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Trends in the Dates of Ice Freeze-up and Breakup over Hudson Bay, Canada

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ABSTRACT. Hudson Bay experiences a complete cryogenic cycle each year. Sea ice begins to form in late October, and the Bay is usually ice-free in early August. This seasonally varying ice cover plays an important role in the regional climate. To identify secular trends in the cryogenic cycle, we examined variability in the timing of sea-ice formation and retreat during the period 1971–2003. The dates of ice freeze-up and breakup at 36 locations across Hudson Bay were catalogued for each year from weekly ice charts provided by the Canadian Ice Service. We used the nonparametric Mann-Kendall test to determine the statistical significance of the trends and the Theil-Sen approach to estimate their magnitude. Our results indicate statistically significant trends toward earlier breakup in James Bay, along the southern shore of Hudson Bay, and in the western half of Hudson Bay, and toward later freeze-up in the northern and northeastern regions of Hudson Bay. These trends in the annual ice cycle of Hudson Bay coincide with both the regional temperature record and the projections from general circulation models. If this trend toward a longer ice-free season continues, Hudson Bay will soon face important environmental challenges.

Key words: breakup, climate change, freeze-up, Hudson Bay, sea ice, temperature

RÉSUMÉ. Chaque année, la Baie d'Hudson connaît un cycle cryogénique complet. La formation de la glace marine commence en fin d'octobre et la baie est habituellement exempte de glace en début d'août. La présence saisonnière du couvert de la glace de la Baie d'Hudson revêt une importance primordiale sur le climat régional. Dans cet article, on étudie la variabilité des dates de formation et de retrait de la glace marine de la Baie d'Hudson dans le but d'identifier des tendances séculaires durant la période 1971 à 2003. Les dates de formation et de retrait de la glace marine ont été cataloguées pour tous les ans dans le cas de 36 endroits à travers la Baie d'Hudson et la Baie James en utilisant des images hebdomadaires publiées par le Service canadien des glaces. Le test non paramétrique Mann Kendall a été utilisé pour déterminer la signification statistique des tendances alors que la méthode de Theil Sen nous a fourni un estimé de l'ampleur de ces mêmes tendances. Notre analyse statistique nous indique qu'il existe des tendances significatives vers une date de déglacement plus avancée dans la Baie James, le long de la côte sud de la Baie d'Hudson, et dans la partie ouest de la Baie d'Hudson. De plus, des tendances significatives vers un gel plus tardif ont été observées dans les régions du nord et du nord-est de la Baie d'Hudson. Ces tendances dans le cycle annuel de glace de la Baie d'Hudson coïncident avec les tendances des températures de la région de même qu'avec les projections des modèles de circulation générale. Si cette tendance vers une durée plus courte du couvert de glace continue, la région de la Baie d'Hudson relèvera des défis environnementaux importants dans un proche avenir.

Mots clés: Baie d'Hudson, changements climatiques, déglacement, formation, glace marine, température

INTRODUCTION

Coupled atmosphere-ocean general circulation models are used to provide climate-change projections for various scenarios of greenhouse gas emissions. These climate models, using the IS92 forcing scenarios with the inclusion of the cooling effect of sulphate aerosols, predict an increase of 1.0˚ to 3.5˚C in global surface mean temperature by 2100 (Cubasch et al., 2001). IS92 refers to a series of six climate-change scenarios from the Intergovernmental Panel on Climate Change (IPCC). These scenarios were created in order to embody a large range of assumptions regarding future economic, social, and environmental conditions, all affecting the evolution of greenhouse gas emissions (Leggett et al., 1992). In the Hudson Bay region, the projected warming is expected to be greater, with average temperature for 2070–99 from 4.8˚ to 8.0˚C higher than the average for 1961–90 (Gagnon and Gough, 2005). Climatic changes are amplified in high-latitude environments because of changes to the sea-ice cover and the snow cover over land. Sea ice reflects solar radiation into the atmosphere and to space, thereby reducing the absorption of solar energy by the ocean. If the ice-free season were longer as a result of earlier breakup and later freeze-up, the ocean would likely absorb more energy from the sun and hence warming would be accentuated in the Hudson Bay region. In this study, we examined the variability in the dates of ice freeze-up and breakup over

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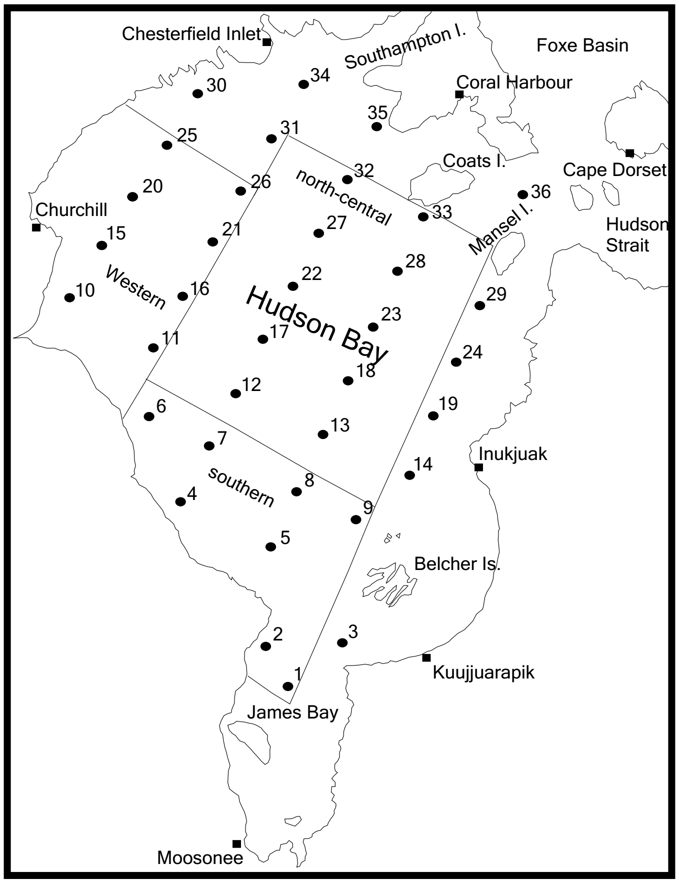


FIG. 1. Location map of Hudson Bay. The numbered dots indicate the 36 grid points from which the dates of ice breakup and freeze-up were derived, while the squares depict the location of the weather stations. Also shown are the three regions from which the trends in breakup and freeze-up dates were calculated.

Hudson Bay during the period 1971–2003 to identify long-term trends in the cryogenic cycle.

Hudson Bay and James Bay together extend over 1 300 000 km^2, forming the largest inland sea in North America (Martini, 1986; Etkin, 1991). They are surrounded by landmasses, and exchanges of water are limited to narrow channels in the northern section of Hudson Bay (Fig. 1). Cold Arctic water enters Hudson Bay through Roes Welcome Sound, located to the west of Southampton Island in northwestern Hudson Bay, while Atlantic water comes into the Bay through the middle and northern channels that connect it to Hudson Strait (Prinsenberg, 1986a). Water circulation within Hudson Bay is cyclonic. Warmer water exits through Hudson Strait as a surface flow in the northeast (Prinsenberg, 1986a, b). This large body of salt water, referred to hereafter as "Hudson Bay" or "the Bay," freezes completely each winter and becomes ice-free during the summer. Second-year ice is found on rare occasions, but is limited to northeastern Hudson Bay (Etkin and Ramseier, 1993). Typically, Hudson Bay is completely ice-covered by late December and is free of ice from mid-August to late October (Markham, 1986; Wang et al., 1994a; Mysak et al., 1996). The southwestern region of Hudson Bay is one of the last regions to experience breakup in the summer because of advection of ice by winds and ocean currents (Etkin, 1991). Because sea ice is still present well into summer, Hudson Bay experiences anomalously cold temperatures in comparison with other regions situated at similar latitudes (Maxwell, 1986; Rouse, 1991; Gough and Leung, 2002). At Churchill (Manitoba), for example, the average temperature in July, the warmest month of the year, is 12˚C, and only four months have monthly mean temperatures above the freezing point.

