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Historical Analysis of Sea Ice Conditions in M’Clintock Channel and the Gulf of Boothia, Nunavut: Implications for Ringed Seal and Polar Bear Habitat

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ABSTRACT. Sea ice is an integral part of the marine ecosystem in the Arctic and important habitat for ringed seals and polar bears. To study changes in sea ice characteristics indicative of ringed seal habitat (and linked, through predator/prey relationships, to polar bear habitat), we examined historical changes in sea ice concentration and type within M’Clintock Channel and the Gulf of Boothia, two regions of the Canadian Arctic Archipelago, during 1980–2000. Results suggest large interannual variability in winter ice conditions over the 21-year study period. In M’Clintock Channel, first-year ice types dominated consistently, while in the Gulf of Boothia, thick ice types dominated in some years. For breakup and consolidation, the regional spatial patterns differed significantly, occurring in opposite directions (N-S vs. S-N) in the two regions. The dates showed considerable interannual variability in both regions, suggesting no clear pattern of either earlier breakup or later consolidation. Analysis of satellite data confirmed the results obtained from digital ice charts. Ringed seal habitat suitability indices (HSI) indicate that both regions contained primary, secondary, and tertiary HSI classes. No trends were evident in the secondary or tertiary classes, but changes in the primary class were evident in M’Clintock Channel over the five-year period 1997–2001. Dynamic and thermodynamic sea ice processes are important to ringed seal habitat (and ultimately, polar bear habitat) at regional and hemispheric scales in the current context of climate variability and change.

Key words: sea ice, climate variability, ringed seal habitat, *Phoca hispida*, polar bear, *Ursus maritimus*, M’Clintock Channel, Gulf of Boothia

RÉSUMÉ. La glace de mer fait partie intégrante de l’écosystème marin de l’Arctique et constitue un important habitat pour le phoque annelé et l’ours polaire. Au cours des années comprises entre 1980 et 2000, afin d’étudier les changements dans les caractéristiques de glace marine dénotant un habitat de phoque annelé (et donc associé à un habitat d’ours polaire par l’intermédiaire de la relation prédateur / proie), on a examiné des changements historiques dans la concentration et le type de glace de mer à l’intérieur du détroit de M’Clintock et du golfe de Boothia, deux régions de l’archipel Arctique canadien. Les résultats suggèrent qu’il existe une grande variabilité interannuelle dans les conditions de glace d’hiver sur cette période de 21 ans. Dans le détroit de M’Clintock, les types de glace de l’année prédominaient de façon constante, tandis que dans le golfe de Boothia, ceux de glace épaisse prédominaient certaines années. En ce qui concerne la débâcle et la consolidation, les schémas spatiaux régionaux différaient sensiblement, se produisant dans des directions opposées (N.-S. c. S.-N.) dans les deux régions. Les dates révèlent une variabilité interannuelle considérable dans les deux zones, ce qui suggère qu’il n’existe pas de schémas précis de débâcle précoce ou de consolidation tardive. L’analyse de données satellitaires a confirmé les résultats obtenus à partir de cartes numériques des glaces. Les indices de qualité des habitats du phoque annelé montrent que les deux régions renferment des classes d’habitat primaire, secondaire et tertiaire. On n’a décelé aucune tendance dans les classes secondaire ou tertiaire, mais des changements pour la classe primaire étaient évidents dans le détroit de M’Clintock au cours des cinq années comprises entre 1997 et 2001. Les processus dynamiques et thermodynamiques de la glace de mer sont importants pour l’habitat du phoque annelé (et, en bout de ligne, pour celui de l’ours polaire) à l’échelle régionale et hémisphérique dans le contexte actuel de la variabilité et du changement climatiques.

Mots clés: glace de mer, variabilité climatique, habitat du phoque annelé, *Phoca hispida,* ours polaire, *Ursus maritimus,* détroit de M’Clintock, golfe de Boothia

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INTRODUCTION

In response to a CO_2-enhanced atmosphere, polar regions of the planet will likely experience amplification in temperature (IPCC, 2001), thought to result from a variety of feedback mechanisms operating across the ocean–sea ice–atmosphere interface. Although several of these feedbacks have been identified, a significant component of

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the system appears to be the "sea ice–albedo" feedback mechanism (IPCC, 2001), which suggests that as the extent of sea ice is reduced (particularly in spring and fall), the ocean absorbs more energy, and a further reduction in sea ice extent occurs. This positive feedback raises the regional atmospheric temperature, thereby producing a further reduction in ice concentration (percent cover per unit area).

