnitude north of Hudson Bay although it is not significantly different (because
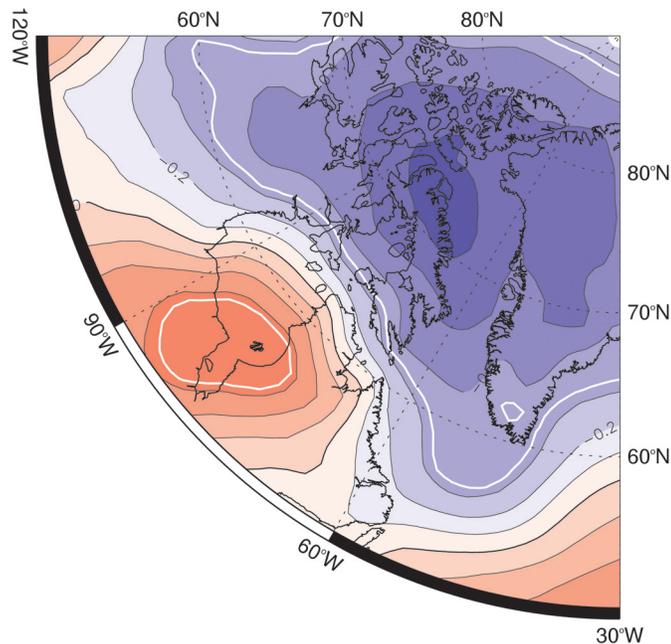
FIG. 10. Correlation between the mean Churchill temperature for the first three weeks of June and gridded mean sea level pressure (mslp) from ECMWF for 1971–2008. Positive (negative) correlations are shown in red (blue) with a contour interval of 0.2. Regions where the relationship is significant (< 5% level) are enclosed by the thick white line.
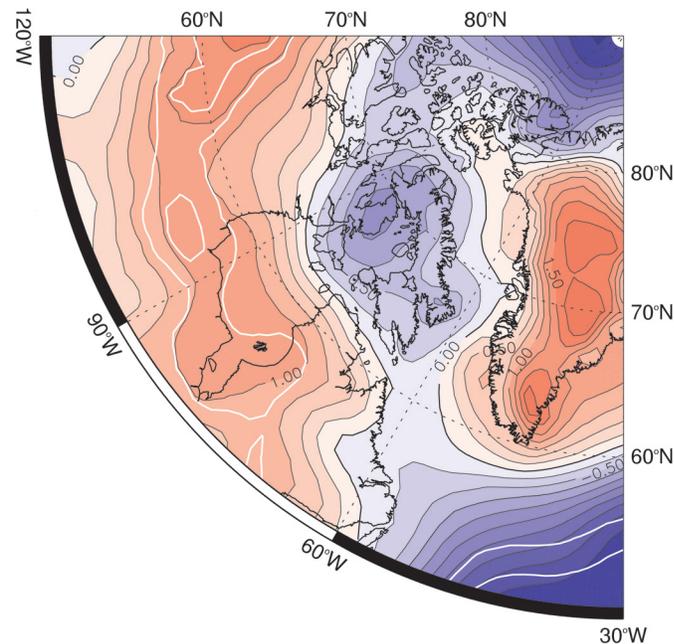
FIG. 11. Difference in the mean June mean sea level pressure before and after the step-change in sea ice breakup (1989–2008 minus 1971–88). Increases in pressure are shown in red and decreases in blue, with 1 hPa isobar. Regions where the pressure difference is significant at levels less than 10% and less than 5% are shown enclosed by successive thick white lines.

of greater mslp variability). The combination of these two regional trends has acted to enhance the meridional pressure gradient across Churchill and western Hudson Bay, leading to the higher frequency of westerly winds observed. This change in pressure pattern is reflected in a step at about this time in the summer North Atlantic Oscillation (NAO) index of Folland et al. (2009: Fig. 3), which is broadly similar to the NAM index. There were also marked changes from the 1980s to the 1990s in the more generally used "winter" indexes of the NAO (e.g., Hurrell et al., 2003).

While there have been several studies attempting to determine the cause of observed changes in Arctic mslp during boreal winter (e.g., Gillett et al., 2005), the changes in summer are much less pronounced and are therefore less well suited to such an examination. Thus, it is not possible to directly ascribe the recent changes in western Hudson Bay climate to human activity. Nevertheless, it is worth noting that the observed change towards a more positive NAM in June is similar to the pattern of projected mslp trend in summer during the 21st century as portrayed by coupled climate models forced by increasing CO_2 (Chapman and Walsh, 2007; Folland et al., 2009).