Gagnon and Gough (2005) observed that most of the differences between models in their climate-change projections for Hudson Bay were caused in part by changes to the seasonality of the ice cover. Nevertheless, in all the models analyzed, the ice-free season was lengthened by a later freeze-up date, an earlier breakup date, or both. The warming trend indicated in these climate-change projections will have important consequences for the natural ecosystems and infrastructure of Hudson Bay. The identification of a trend toward a longer ice-free season in the historical ice record of the region would support the climate-change projections. Earlier spring breakup and later freeze-up in the autumn would benefit the Port of Churchill, whose shipping season is currently limited by the presence of the ice cover. The town of Churchill benefits from a connection to the Canadian railway system and is an important seaport for grain shipment from the Prairies to European markets (MacIver, 1983; Markham, 1986). On the other hand, the adverse ecological consequences of climate change on the region could outweigh the economic benefits. For example, a longer ice-free season would be detrimental to the polar bear population of western Hudson Bay, whose existence depends on the presence of the ice cover. Polar bears use the sea ice as a platform to catch seals and will be significantly affected by changes in the annual sea-ice cycle (Stirling and Derocher, 1993; Stirling et al., 1999; Derocher et al., 2004).

Previous research has revealed that the extent of the Arctic ice cover has been decreasing over the last few decades (e.g., Maslanik et al., 1996; Bjorgo et al., 1997; Johannessen et al., 1999; Parkinson et al., 1999; Vinnikov et al., 1999). Only Parkinson et al. (1999), however, analyzed the sea-ice extent of Hudson Bay. They found that during 1978–96, the spatial extent of sea ice over Hudson Bay decreased at a rate of 1.4×10^3 km^2/yr, with negative trends in all seasons but winter. Interannual variability in winter is minimal because of the physical constraints of the Bay: once Hudson Bay is completely ice-covered, the ice extent cannot grow, unlike that of the Labrador Sea, for example. Nevertheless, none of the trends identified for Hudson Bay were statistically significant. In addition, the results from the above study were based on passive microwave observations, which are known to underestimate the ice concentration during the melt season because of the extensive puddles that form on the ice cover (Markham, 1986; Etkin and Ramseier, 1993).

Although research has shown that ice observations, particularly the freeze-up and breakup dates, are useful indicators of climate change and variability (Palecki and Barry, 1986; Robertson et al., 1992; Reycraft and Skinner, 1993; Anderson et al., 1996; Magnuson et al., 2000), the use of those variables in Hudson Bay research is limited to the work of Gough et al. (2004) and Stirling et al. (1999). Gough et al. (2004) calculated that during 1971–99, breakup in southwestern Hudson Bay had been occurring five days earlier per decade. Stirling et al. (1999) noted a similar trend towards earlier ice breakup in western Hudson Bay during 1979–98, although it lacked statistical significance. The timing of ice breakup continued to be monitored in the latter region, and Stirling et al. (2004) reported a statistically significant trend toward earlier breakup off the Manitoba coast (but not off the Ontario coast) during 1971–2001. In the above studies, the dates of ice freeze-up and breakup were derived from sea-ice concentration data, which refers to the surface area that is covered with ice and is given in tenths (0 to 10/10). These studies, however, were limited in both temporal and spatial extent. We present a more comprehensive analysis that includes all of Hudson Bay and uses more than 30 years of data now available from the region.

DATA AND ANALYSIS

Data

The Canadian Ice Service (CIS) has issued ice concentration data for Hudson Bay since 1971. These data are mapped out weekly except in the winter months (January–May), when they are issued bi-weekly or monthly. The CIS images are created by incorporating all available information on ice conditions from satellite images, ship and aircraft observations, observations from shore, and climatic information. (Reconnaissance flights over Hudson Bay, to determine when ice conditions will permit commercial navigation, begin in late spring and continue until breakup, according to Ingram and Prinsenberg, 1998.) We obtained the ice concentration from those images for 36 points across Hudson Bay (Fig. 1) and catalogued the dates of ice freeze-up and breakup for each year with an accuracy of ±1 week, using the methodology of Etkin (1991), which was later adapted by Stirling et al. (1999) and Gough et al. (2004). Therefore, we defined breakup as the earliest date when the ice concentration was 5/10 or less. Freeze-up, on the other hand, was considered to have occurred when the ice concentration reached 5/10 or more during October–December. These thresholds in deriving the dates of sea-ice formation and breakup agree with the terminology used by both the CIS and the World Meteorological Organization (WMO). The CIS denotes an ice concentration between 4/10 and 6/10 as "open drift ice," while the WMO calls it "open pack ice" (Catchpole and Halpin, 1987; CIS, 1999).

In addition to determining the dates of ice freeze-up and breakup at these 36 discrete geographical points, we identified the mean dates of ice breakup for three regions, representing western, southern, and north-central Hudson Bay (Fig. 1). For this purpose, a grid with sampling points at one-degree intervals of latitude and longitude was superimposed on the weekly ice concentration charts from the CIS. For each region, we obtained the weekly ice concentration values for all the points situated in that region and averaged them. The first date when the averaged ice concentration for a particular region fell to 5/10 or less was considered the breakup date, and the first date when averaged ice concentration reached 5/10 or more, the freeze-up date.

The technology used to create these ice-concentration charts has improved substantially. The visual and infrared Advanced Very High Resolution Radiometers (AVHRR) from the National Oceanographic and Atmospheric Administration (NOAA), with a spatial resolution of 1 km, have been a primary source for creating these ice concentration charts. In 1978, the Side-Looking Airborne Radar (SLAR) improved the spatial resolution to 100 m, which was further increased to the 5–30 m range in 1990 with Synthetic Aperture Radar (SAR). Information from the latter became available from outer space in 1992 at a resolution of 100 m. In addition to the increase in spatial resolution, the use of these radar satellites allowed for observations to be taken on cloudy days and both day and night. In early 1996, RADARSAT, which uses a SAR sensor, became the first satellite dedicated to ice monitoring with a resolution of 25 m (CIS, 2002). The amount of uncertainty introduced by these improvements in satellite technology is unknown. Nevertheless, the quality of these charts is high, as their primary purpose is to support shipping activities in northern Canadian waters (CIS, 2002), and they are therefore the best source from which the dates of ice freeze-up and breakup could be derived for Hudson Bay.

Hudson Bay behaves essentially as a closed ocean body in that its climate is mainly controlled by air temperature variations and is not strongly influenced by advection of ice and water from other ocean basins (Saucier and Dionne, 1998). In fact, Gough and Allakhverdova (1999) noted that the duration of the ice thickness and ice cover of Hudson Bay is essentially controlled by air temperature variations, a result in agreement with Etkin (1991) and Wang et al. (1994a). Thus, monthly air temperature data were procured from the homogenized and historical temperature dataset developed at Environment Canada (Vincent, 1998; Vincent and Gullett, 1999) for seven stations situated in the Hudson Bay region (Fig. 1). Seasonal and annual temperature time series were calculated from the monthly values, and anomalies were computed as departures from the 1971–2000 period. Hudson Bay and most of northern Canada do not conform to the four-season pattern normally found in southern Canada. Nevertheless, we used the standard climatological seasons—that is, December to February for winter, March to May for spring, June to August for summer, and September to November for autumn—to facilitate the discussion. The resulting temperature time series were analyzed for secular trends and then compared with time series of freeze-up and breakup to enable physical explanations of the observed variability in the seasonality of the Hudson Bay ice cover.