Recent evidence suggests that this response has in fact already begun in the Arctic. Between 1978 and 1998, there was an annual average reduction of about 34 600 km^2 in the extent of sea ice over the entire Northern Hemisphere (Parkinson et al., 1999). This reduction is spatially heterogeneous, with larger decreases in extent in particular locations (e.g., the Chukchi and Laptev Seas) and slight increases in extent in other regions (e.g., Baffin Bay). Independent evidence from other investigators confirms a reduction in both sea ice extent (Johannessen et al., 1999) and thickness (Rothrock et al., 1999).

Sea ice forms an integral part of the marine ecosystem at high latitudes. Changes in the sea ice and associated snow cover will affect light transmission and thermodynamic processes operating within the snow/sea ice system (Barber et al., 1995). These changes affect lower trophic systems. Kinematic and topographic changes in the snow/sea ice system can affect organisms at higher trophic levels through the control that sea ice exerts on the redistribution of snow (Welch and Bergmann, 1989; Iacozza and Barber, 1999) and on the spatial distribution of various sea ice types (e.g., multiyear, first-year, rubble; Stirling and Derocher, 1993).

Polar bears use both fast and marginal types of sea ice as platforms for travel and foraging. In particular, since ringed seal habitat is a primary food source for polar bears, the habitats of the polar bears are closely related to those of ringed seals. These habitats include areas immediately adjacent to pressure ridges, between multiyear and first-year floes, and at the floe edge between marginal and landfast sea ice (Stirling and Derocher, 1993; Stirling et al., 1993). We examined aspects of sea ice type from the perspective of preferred habitats for ringed seals and polar bears to determine whether sea ice conditions have changed in the two study regions. In particular, we are interested in whether the extent and distribution of ringed seal habitat (based on specific sea ice conditions) has changed in recent years. This information can then be combined with telemetry data, hunter statistics, and traditional knowledge of polar bear abundance and distribution in management of this species.

We investigated characteristics of sea ice related to ringed seal habitat in reference to two time scales: 1) 21 years (1980–2000), for general sea ice conditions within M'Clintock Channel and the Gulf of Boothia; and 2) five years (1997–2001), for ringed seal habitat identified through remote sensing in the same regions. The spatial scales of these two time frames are different because of differences in the input data; the 21-year scale is mapped at 1:10 000 and the five-year scale at 1:1000. Our five research objectives (the first three done at 1:10 000, and the last two at 1:1000) are listed below:

1) Provide a general overview of sea ice conditions (ice type concentration and floe size) in M'Clintock Channel and the Gulf of Boothia from 1980 to 2000.
2) Estimate consolidation dates and spatial pattern of consolidation (annually during 1980–2000).
3) Estimate breakup dates and spatial pattern of breakup (1980–2000).
4) Present the areal fractions and spatial patterns of multiyear, first-year, and rubble ice areas (1997–2001).
5) Compute and map a ringed seal Habitat Suitability Index (HSI) for M'Clintock Channel and the Gulf of Boothia and determine whether this HSI has changed over the period from 1997 to 2001.

These objectives cover how and where sea ice conditions have changed, how these changes relate to ringed seal habitat, and by inference, how such change may manifest itself in variability of polar bear habitat.

METHODS

Study Area

Our study focuses on two different polar bear management areas: M'Clintock Channel (MC) and the Gulf of Boothia (GB; Fig. 1). The MC management area is approximately 140 000 km^2 (excluding land), while the GB is approximately 67 000 km^2.

Data Description

Digital Ice Charts: The primary data sources for the first three research objectives consist of weekly regional digital ice charts for the Canadian Arctic produced by the Canadian Ice Service. These charts integrate all the information available at the time, including but not limited to weather conditions, visual observations, and data obtained from instruments carried on aircraft and on satellites. The data are charted using an international "egg" code to classify areas by ice concentration, type, floe size, etc.