DISCUSSION AND CONCLUSIONS

The work of Regehr et al. (2007) clearly shows that the western Hudson Bay polar bears are extremely sensitive to the sea-ice breakup date. The detailed analysis of the breakup given here is therefore important for making future

predictions and examining the current and past changes in the health of the local polar bear population.

In this paper, we have followed the work of Gagnon and Gough (2005) and Stirling and Parkinson (2006). Specifically, we have re-examined the sea-ice breakup in western Hudson Bay using the two independent methods of passive microwave ice concentration data and CIS regional charts. Both data sets show a trend to earlier breakup dates. The use of passive microwave–derived concentration is a poor technique for examining summer breakup because it is well known that the greatest errors in the data are related to this season (Cavalieri et al., 2008). However, it should be expected that given a sufficiently long time series, the error in the breakup dates for individual years will become less significant. Had the same technology been used throughout this period, passive microwave sensors would likely have yielded the best data for this analysis. This is unfortunately not the case because there is an unquantifiable change in the systematic error from the transition between the SMMR and SSM/I sensors in 1987. Comparisons of concentration data during the overlap between the two systems, from both the adjacent Foxe Basin and the closest days to breakup in western Hudson Bay, reveal that this change in the systematic error would increase the measured trend to earlier breakup.

The CIS charts may give better estimates of concentration at this time of year (Etkin and Ramseier, 1993) although methods used have changed over the time period and it is not possible to quantify the effect of these changes on the overall trend. However, given the higher resolution

and the longer time series available, analysis of the CIS charts is probably the better technique to use in studying the longer-term breakup trends. Our method uses all of the ice-extent information available in the charts, which is an improvement on previous methodology. From this analysis, the trend toward earlier breakup from 1971 to 2008 is -0.50 ± 0.06 days per year. The same trend is obtained from the passive microwave data if we correct the 1979–87 breakup date by subtracting two days, to account for differences in the time of satellite overpasses. This trend is less than those calculated by previous authors (Gagnon and Gough, 2005; Stirling and Parkinson, 2006), but it is also misleading as it suggests a continuous trend. There has clearly not been a continuous trend in the data, and the change is best described by a step to 12 days earlier breakup occurring between 1988 and 1989, with no significant trend before or after this date. This step-change is very different from the three-week change that is the figure currently being used in discussions about the western Hudson Bay polar bear population (Regehr et al., 2007).

Previous studies have examined the trend in late spring temperature, April–June average (Stirling et al., 1999; Dyck et al., 2007). However, a more detailed examination of the daily temperatures demonstrates that the most likely relationship between the step-change to early ice breakup and temperature is the increase in the temperature over the first three weeks of June. These related phenomena of increased temperatures and sea-ice breakup appear to be correlated with an increased frequency of southwesterly winds, which can be related to changes in the distribution of pressure over northern North America at this time. It remains to be determined whether such changes in atmospheric circulation are a consequence of human activity or simply natural variability.