Statistical Analysis

The Mann-Kendall (MK) test determines the statistical significance of the trends:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(Y_j - Y_i), \quad [1]$$

where S is the sum of the signs of the slopes of all possible pairs in the dataset, and n refers to the time series length (Kendall and Gibbons, 1990). This test determines whether the Y values tend to increase or decrease with time. Since all the time series analyzed in the current study contained more than 10 observations, a normal distribution with a mean of zero was calculated for S under the null hypothesis of no trend. This normal distribution allows for a p-value to be calculated to identify the statistical significance of the trends. Helsel and Hirsch (1992) provide further details on this normal approximation. The MK test is also referred to as Kendall's tau when the x-axis is time. It is nonparametric and hence has advantages over parametric tests such as the t-test as it does not require the assumption of normality of the observations and is not affected by missing values (Helsel and Hirsch, 1992). We used the MK to determine whether a trend was statistically significant at the 0.10, 0.05, and 0.01 significance levels, corresponding to confidence levels of 90%, 95%, and 99%, respectively, for a two-sided probability.

The MK test does not provide an estimate of the trend magnitude, so we used an algorithm derived by Hirsch et al. (1982), the Theil-Sen approach (TSA), for that purpose. The TSA is also nonparametric and provides a more robust slope estimate than the least-squares method, because outliers or extreme values in the time series affect it less (Sen, 1968). The trend slope estimate (β) is defined as:

$$\beta_1 = median\left(\frac{Y_j - Y_i}{t_j - t_i}\right), \text{for all } i > j, \quad [2]$$

where Y is the variable tested for trend (the breakup date, for example), and t is time. β represents the median of the slopes obtained from all possible combinations of two points in the time series.

Serial correlation exists in a time series when observations are correlated with preceding or subsequent observations. The MK test is valid only if there is no serial correlation in the dataset. A positive serial correlation increases the sample variance, and thereby the probability of the test statistic to falsely detect a statistically significant trend (Helsel and Hirsch, 1992). The time series were tested for serial correlation using the following equation:

$$\frac{-1 - 1.645\sqrt{n-2}}{n-1} \le r_1 \le \frac{-1 + 1.645\sqrt{n-2}}{n-1}, \quad [3]$$

where r_1 is the lag-1 autocorrelation coefficient (Salas et al., 1980). If the lag-1 autocorrelation coefficient falls inside the above interval, the time series is assumed to be composed of independent observations; otherwise the data are serially correlated at the 90% confidence level (Yue et al., 2002).

A time series is assumed to include three components: the trend, usually assumed to be linear; the lag-1 serial correlation; and the white noise (Zhang et al., 2000). Von Storch (1995) proposed to eliminate the influence of serial correlation on the MK test by pre-whitening the time series. This method, which has been widely used (e.g., Hamed and Rao, 1998; Zhang et al., 2000, 2001; Burn and Elnur, 2001), consists of removing the lag-1 serial correlation from the time series through autoregressive and integrated moving average (ARIMA) models. The significance of the trend is tested using the MK test on the pre-whitened time series, which consists of the residuals from the ARIMA model and is composed of independent observations. However, Yue et al. (2002) showed that this pre-whitening method, in addition to eliminating the serial correlation component from a time series, removes part of the trend in the data. Therefore, they proposed to remove a first-order trend from the time series before pre-whitening it. Moreover, the presence of a trend in a time series can result in erroneous detection of serial correlation (Yue et al., 2002). Some time series in the current study did not meet the stationary requirement of ARIMA modelling when the trend was not a priori removed from the time series.

In this research, we used the Yue et al. (2002) method before assessing the statistical significance of the trend in the presence of serial correlation. This method comprises four steps. First, the slope of the sample data is estimated using the TSA. If the slope differs from zero, the trend is assumed to be linear and it is removed from the time series. Second, the AR (1) component is extracted from the detrended time series. Third, the residual time series and the linear trend are combined together. Fourth, the MK test is then applied to the time series to determine whether the trend is statistically significant at the significance level selected. In the absence of serial correlation, only the first and fourth steps are performed.

RESULTS

Ice Cover

Breakup first occurs in James Bay in late June. This is likely a consequence of thawing and physical erosion engendered by the winds that travel over the relatively

TABLE 1. Means and standard deviations of the dates of ice freeze-up and breakup for the 36 points from which ice concentration was obtained.

Point	Co-ordinates	Freeze-up (Julian days)		Breakup (Julian days)	
		Mean	SD	Mean	SD
1	54.0° N, 81.0° W	–	–	180 (Jun 28)	15.5
2	54.5° N, 82.0° W	330 (Nov 25)	10.1	175 (Jun 23)	11.1
3	55.0° N, 80.0° W	–	–	180 (Jun 28)	15.1
4	56.0° N, 86.0° W	330 (Nov 25)	8.9	198 (Jul 16)	13.2
5	56.0° N, 83.0° W	338 (Dec 3)	8.3	202 (Jul 20)	12.9
6	57.0° N, 88.0° W	331 (Nov 26)	8.5	202 (Jul 20)	13.9
7	57.0° N, 86.0° W	336 (Dec 1)	10.3	208 (Jul 26)	14.7
8	57.0° N, 83.0° W	339 (Dec 4)	9.3	202 (Jul 20)	11.2
9	57.0° N, 81.0° W	–	–	196 (Jul 14)	13.8
10	58.0° N, 92.0° W	327 (Nov 22)	9.3	182 (Jun 30)	22.7
11	58.0° N, 89.0° W	335 (Nov 30)	10.4	205 (Jul 23)	15.1
12	58.0° N, 86.0° W	335 (Nov 30)	9.7	204 (Jul 22)	12.3
13	58.0° N, 83.0° W	–	–	201 (Jul 19)	11.2
14	58.0° N, 80.0° W	–	–	–	–
15	59.0° N, 92.0° W	328 (Nov 23)	8.8	197 (Jul 15)	14.6
16	59.0° N, 89.0° W	332 (Nov 27)	8.3	202 (Jul 20)	12.1
17	59.0° N, 86.0° W	334 (Nov 29)	8.8	202 (Jul 20)	12.3
18	59.0° N, 83.0° W	334 (Nov 29)	8.5	195 (Jul 13)	14.3
19	59.0° N, 80.0° W	–	–	–	–
20	60.0° N, 92.0° W	326 (Nov 21)	8.6	192 (Jul 10)	17.2
21	60.0° N, 89.0° W	329 (Nov 24)	8.6	197 (Jul 15)	11.5
22	60.0° N, 86.0° W	331 (Nov 26)	8.4	201 (Jul 19)	10.5
23	60.0° N, 83.0° W	332 (Nov 27)	7.5	196 (Jul 14)	12.8
24	60.0° N, 80.0° W	334 (Nov 29)	8.4	–	–
25	61.0° N, 92.0° W	323 (Nov 18)	8.5	–	–
26	61.0° N, 89.0° W	326 (Nov 21)	8.5	191 (Jul 9)	12.6
27	61.0° N, 86.0° W	328 (Nov 23)	8.5	195 (Jul 13)	11.8
28	61.0° N, 83.0° W	329 (Nov 24)	8.6	194 (Jul 12)	12.7
29	61.0° N, 80.0° W	330 (Nov 25)	9.3	–	–
30	62.0° N, 92.0° W	319 (Nov 14)	9.5	–	–
31	62.0° N, 89.0° W	323 (Nov 18)	8.3	–	–
32	62.0° N, 86.0° W	324 (Nov 19)	7.8	186 (Jul 4)	14.3
33	62.0° N, 83.0° W	324 (Nov 19)	9.6	183 (Jul 1)	16.3
34	63.0° N, 89.0° W	318 (Nov 13)	8.7	–	–
35	63.0° N, 86.0° W	316 (Nov 11)	10.5	–	–
36	63.0° N, 80.0° W	320 (Nov 15)	10.2	183 (Jul 1)	13.0