We used the digital charts for the last week of March in each year to investigate the long-term trends in winter sea ice conditions in the M'Clintock Channel and Gulf of Boothia regions. These ice charts were assumed to be representative of the ice conditions for the winter period during each year. (A reasonable assumption, as much of the ice became shorefast in the early winter within each study region.) The digital ice charts were imported into ARCView® GIS. The proportions of each ice type and floe size were calculated for each year. Ice types reported on the weekly ice charts included new ice, grey ice, grey-white ice, first-year ice, thin first-year ice, medium first-year ice, thick first-year ice, old ice, second-year ice, and

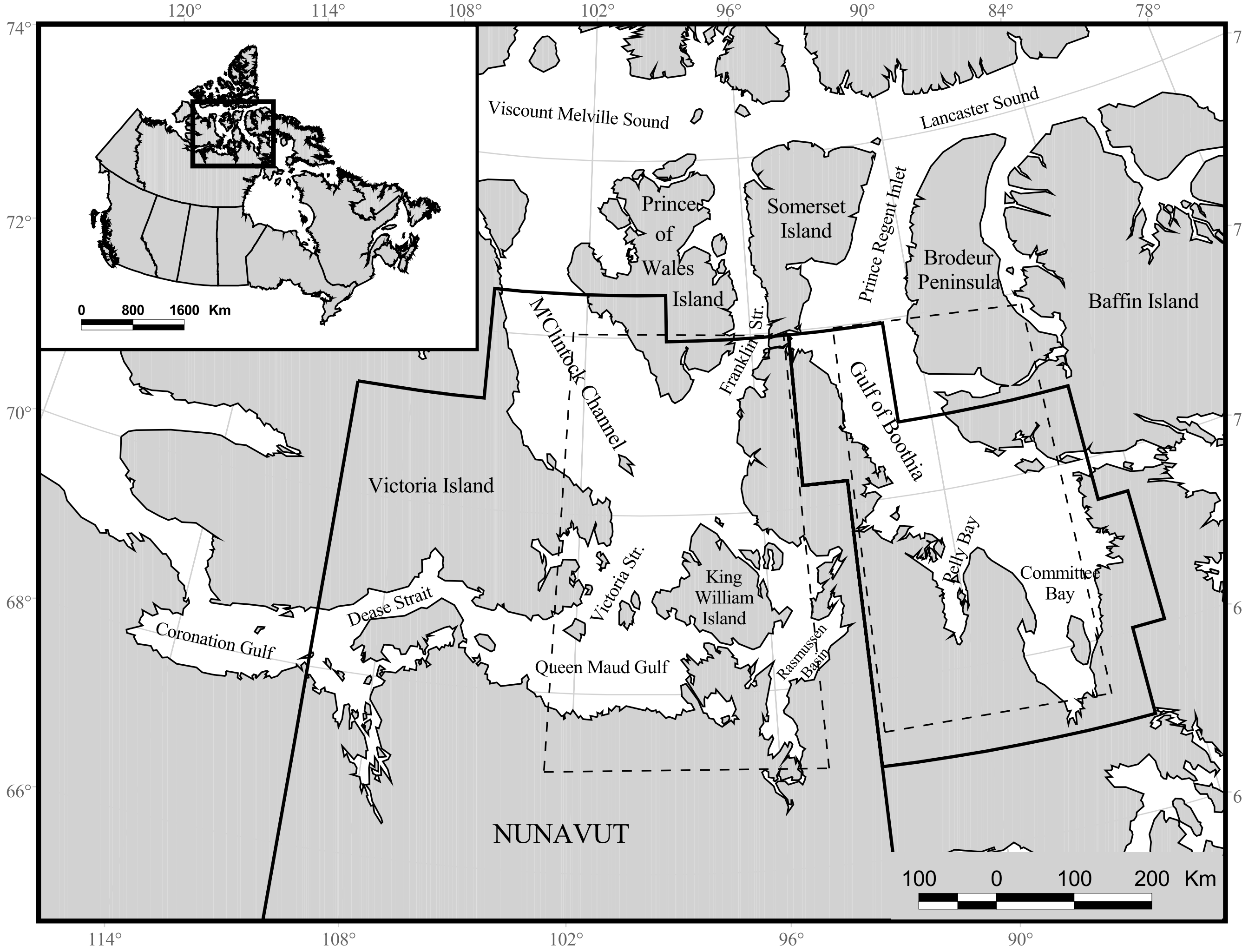

FIG. 1. Site map of the study region, showing the M'Clintock Channel (MC) and Gulf of Boothia (GB) polar bear management zones. The dashed lines indicate the areas covered in the ScanSAR imagery that were used to classify the ringed seal habitat.

multiyear ice (WMO, 1970). Prior to 1983, the weekly ice charts did not differentiate among first-year ice types (first-year ice, thin-, medium-, and thick first-year ice) or old ice types (old ice, second-year and multiyear ice). Therefore, the proportions of ice types were grouped into three classes: thin ice (consisting of new ice, grey ice and grey-white ice), first-year ice (first-year ice, thin first-year ice, medium first-year ice, thick first-year ice), and thick ice (old ice, second-year ice and multiyear ice). Floe sizes reported on the ice charts consisted of small, medium, big, giant, vast, and fast ice floes (WMO, 1970). These ice classes and floe sizes were used to investigate the winter ice conditions in the M'Clintock Channel and Gulf of Boothia study regions from 1980 to 2000.