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REFERENCES

Agnew, T.A., and Howell, S. 2002. Comparison of digitized Canadian ice charts and passive microwave sea-ice concentrations. Geoscience and Remote Sensing Symposium, IGARSS 2002, Vol. 1:231–233, doi:10.1109/IGARSS.2002.1024996.
———. 2003. The use of operational ice charts for evaluating passive microwave ice concentration data. Atmosphere-Ocean 41(4):317–331.
Cavalieri, D.J., Crawford, J., Drinkwater, M., Emery, W.J., Eppler, D.T., Farmer, L.D., Goodberlet, M., et al. 1992. NASA sea ice validation program for the DMSP SSM/I: Final report. NASA Technical Memorandum 104559. Washington, D.C.: National Space and Aeronautics Administration.
Cavalieri, D.J., Parkinson, C.L., Gloersen, P., Comiso, J.C., and Zwally, H.J. 1999. Deriving long-term time series of sea ice cover from satellite passive-microwave multisensory data sets. Journal of Geophysical Research 104(C7):15803–15814.
Cavalieri, D., Parkinson, C., Gloersen, P., and Zwally, H.J. [1996] 2008. Sea ice concentrations from Nimbus-7 and DMSP SSM/I passive microwave data, [1978–2007]. Boulder, Colorado: National Snow and Ice Data Centre. Digital media. http://nsidc.org/data/nsidc-0051.html.
Chapman, W.L., and Walsh, J.E. 2007. Simulations of Arctic temperature and pressure by global coupled models. Journal of Climate 20:609–632.
CIS (Canadian Ice Service). 2000. The Canadian Ice Service digital charts database: History of data and procedures used in the preparation of regional ice charts. Ballicater Consulting Ltd. Report 00-02. http://ocean.dmi.dk/GCOS/documents/toolbox/CISDCD_History_and_Procedures.pdf.
Climate Prediction Center. 2009. Monthly mean Arctic Oscillation index since January 1950. http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii.table.
Dyck, M.G., Soon, W., Baydack, R.K., Legates, D.R., Baliunas, S., Ball, T.F., and Hancock, L.O. 2007. Polar bears of western Hudson Bay and climate change: Are warming spring air temperatures the "ultimate" survival control factor? Ecological Complexity 4:73–84.
Environment Canada. 2008. National Climate Data and Information Archive. http://www.climate.weatheroffice.gc.ca/climateData/canada_e.html.
ESRI (Environmental Systems Research Institute, Inc.). 2008. ArcGIS. www.esri.com/software/arcgis/.
Etkin, D.A. 1991. Break-up in Hudson Bay: Its sensitivity to air temperatures and implications for climate warming. Climatological Bulletin 25:21–34.
Etkin, D.A., and Ramseier, R.O. 1993. A comparison of conventional and passive microwave sea-ice datasets for Hudson Bay. Atmosphere-Ocean 31:359–378.
Fetterer, F., Knowles, K., Meier, W., and Savoie, M. [2002] 2008. Sea ice index. Boulder, Colorado: National Snow and Ice Data Center. Digital media. http://nsidc.org/data/docs/noaa/g02135_seaice_index/index.html.
Folland, C.K., Knight J., Linderholm, H.W., Fereday, D., Ineson, S., and Hurrell, J.W. 2009. The summer North Atlantic Oscillation: Past, present and future. Journal of Climate 22:1082–1103.
Gagnon, A.S., and Gough, W.A. 2005. Trends in the dates of ice freeze-up and breakup over Hudson Bay, Canada. Arctic 58(4):370–382.
Gillett, N.P., Allan, R.J., and Ansell, T.J. 2005. Detection of external influence on sea level pressure with a multi-model ensemble. Geophysical Research Letters 32, L19714, doi:10.1029/2005GL023640.
Hurrell, J.W., Kushnir, Y., Ottersen, G., and Visbeck, M. 2003. An overview of the North Atlantic Oscillation. In: Hurrell, J.W., Kushnir, Y., Ottersen, G., and Visbeck, M., eds. The North

Atlantic Oscillation: Climatic significance and environmental impact. Geophysical Monograph 134. Washington, D.C.: American Geophysical Union. 1–35.

Kirchner, I., Stenchnikov, G.L., Graf, H.-F., Robock, A., and Antuña, J.C. 1999. Climate model simulation of winter warming and summer cooling following the 1991 Mount Pinatubo volcanic eruption. Journal of Geophysical Research 104(D16):19039–19055.

Lund, R., and Reeves, J. 2002. Detection of undocumented changepoints: A revision of the two-phase regression model. Journal of Climate 15:2547–2554, doi:10.1175/1520-0442(2002) 015<2547:DOUCAR>2.0.CO;2.

Mesquita, M.D.S., Kvamstø, N.G., Sorteberg, A., and Atkinson, D.E. 2008. Climatological properties of summertime extra-tropical storm tracks in the Northern Hemisphere. Tellus 60A:557–569, doi:10.1111/j.1600-0870.2008.00305.x.

Ogi, M., Yamazaki, K., and Tachibana, Y. 2004. The summertime annular mode in the Northern Hemisphere and its linkage to the winter mode. Journal of Geophysical Research 109, D20114, doi:10.1029/2004JD004514.

Picard, G., and Fily, M. 2006. Surface melting observations in Antarctica by microwave radiometers: Correcting 26-year time series from changes in acquisition hours. Remote Sensing of Environment 104:325–336.

Regehr, E.V., Lunn, N.J., Amstrup, S.C., and Stirling, I. 2007. Effects of earlier sea ice breakup on survival and population size of polar bears in western Hudson Bay. The Journal of Wildlife Management 71(8):2673–2683.

Shokr, M., and Markus, T. 2006. Comparison of NASA Team 2 and AES-York ice concentration algorithms against operational ice charts from the Canadian Ice Service. IEEE Transactions on Geoscience and Remote Sensing 44(8):2164–2175.

Stirling, I., and Parkinson, C.L. 2006. Possible effects of climate warming on selected populations of polar bears (*Ursus maritimus*) in the Canadian Arctic. Arctic 59(3):261–275.

Stirling, I., Lunn, N.J., and Iacozza, J. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic change. Arctic 52(3):294–306.

Uppala, S.M., Kallberg, P.W., Simmons, A.J., Andrae, U., Bechtold, V.D., Fiorino, M., Gibson, J.K., et al. 2005. The ERA-40 re-analysis. Quarterly Journal of the Royal Meteorological Society 131:2961–3012.

Vincent, L.A. 1998. A technique for the identification of inhomogeneities in Canadian temperature series. Journal of Climate 11:1094–1104.