warm landmasses of northern Ontario following snowmelt (Table 1). Breakup occurs in early July in northwestern Hudson Bay, where ice is removed by the strong and prevailing northwesterly winds and ocean currents (Maxwell, 1986). An accurate breakup date could not be determined for the points situated in the northwestern region (points 25, 30, 31, 34, and 35), because in many years breakup had already occurred when the first weekly ice charts were issued (Maxwell, 1986; Wang et al., 1994b). Missing values were also common for a few points located along meridian 80° W (points 14, 19, 24, and 29), and consequently reliable trend analyses could not be performed for these four coordinates. Early breakup in eastern Hudson Bay is attributed to the northward flow of freshwater that follows spring runoff in James Bay (Markham, 1986). The area of open water in northwestern Hudson Bay expands both southward and eastward throughout July. However, in the southwestern part of Hudson Bay, the last region to experience breakup, an ice concentration of 5/10 or less is not reached, on average, until the third week of July.

Ice formation begins in the northern part of Hudson Bay in late October, and the ice becomes consolidated (i.e., an ice concentration of 5/10 or more) during the second week of November (Table 1). As cold Arctic air masses advance over the region, the Hudson Bay ice cover progresses in a southward and eastward direction throughout November (Maxwell, 1986). Southeastern Hudson Bay and eastern James Bay do not freeze over before December. An accurate freeze-up date could not be determined for the points located in the latter two regions (points 1, 3, 9, 13, 14, and 19) because in many consecutive years freeze-up had not yet occurred when the CIS published its last weekly ice chart of the season.

A few examples of the resulting time series of the breakup and freeze-up dates are shown in Fig. 2. The time series of freeze-up dates contain fewer data than those of breakup dates because of gaps in the freeze-up time series. All the breakup time series are composed of 32 or 33 observations. For reasons previously mentioned, however, the freeze-up dates were missing for a number of years, particularly for points at lower latitudes. Time series of less than 25 years' duration (mainly limited to southeastern Hudson Bay) were omitted from the analysis. These time series also show that there is strong interannual variability in the timing of freeze-up and breakup over Hudson Bay, and the standard deviations indicate that this variability is generally of greater magnitude for the breakup dates than for the freeze-up dates (Table 1). Individual grid points typically have standard deviations varying from 7.5 to 10.5 days for freeze-up and from 10.5 to 22.7 days for breakup. Moreover, the breakup date has the highest variability at points located closest to the western shore of Hudson Bay. At point 20, for example, breakup occurs, on average, on 10 July, with a standard deviation of ±17.2 days. At this location, breakup has taken place as early as 1 June (2003) and as late as 14 August (1988). This interannual variability in the breakup date decreases toward the east, to ±11.5 days at point 21 and ±10.5 days at point 22.

There is statistically significant serial correlation in the freeze-up and breakup dates in some regions. There is positive serial correlation in the freeze-up dates in the centre of Hudson Bay. For example, the lag-one autocorrelation coefficients are 0.24 at both point 22 and point 23, but these lack statistical significance. Negative serial correlation prevails in western Hudson Bay, but only in northwestern Hudson Bay are the lag-one autocorrelation coefficients statistically significant (for instance, $r_1 = -0.33$, $p < 0.10$ at point 25; $r_1 = -0.38$, $p < 0.05$ at point 31). In other parts of Hudson Bay, the lag-one autocorrelation coefficient is near zero, which implies that the freeze-up dates are independent of one another. Positive serial correlation, which indicates that ice conditions in one year depend on those of the previous year, results from heat storage in the seawater of Hudson Bay. Negative serial correlation refers to a tendency for the freeze-up or breakup dates to oscillate, with above-average values immediately

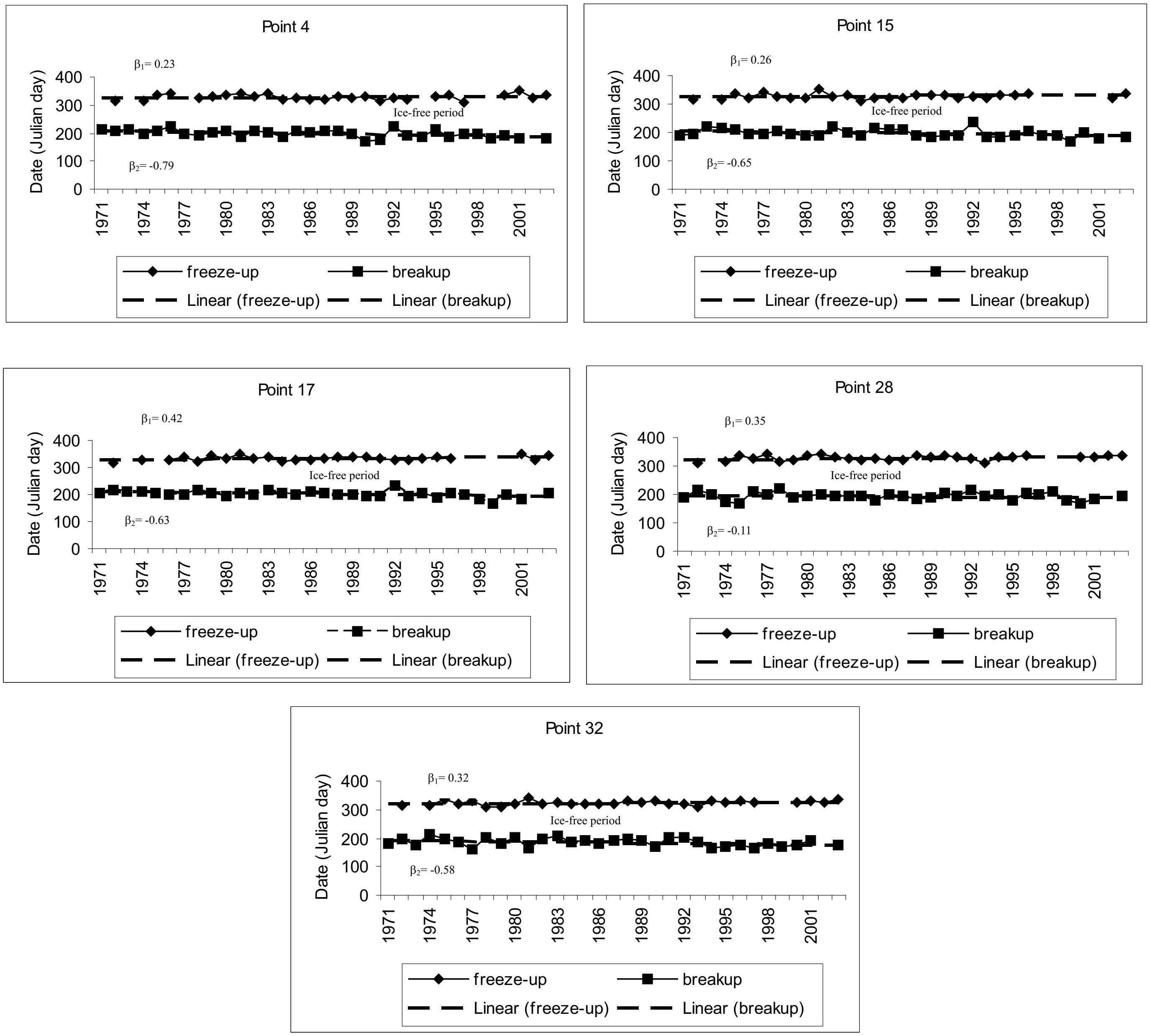


FIG. 2. Time series of the annual breakup and freeze-up date for points 4, 15, 17, 28, and 32. The two dash lines represent the linear trend obtained using the TSA. The intercept is defined as $\beta_0 = Y_{med} - \beta_1 \times t_{med}$ where Y_{med} and t_{med} are the medians of Y and t, respectively. β_1 and β_2 represent the magnitude of the freeze-up and breakup trends, respectively.

followed by below-average values (Burt and Barber, 1996). The upwelling of cold water from below the surface into the surface layer, which is induced by the prevailing northwesterly winds over the region, could explain this lack of memory from one year to the next in the timing of freeze-up in northwestern Hudson Bay.