Digital ice charts for each week from the beginning of June to the end of October were analyzed to define the timing of breakup and consolidation in the two study areas on a pixel-by-pixel basis. For this project, breakup was defined as the first week in summer when ice concentration in a pixel was less than 30%. Consolidation was defined as the first autumn date for which ice concentration was greater than 70%. Because the digital ice charts are not produced on the same day each year, the date of production was changed to week of the year, starting with January 1–7 (week 1).

The digital ice charts were imported into a GIS, and the areas of interest were extracted. Each weekly ice chart was converted to a raster image, in which each pixel represented 1 km^2, and then each pixel was reclassified according to the ice concentrated within it. For ice breakup, each pixel in the June-to-September ice charts was reclassified as zero (> 30% ice concentration) or one (< 30% ice concentration). For ice consolidation, each pixel in the September and October ice charts was reclassified as zero (< 70% ice concentration) or one (> 70% ice concentration). Determination of the dates (or week) of breakup and consolidation for each pixel involved the sequential addition of ice charts using the map calculator feature in the GIS and reclassification of the resultant image. Each new week was added to the reclassified map, which was then reclassified to delineate areas that had undergone either breakup or consolidation. The procedure of adding weeks to the reclassified map and then reclassifying the map was continued until all ice charts were used or until the ice in the area had undergone complete breakup or consolidation. The final product was a series of maps, one map for each year from 1980 to 2000, each showing the dates of breakup and consolidation in that year in each pixel within the two study areas. The yearly maps of the dates of breakup and consolidation were then averaged to produce a single map showing the average breakup and consolidation patterns over the 21-year study period, expressed in week number.

Variability of the average breakup and consolidation patterns over the 21-year study period was also computed pixel by pixel. A map showing coefficient of variation expressed in weeks illustrates the variability in breakup and consolidation for both MC and GB. The map, which displays variability as a number of weeks identified by colour, allowed direct comparison between study areas and between breakup and consolidation.

Yearly anomalies for breakup and consolidation were computed for the two study areas. Anomaly maps and histograms were produced using the difference between the yearly breakup (consolidation) date and the average breakup (consolidation) week, on a pixel-by-pixel basis. Because both M'Clintock Channel and Gulf of Boothia contained areas that did not break up either in a given year or on average, we assigned an arbitrary value of 60 weeks to those areas. The anomalies calculated by subtracting the yearly week number from this large value resulted in values greater than ± 33 weeks. Additionally, because the digital ice charts are produced weekly, anomalies of one week (either earlier or later than the average) were considered statistically equivalent to the average. Negative anomalies indicated that breakup or consolidation was earlier than the 21-year average, while positive anomalies indicated a date later than the 21-year average. Large positive anomalies (greater than 33) indicated that, for a particular pixel, breakup did not occur in that year, though it did occur on average. Large negative anomalies (greater than -33) indicated that breakup occurred for a particular pixel in a particular year but did not occur on average. The anomaly histograms were tested using a Kolmogorov-Smirnov test (two-tailed test) to determine whether the distribution of the anomalies differed from the "normal" distribution expected if the anomalies had no positive or negative trend. Testing of all histograms used a significance level of 0.05.

Hurst exponent analysis was conducted on trends of each ice class over the 21-year study period to determine whether any statistically significant periodicity exists in the data. The Hurst exponent is a statistical procedure used to identify the degree of independence a time series has from one period to another. It uses a time series index in which the number of observations is partitioned and averaged. The range is then divided by the standard deviation to produce a normalized or rescaled range value (R/S) (Fischer and Akay, 1996). The Hurst exponent is calculated from the rescaled range and takes on a value between zero and one for each time series (in our case, for each ice class for the 21 years). If the series is highly autocorrelated (or persistent), the exponent will be close to one. This would suggest that each data value is related to some number of preceding values. If the exponent is close to zero, the series is said to be anti-persistent or non-persistent. In this case, each data value is more likely to have a negative correlation with preceding values. A Hurst exponent of 0.5 indicates that the sequences in the series are essentially random and the estimated correlation series is zero everywhere, except at lag zero (Fischer and Akay, 1996).

Satellite Data: Satellite data were used to investigate changes in the spatial patterns of the various ice types and to compute a ringed seal Habitat Suitability Index (HSI) (objectives 4 and 5). The HSI is limited to 1997–2001, as this was the period of appropriate RADARSAT-1 coverage. Active microwave radar data (RADARSAT-1) were chosen to investigate the spatial patterns of sea ice because the sensor had all-weather, day-night capability and produced high spatial resolution, and a predefined technique was available for estimating ringed seal habitat suitability following the approach of Nichols (1999). For this study, ScanSAR wide data were used for their high temporal and broad spatial coverage. These data have a spatial resolution and pixel spacing of 50 m. For both study areas, at least 90% of the area was imaged over the study period.

Areal fractions and spatial patterns of various ice types were calculated annually for the M'Clintock Channel and Gulf of Boothia study areas from 1997 to 2001. RADARSAT-1 ScanSAR images acquired for spring and summer were used to determine the fractions of multiyear, rubble, smooth first-year, and rough first-year sea ice within the two study areas. Since the study areas are so large, several images were required for each year. These images were digitally seamed (i.e., joined) to produce a spatially contiguous dataset for each study area.

The ScanSAR images were preprocessed before classification of ice types. This preprocessing involved 2 × 2 pixel block averaging done on the raw data to eliminate or reduce the speckle (an artifact of synthetic aperture radar coherence) in the data. This averaging produced a final product with pixel spacing of 200 m.

The segmentation of ice types involved comparison of a winter image and a melt onset/early advanced melt image (Nichols, 1999). For the two study areas, winter was defined as late March/early April and melt onset/early advanced melt as June/early July. To differentiate between the multiyear and rubble ice types, we acquired and compared these two images for both study areas each year from 1997 to 2001. Visual classification of ice classes was based on the spectral changes from the winter image to the melt onset image for each year.

ScanSAR data for 1997 did not cover the entire study area (Fig. 1), since data for a portion of M'Clintock Channel and the edge of the Gulf of Boothia region were

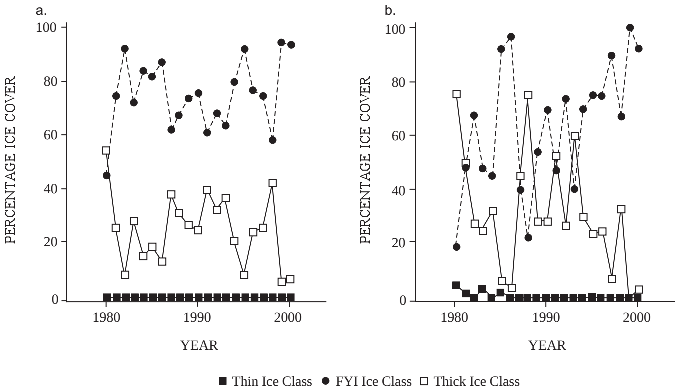

FIG. 2. Proportions of ice classes within the (a) M'Clintock Channel and (b) Gulf of Boothia study areas from 1980 to 2000. These conditions were derived from weekly digital ice charts for the last week in March.

not available. To permit accurate comparison of the fractions and spatial patterns of the ice types, we reduced the study area for all five years to the 1997 area.

The ringed seal Habitat Suitability Index (HSI) was based on the features and ice types segmented from the satellite data for the M'Clintock Channel and Gulf of Boothia study areas in 1997–2001. This index is based on preferred habitat selection of the various ice types (Smith and Stirling, 1975; Finley et al., 1983; Frost et al., 1988; Hammill and Smith, 1988). First-year pressure ridges, visually identified in the satellite images as linear or sinusoidal features, as well as the habitats around the perimeter of the ice types, were reclassed as a 'first' HSI class (HSI class 1). Within the Gulf of Boothia, the edge of the mobile ice was also classified as primary habitat. Smooth first-year sea ice was reclassed as a 'second' HSI class (HSI class 2). The remaining ice types (rough first-year sea ice, rubble and multiyear sea ice) were coded as a 'third' HSI class (HSI class 3).