For the breakup dates, statistically significant positive serial correlation was observed ($r_1 = 0.35$, $p < 0.05$ at point 21) only in northwestern Hudson Bay. There is also positive serial correlation in James Bay, but it lacks statistical significance. In southern Hudson Bay, negative serial correlation prevailed, but without statistical significance. The sign of the serial correlation for the three regions depicted in Figure 1 also agrees with the results of point-based analysis: if the serial correlation is positive (or negative), so is the value based on points. Positive lag-one autocorrelation is found in the breakup dates of western Hudson Bay (r = 0.42, df = 31, $p < 0.05$) and north-central Hudson Bay (r = 0.44, df = 31, $p < 0.05$), while there is weak negative serial correlation in southern Hudson Bay (r = -0.16, df = 31, $p = 0.39$). The presence of serial correlation in the time series was accounted for before running the MK test.

The trend analyses indicate that Hudson Bay sea ice has been forming later and breaking up earlier during 1971–2003 (Fig. 3). In fact, the null hypothesis of no trend is

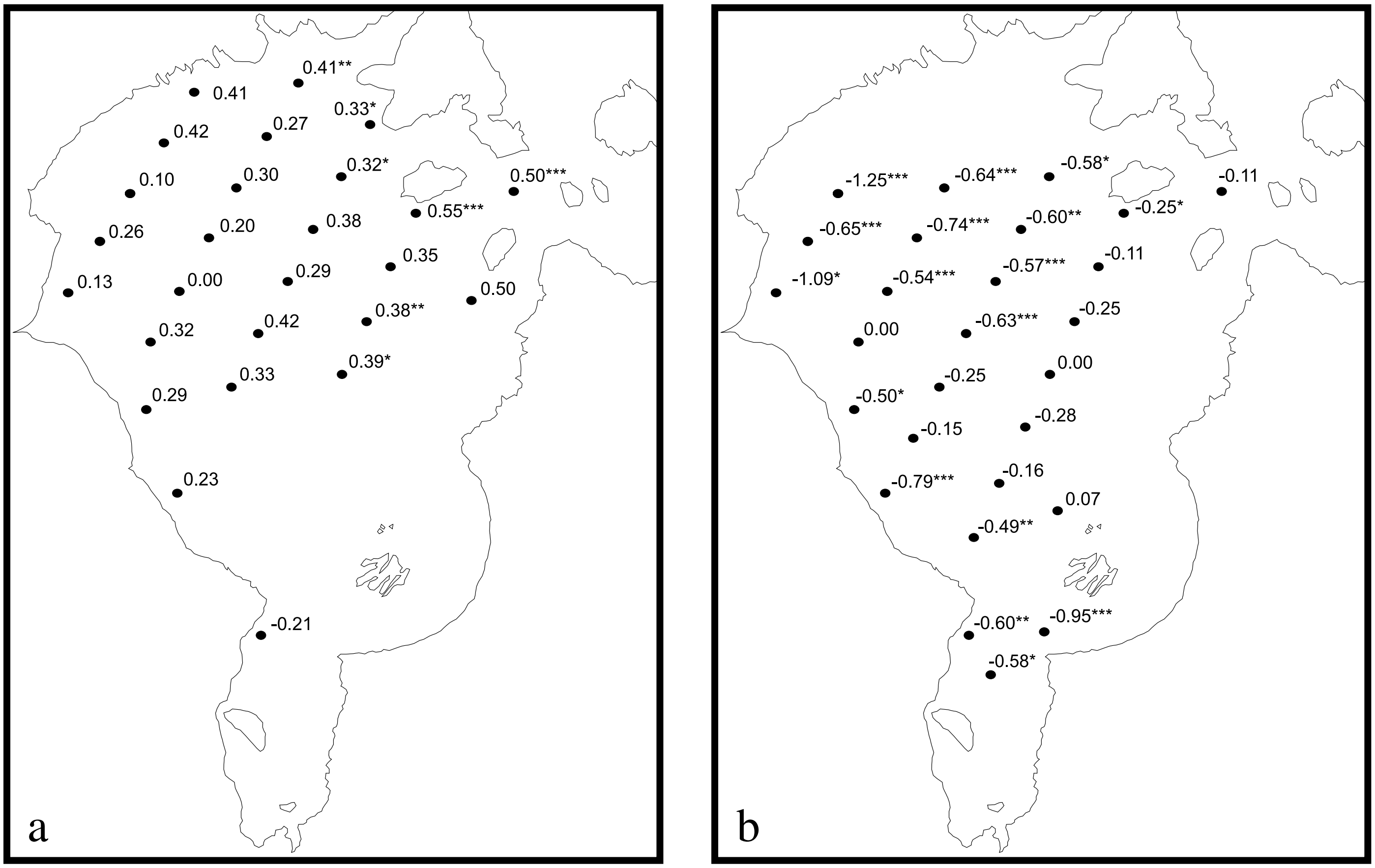


FIG. 3. Results of the Mann-Kendall test on the freeze-up (a) and breakup (b) dates. The numbers displayed refer to the Theil-Sen slope estimate in Julian days per year. Asterisks represent p-value smaller than 0.01 (***), 0.05 (**), and 0.10 (*).

rejected with more than 90% confidence in James Bay, along the southern shore of Hudson Bay, and in the western half of Hudson Bay, where trends toward earlier breakup were detected. The results of the MK test indicate that there are no statistically significant trends in the south-central part of Hudson Bay or in the eastern half of Hudson Bay. An interesting spatial pattern also arises from this study, particularly for the northern half of Hudson Bay. The magnitude of the breakup trend is greatest in western Hudson Bay and decreases towards the east. For instance, the magnitude of the trend at point 20 (60˚ N, 92˚ W) is five times the magnitude at point 23 (60˚ N, 83˚ W).

The MK test unveils trends statistically significant at the 90% confidence level or more showing that sea-ice formation in northern Hudson Bay has been occurring from 0.32 to 0.55 days later each year than in the previous year. Statistically significant trends toward later sea-ice formation are also observed in northeastern Hudson Bay (points 18 and 23), with ice forming on average about 0.4 days later each year in that region. No statistically significant trends were detected in other parts of Hudson Bay. Nevertheless, the sign of the trends suggests later occurrence of freeze-up over most of the Bay except at point 2, located near the west coast of James Bay, where a small (and not significant) trend toward earlier sea-ice formation is observed.

Since most of the trends in the freeze-up and breakup dates were calculated at discrete geographical points, the spatial autocorrelation between adjacent grid points was calculated using the Pearson's correlation coefficient to determine whether any problems are associated with such an analysis. The results indicate strong correlation between individual grid points in the freeze-up dates for Hudson Bay. As an example, Figure 4 displays the results of this correlation analysis between point 17 and its adjacent grid points. The correlation between adjacent grid points is also high for the breakup date, except for southern Hudson Bay. The modelling study of Saucier et al. (2004) demonstrated the important contribution of sea-ice advection to the growth of the ice cover of southern Hudson Bay, which was previously demonstrated statistically by Etkin (1991). For instance, points 4 and 5 have a moderately low correlation in their breakup date ($r = 0.37$, $df = 30$, $p < 0.05$), although it is still statistically significant. Nevertheless, the trend analysis in the breakup date over the three regions depicted in Figure 1 is in agreement with our point-based analysis. A statistically significant trend towards earlier breakup is observed in western Hudson Bay, with a trend of more than 0.8 days per year ($df = 31$, $p < 0.05$). This means that by 2003, breakup was occurring approximately 26 ± 7 days earlier than in 1971 (Table 2). A trend towards earlier breakup is also observed

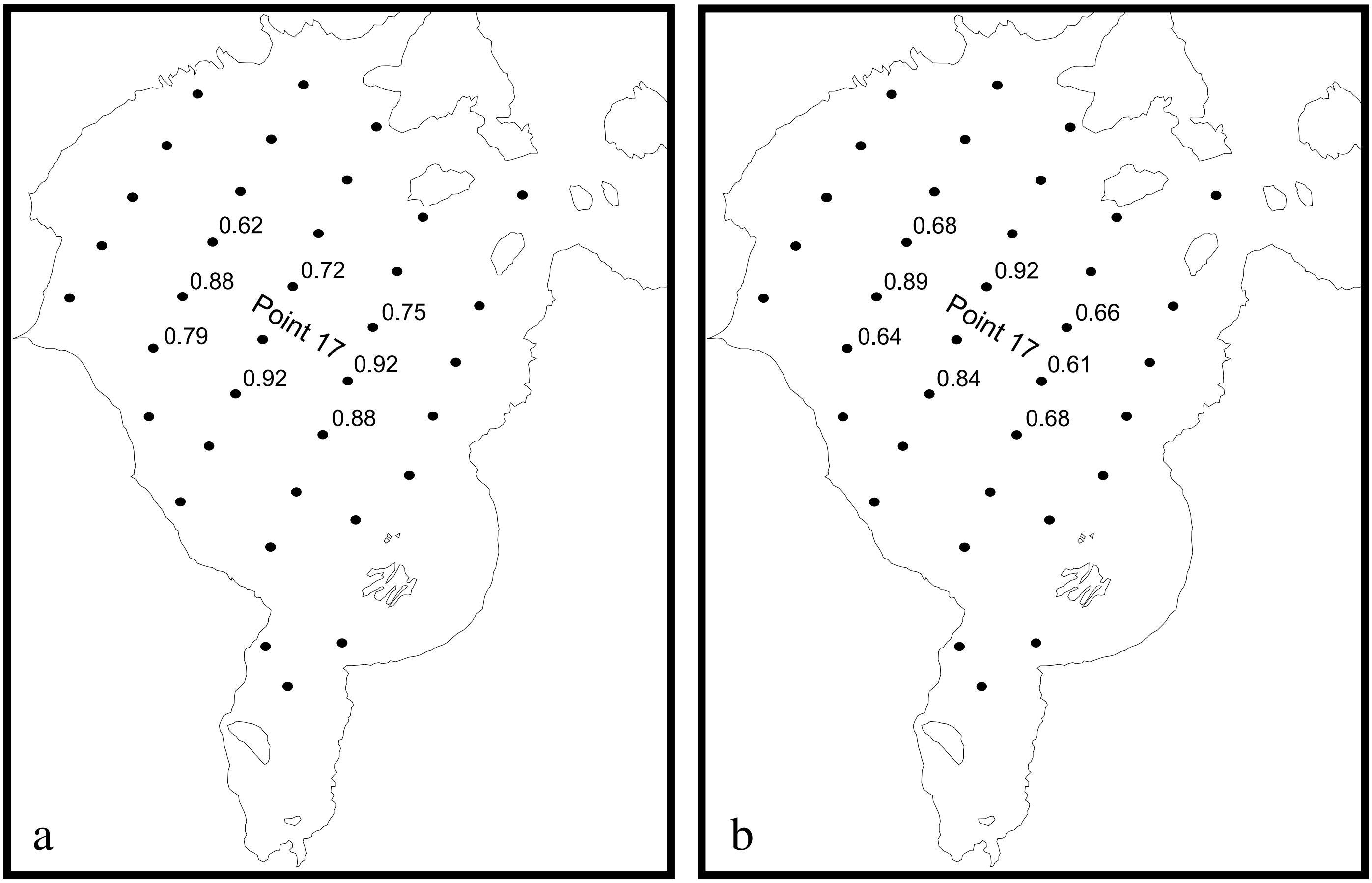


FIG. 4. Results of correlation analysis between point 17 and adjacent grid points for (a) freeze-up and (b) breakup.

in north-central Hudson Bay but is of lower magnitude than in western Hudson Bay (trend = -0.29 days/yr, df = 31, $p < 0.05$). No statistically significant trend was detected in southern Hudson Bay; however, a negative trend appears there when only the points near the southwestern shore of Hudson Bay are included in the regional average.

Temperature

The MK test reveals statistically significant temperature trends in the Hudson Bay region. Mean annual temperatures have significantly warmed at all weather stations except Inukjuak, with trends varying from a minimum 0.5˚C per decade at Churchill to a maximum of approximately 0.8˚C per decade at Chesterfield Inlet (Table 3). Although no statistically significant trend was identified at Inukjuak, the sign of the TSA indicates a smaller warming trend of 0.4˚C per decade. Seasonally, all weather stations have experienced warming in winter, but only at Kuujjuarapik and Moosonee, where temperatures have warmed by more than 1˚C per decade, are the trends statistically significant. Statistically significant warming trends observed in spring had a high significance level at Cape Dorset and lower significance at Chesterfield Inlet and Moosonee. Spring temperatures have also increased at the other four weather stations, but the trend is minimal at Churchill, because of a near-zero trend in April and a cooling trend in May. Summer temperatures have warmed at all weather stations, and only during this season is the sign of the trend spatially consistent across the Bay for the three months of the season. Autumn temperatures have warmed at all weather stations, but only at Kuujjuarapik and Inukjuak, both located on the eastern side of Hudson Bay, are the trends statistically significant. To sum up, the climate of Hudson Bay has warmed at all weather stations and during all seasons during 1971–2001. Cooling trends were observed in some months; however, none were statistically significant, and they did not influence the seasonal average.

The warming in the Hudson Bay region has not been unidirectional, as different periods with opposite temperature change signals are observed in the entire length of record at all weather stations. For example, the temperature record at Moosonee reveals three different time periods. Mean annual temperature increased from 1930 until the mid-1950s. A cooling period that extended until about 1975 followed this warming period. Since 1975, significant warming has occurred (Fig. 5A). This temporal pattern in the historical temperature record is not unique to Moosonee, but is also observed at other stations in the region (e.g., Churchill, Fig. 5B), and it agrees with the

TABLE 2. Ice concentration by year in western Hudson Bay. The line represents the interannual variability in the breakup date.