We used a Spearman rank correlation method to determine whether any trends existed in the habitat suitability index data (HSI classes) over the five-year study period, given that the data were collected as ordinal variables. We selected this nonparametric approach because the HSI distributions did not meet the assumptions of an equivalent parametric analysis.

RESULTS

Winter Sea Ice Type Analysis

Descriptive statistics for the various ice classes indicate that first-year ice was the predominant class for most of the 21-year period in both study areas, with means of 75% ± 13% S.D. for M'Clintock Channel and 63% ± 24% S.D. for the Gulf of Boothia (Fig. 2). The means indicate that the first-year ice class was statistically greater in MC than in GB, while the large standard deviations suggest large interannual variability in the proportion of this ice class in both areas. Large standard deviations were also observed for thin and thick ice classes. These statistics were consistently greater for the Gulf of Boothia, suggesting more variability in the ice classes over time.

First-year ice class dominated the MC study area throughout the entire study period. However, the same was not true for the GB area (Fig. 2), where from 1987 to 1993, there was a regular reversal in the proportion of ice types between the first-year ice class and the thick ice class. After 1993, the first-year ice class dominated, covering more than 65% of the GB area each year. A common trend in both areas was the low proportion of thin ice classes. For M'Clintock Channel, no thin ice types were present at the end of March, while for the Gulf of Boothia the maximum coverage of the thin ice type was 5% during the study period.

Correlation analysis was performed on the ice class data to identify any statistically significant trends in the temporal variability of sea ice cover in the study areas. The analysis suggests that the temporal patterns of ice concentration classes were consistent between areas over the 21-year study period (Fig. 2). As the proportion of first-year ice class in MC increased, first-year sea ice in GB increased as well ($r = 0.71$, $p < 0.05$, $n = 21$). A similar result was observed for the thick ice classes ($r = 0.73$, $p < 0.05$, $n = 21$). No statistically significant relationship between the two study areas was observed for the thin ice class.

Correlation analysis was also performed on the individual ice classes within each study area to determine whether any trends existed over the sampling period. For M'Clintock Channel, there was no statistically significant change in any ice class from 1980 to 2000. However, statistically significant trends were found for the thin and first-year ice classes in the Gulf of Boothia, a negative trend for the thin ice class ($r = -0.58$, $p < 0.05$, $n = 21$), suggesting a decrease in coverage over the study period, and a positive trend for the first-year ice class ($r = 0.53$, $p < 0.05$, $n = 21$), suggesting an increase in its areal extent from 1980 to 2000.

Hurst exponent analysis for the ice classes suggests that the time series in all the ice classes for both the M'Clintock Channel and Gulf of Boothia study areas are essentially random. The Hurst exponents calculated for the five ice classes were approximately 0.5, ranging from 0.47 for the thick ice class in MC to 0.61 for the thin ice class in GB. We speculate that the randomness of these time series may result both from the short time period examined and from the relationship between synoptic scale reductions in sea ice at the hemispheric scale and those in the archipelago. We revisit this speculation in the discussion and conclusions section.

Winter Floe Size Analysis

Analysis of the proportions of floe size classes within the two study areas indicated that at the end of winter, more than 75% of both study areas contained floe sizes that were

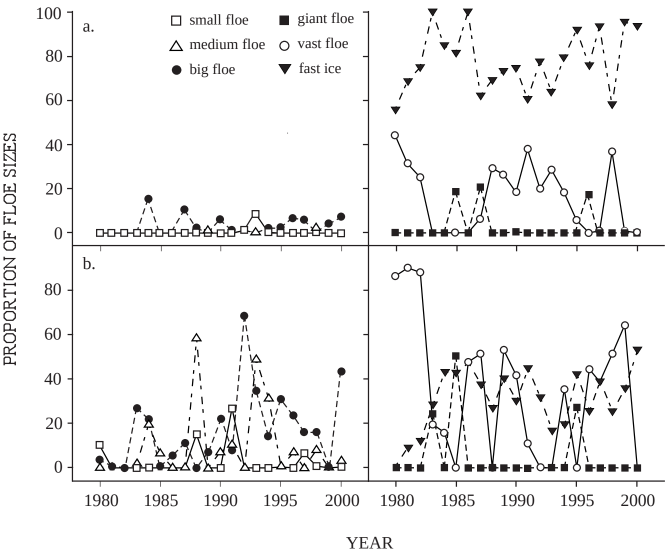

FIG. 3. Proportions of floe sizes within the (a) M'Clintock Channel and (b) Gulf of Boothia study areas from 1980 to 2000. These conditions were derived from weekly digital ice charts for the last week in March.

classified as vast or fast ice (Fig. 3). Further examination revealed that, on average, 77% of M'Clintock Channel was covered by fast ice and 16% by vast floes (level continuous pieces of ice, 2–10 km across). These results are significantly different from those observed for the Gulf of Boothia (31% coverage by fast ice and 35% by vast floes). The comparison suggested that the ice in M'Clintock Channel was more stable (i.e., more fast ice) than that in the Gulf of Boothia. Consistently large standard deviations associated with the means for the various floe sizes suggest substantial interannual variability for this parameter during the study period.