Time	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03
05/21																																8	
05/28									9												9					7						7	
06/04							8	9	9	9			9	9		9	8	9	8	4	9			9		8						7	
06/11				9	9	8	8	9	9	9	8	9	9	9	9	8	8	9	7	2	8	9	9	9	6	8	7	5	6	9		7	4
06/18	8	9	9	9	9	7	7	9	8	9	7	9	9	9	9	7	9	8	7	0	8	9	9	8	6	7	6	5	4	8	7	NA	4
06/25	7	9	9	9	8	6	6	7	7	8	6	9	8	8	9	6	8	9	8	4	6	9	8	7	4	7	6	4	1	8	5	NA	4
07/02	6	8	9	9	8	5	3	7	4	5	4	9	8	6	9	6	8	9	6	0	4	9	6	4	4	5	3	0	0	6	1	NA	1
07/09	5	7	8	8	8	2	0	6	1	3	3	6	8	6	9	4	7	8	4	1	3	9	3	4	2	3	2	0	0	5	1	NA	1
07/16	4	6	6	4	4	1	0	7	0	1	1	5	4	5	5	3	6	8	2	0	0	6	3	2	1	4	1	0	0	4	0	3	0
07/23	2	3	3	3	3	0	0	2	0	0	0	3	2	1	3	1	1	6	0	0	0	4	1	2	1	2	0	0	0	3	0	1	0
07/30	1	0	2	1	1	0	0	2	0	0	0	2	1	0	4	0	1	2	0	0	0	3	1	1	0	1	1	0	0	2	0	0	0
08/06	0	0	1	0	0	0	0	1	0	0	0	1	0	0	1	2	0	1	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0
08/13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
08/20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
08/27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 3. Trend of mean air temperature from 1971 to 2001.[1] The numbers in the table indicate the Theil-Sen slope estimate in ˚C/10 yr. A bold number refers to a *p*-value smaller than 0.01(***), 0.05 (**), and 0.10 (*).

Trend (˚C/10 yr)	Cape Dorset	Chesterfield Inlet	Churchill	Coral Harbour	Inukjuak	Kuujjuarapik	Moosonee
Spring	**0.77	*0.57	0.14	0.57	0.52	0.59	*0.78
March	**1.33	***1.90	**1.50	*0.94	0.69	*1.10	0.94
April	*0.85	0.50	-0.05	0.18	0.72	0.46	0.63
May	0.35	-0.17	-0.47	0.13	0.18	0.33	0.72
Summer	0.50	***0.78	***0.94	**0.48	**0.73	**0.60	**0.58
June	0.19	**0.82	***1.00	0.43	0.41	0.38	0.62
July	**0.62	***0.89	***0.86	**0.67	***1.35	***0.78	**0.44
August	0.31	***0.67	**0.75	0.38	**0.70	**0.76	***0.82
Autumn	0.54	0.63	0.46	0.63	**0.54	**0.50	0.16
September	*0.50	*0.58	**0.83	0.55	0.62	*0.60	**0.70
October	0.35	0.70	0.35	0.24	0.26	0.42	0.15
November	0.88	0.55	-0.24	0.77	0.44	0.56	0.20
Winter	0.65	0.65	0.84	0.21	0.40	**1.00	***1.08
December	***2.77	**1.82	1.25	***2.20	*1.67	***2.57	**1.85
January	-0.26	-0.14	0.50	-0.52	-0.50	0.50	**1.08
February	0.44	0.06	0.60	-0.38	0.14	0.24	0.67
Annual	*0.65	**0.75	*0.50	*0.57	0.40	*0.64	**0.67

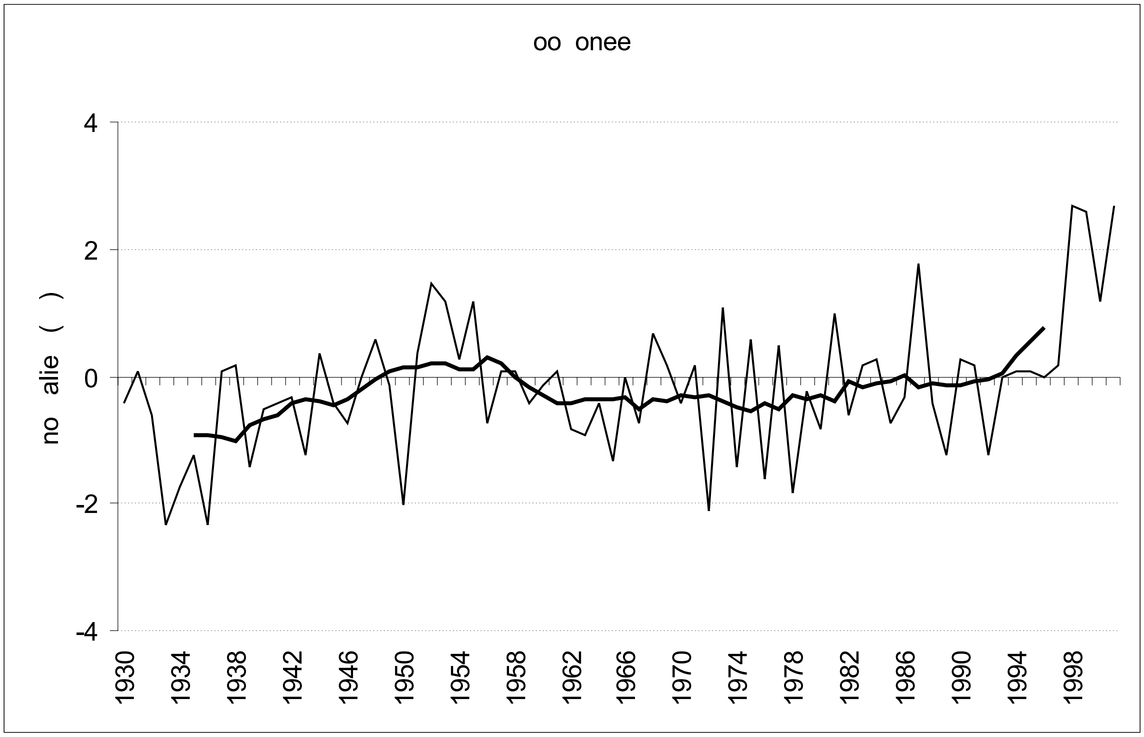
[1] Homogenized monthly temperature data for Canada are available up to 2001.

interdecadal variability of the surface air-temperature trends of the Northern Hemisphere (Maxwell, 1986; Nicholls et al., 1996).

DISCUSSION

In this study, statistically significant trends toward earlier breakup were identified in James Bay, along the southern shore of Hudson Bay, and in the western half of Hudson Bay. Statistically significant trends toward later freeze-up were also observed in the northern and north-eastern regions of Hudson Bay. These trends are in agreement with the reduction in sea-ice extent reported in previous studies for Hudson Bay (Parkinson et al., 1999; Stirling et al., 1999; Gough et al., 2004) and with trends toward decreased ice extent apparent in the Northern Hemisphere (Maslanik et al., 1996; Bjorgo et al., 1997; Johannessen et al., 1999; Parkinson et al., 1999; Vinnikov et al., 1999). In addition, our trends concur with the trends toward earlier ice breakup for lakes situated south of Hudson Bay (Cohen et al., 1994) and earlier peak streamflow for rivers in the same region (Gagnon and Gough, 2002). The trend toward earlier breakup identified by Stirling et al. (1999) for western Hudson Bay, however, lacked statistical significance. Also, only after removing the year 1992 from the time series did Gough et al. (2004) detect a statistically significant breakup trend using the MK test in southwestern Hudson Bay. The 1991 eruption of Mt. Pinatubo in the Philippines resulted in a significant cooling of the global climate during 1991 and 1992.

The largest trends toward earlier breakup are observed at points 3, 10, and 20 (Fig. 3b). Breakup has occurred, on average, 9.5 days earlier per decade at point 3 and more than 10 days earlier per decade at points 10 and 20 during 1971–2003. The strong magnitude of the trend line at point 3 is due to early breakup during the period 1998–2001. This trend, however, could in reality be of slightly smaller magnitude. In 1972 and 1975, breakup had already occurred when the first weekly map was issued. The TSA,



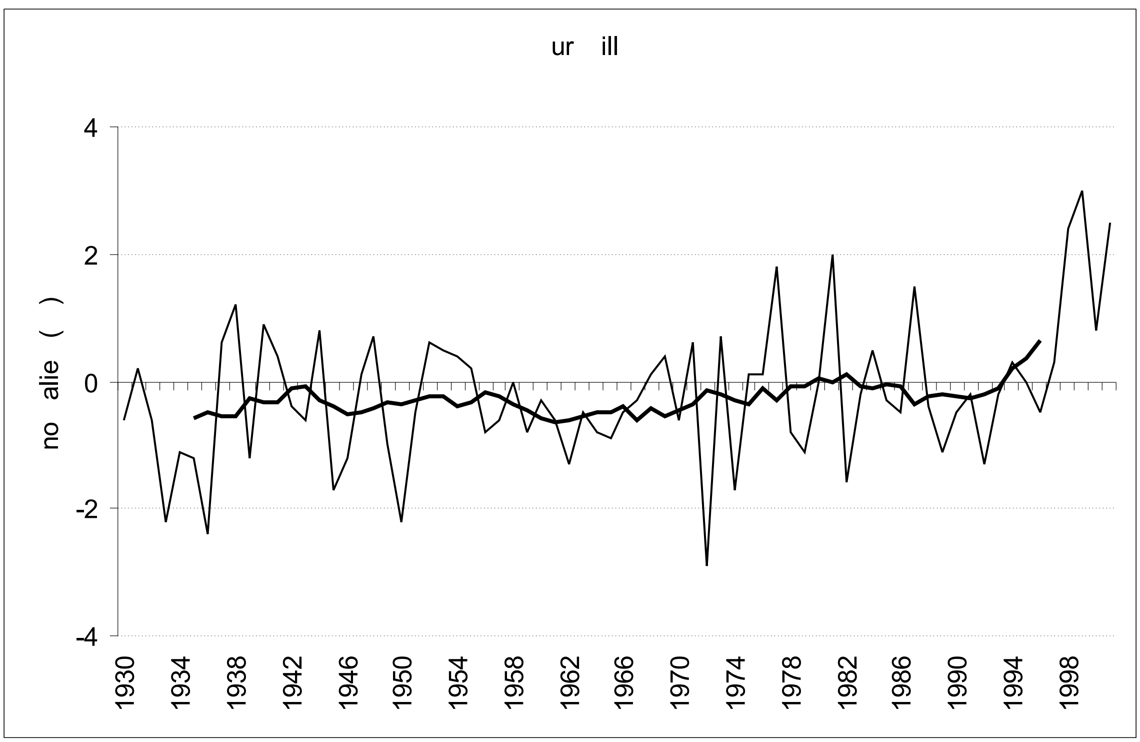


FIG. 5. Temporal evolution of annual mean temperature anomalies at Moosonee and Churchill. Anomalies refer to departures from the 1971–2000 period. The continuous line represents an 11-year central moving average.

however, is not as sensitive to extreme values as are parametric methods. It is unlikely that the trend would change considerably in magnitude if breakup had occurred a week or so before it is currently reported during those two years. A similar pattern is observed at point 10. The above bias, however, was more common in more recent years and in western Hudson Bay so that the trend could also be of slightly higher magnitude in a few instances. To provide further explanation of this bias, the time series of ice concentration with breakup for western Hudson Bay is shown in Table 2. On some occasions, notably in 1990, 1998, and 2003, the 5/10 ice concentration had already been reached by the time the first weekly ice chart became available from the CIS. In those cases, it is possible that breakup had occurred before the actual date included in the time series.

Statistical and modelling studies have demonstrated that air temperature is the main factor influencing the interannual variability of the Hudson Bay annual ice cycle (Etkin, 1991; Saucier and Dionne, 1998; Gough and Allakhverdova, 1999). In fact, the ice cover of Hudson Bay correlates well with the temperature anomalies engendered by the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO), two indices of atmospheric variability (Wang et al., 1994a; Mysak et al., 1996; Gough et al., 2004). In view of the demonstrated role of air temperature in the interannual variability of the Hudson Bay ice cover, the secular trends in air temperature identified in this study should provide explanations for the long-term variability in the dates of ice freeze-up and breakup.

Secular trends in surface air temperature were detected in the Hudson Bay region during the period 1971–2001. The temperature trends identified in this study, however, do not match those of Zhang et al. (2000) because of differences in the length of the time series analyzed (1971–2001 here, as opposed to 1950–98 in Zhang et al., 2000). The increase in spring and early summer temperatures at all weather stations coincides with the early breakup trends. Only in south-central Hudson Bay and the eastern half of Hudson Bay were no statistically significant trends in the breakup date detected. Temperatures have been warming during the breakup period on both sides of Hudson Bay, but, in contrast to the western side, the warming trends on the eastern side have not been temporally consistent during the last three decades. The warming trends in eastern Hudson Bay are the result of anomalously warm temperatures since the mid-1990s, and the warming disappears when the temperature anomalies for the last five years are removed from the time series. In fact, Skinner et al. (1998) observed that temperatures have been gradually cooling in eastern Hudson Bay for a time period that does not include the more recent observations. In addition, the ice cover of south-central Hudson Bay and the eastern half of Hudson Bay might be less sensitive to climate warming than that in the other regions because of the advection of ice by the prevailing northwesterly winds in the region (Etkin, 1991).

Statistically significant trends toward later freeze-up were found in northern and northeastern Hudson Bay. Although these trends lack statistical significance, the TSA indicates that all other regions of Hudson Bay have experienced trends toward later freeze-up, with the exception of point 2 on the western side of James Bay. It is not clear why there is a trend toward earlier freeze-up at this location. Houser and Gough (2003) noted that temperatures during the ice-free season affect the timing of sea-ice formation in Hudson Strait. A similar relationship is proposed for Hudson Bay, as the late summer and autumn temperature anomalies were positive across Hudson Bay during 1971–2001 and coincide with trends towards later freeze-up.

It is important to note that the trends identified in this study were based on approximately 30 years of observations. A question that arises is whether the trends detected in this study are a result of anthropogenic climate change or natural variability of the climate system, as interdecadal variability has been observed in the historical climatic record of Hudson Bay. The temperature record of Hudson Bay, in a way similar to the Northern Hemisphere, shows two main periods of warming. Natural variability driven by changes in solar radiation, volcanic eruptions, and internal variability of the climate system, along with some human-induced influence, were responsible for the climatic changes that occurred in the early part of the record, but the warming trends of the latter part of the 20th century were mainly the result of an increase in greenhouse gases in the atmosphere (Mitchell et al., 2001).

CONCLUSIONS

In this study, we examined the nature of the changes to the seasonality of the Hudson Bay ice cover to advance our understanding of climate change in this region. During 1971–2003, Hudson Bay sea ice began to form later and break up earlier. The trends in the breakup dates are statistically significant in James Bay, along the southern shore of Hudson Bay, and in the western half of Hudson Bay, with magnitudes ranging from -0.49 to -1.25 days per year. The trends in the freeze-up dates are statistically significant in northern and northeastern Hudson Bay, with magnitudes ranging from 0.32 to 0.55 days per year. These trends in the freeze-up and breakup dates agree with the temperature trends at the weather stations situated along the perimeter of Hudson Bay. Sea-ice advection could explain the lower sensitivity of south-central and eastern Hudson Bay to climate warming.

Knowledge of these trends will aid in the development of climate-change impact assessments for the Hudson Bay region. The presence of an ice cover for eight months of the year plays an important role in regulating the regional climate of Hudson Bay, and changes to the seasonality of the ice cover will further enhance the warming projected by general circulation models for the region. If the current pattern continues in the coming decades, the Hudson Bay region will soon face important environmental challenges. A longer ice-free season, the result of later freeze-up and earlier breakup, will have a devastating impact on the polar bear populations that den along the northern shores of Ontario and Manitoba (Derocher et al., 2004). A shorter ice-covered season would be beneficial for the port of Churchill, however, assuming that similar trends are observed in Hudson Strait.

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