Correlation analysis conducted on the floe size classes indicated no statistically significant trends in any floe size class over the study period for either M'Clintock Channel or the Gulf of Boothia.

Breakup and Consolidation Patterns: M'Clintock Channel

On average, M'Clintock Channel undergoes breakup within a ten-week period, from the week of 9–15 July to the week of 3–9 September. According to the average pattern (Fig. 4), breakup originates in the southern parts of the study area (i.e., Queen Maud Gulf and Rasmussen Basin), then progresses eastward and northward into M'Clintock Channel. The last area to break up was the northwestern portion of the study area. Breakup within the largest area occurred on average during the week of 30 July to 5 August (Fig. 4).

Over the 21-year study period, the date of breakup, examined pixel by pixel on the maps, was moderately variable. Each 1 km pixel in the study area exhibited a zero- to five-week variability in the date of breakup, with most areas having a two- to four-week variability (Fig. 5). Large areas in the southern portion of the study area experienced a one- to two-week variability in the date of breakup, while small areas in the northern portion of the study area experienced similar variability. Very few locations exhibited the extremes in variability of breakup dates. The spatial pattern of the variability in date of breakup over the study period was not consistent, with considerable change in variability over small areas.

Average consolidation within M'Clintock Channel occurred over an eight-week period, from the week of 10–16 September to the week of 22–28 October (Fig. 6). The average consolidation pattern within this area was the inverse of the breakup pattern: consolidation began in the northern portion of the study area and advanced southward through M'Clintock Channel into Rasmussen Basin and through Victoria Strait into Queen Maud Gulf (Fig. 6). The last areas to consolidate were located in the western part of the study area (in eastern Coronation Gulf). The majority of consolidation occurred within two periods, the week of 10–16 September and the week of 8–14 October (Fig. 6).

The date of consolidation showed little variability over the 21-year study period. Over the entire M'Clintock Channel study area, variability in consolidation dates was between zero and three weeks, with the largest proportion of the total area showing variability of one to two weeks (Fig. 7). Dates of consolidation in the southernmost portions of the study area were fairly consistent, showing a zero- to one-week variability. Overall, on a pixel-by-pixel basis, the date at which ice concentration was greater than 70% was consistent from 1980 to 2000 for M'Clintock Channel.

An examination of the difference between yearly and average breakup dates revealed that M'Clintock Channel experienced annual breakup patterns similar to the average pattern. This was shown in the anomaly histograms exhibiting a normal distribution, centered on the zero anomaly. In some years, however, large areas did not break up according to the average pattern. For instance, in 1986 and 1990, large positive anomalies (greater than 30) were evident in the histograms. This suggested that in these years, significant portions of the study area did not break up, while the average pattern suggests that breakup should have occurred. Also, in 1986, the distribution was negatively skewed, indicating a later-than-average breakup for a significant portion of the study area. Most of the southern portion of the study area experienced breakup two to five weeks later than average in 1986. This trend was also evident in 1990 and 1992. In other years, the opposite trend in breakup patterns was observed. For instance, in 1981 a significant portion of the study area did break up when, for the 21-year average, breakup did not occur. In 1994, the anomaly histogram was skewed to the left, indicating that a significant portion of the study area experienced breakup earlier by two to five weeks than the average. These variations in the patterns of breakup anomalies suggested than the yearly variation in breakup for M'Clintock Channel was not consistent between years.

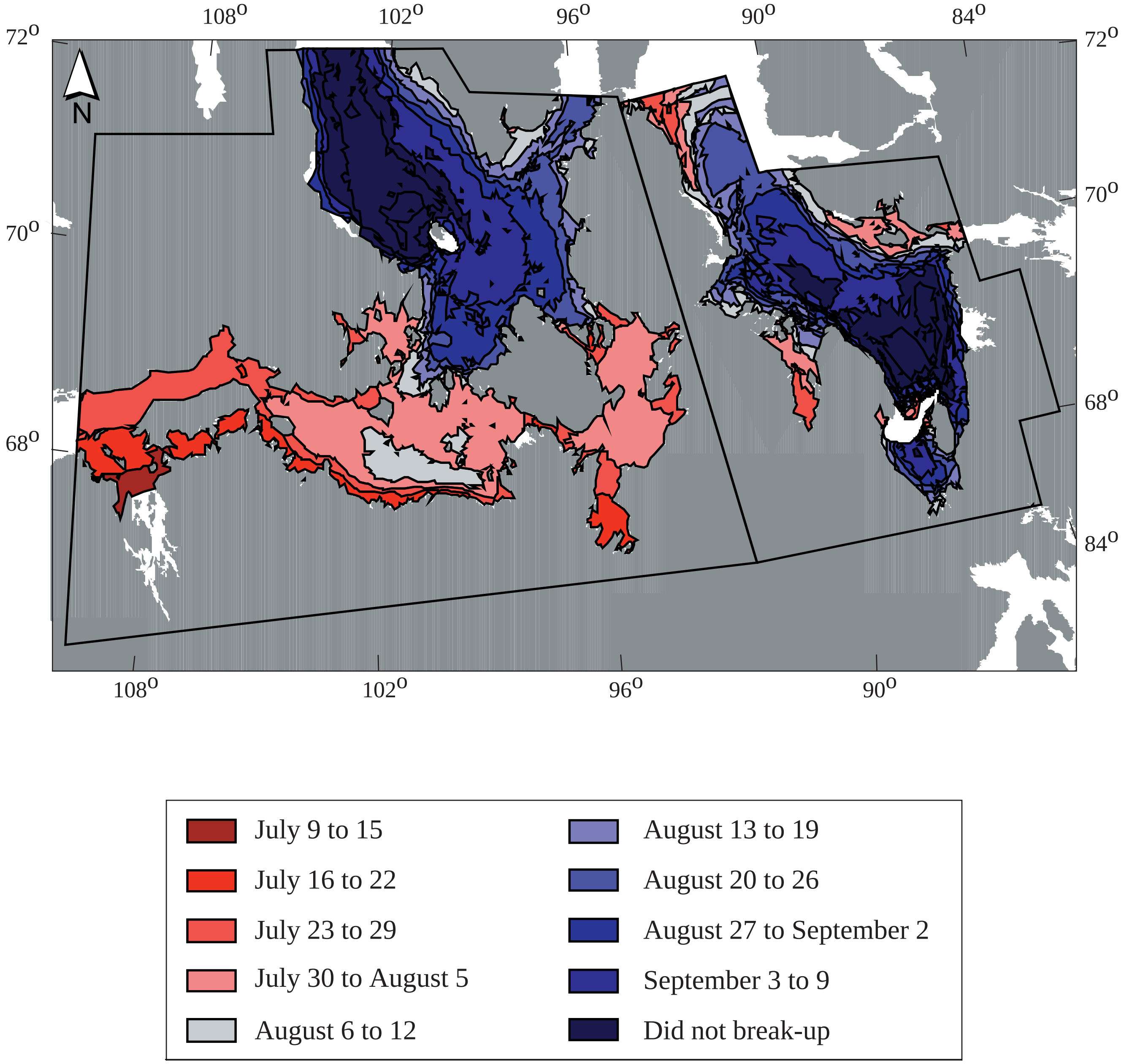

FIG. 4. Average breakup dates for the M’Clintock Channel and Gulf of Boothia study areas from 1980 to 2000.

The spatial pattern of the difference between the date of breakup and the average breakup date also showed considerable variation. During most years, M’Clintock Channel contained both areas with an earlier-than-average breakup date and areas with a later-than-average breakup date. Additionally, the same area may have experienced an earlier breakup in one year and a later breakup in another year.

Analysis of the consolidation anomalies indicated that for each year, the consolidation was significantly different from what would be expected for an average year; however, these anomalies were not as large as the breakup anomalies. Anomalies within most sections of the study area were between two and five weeks earlier or later than average. Very small areas in any year had anomalies greater than five weeks. For most years, the histograms of the consolidation anomalies were positively skewed, indicating that consolidation was occurring later than average. For example, in 1998, most of M’Clintock Channel consolidated two to five weeks later than average. This pattern, to a lesser extent, was also evident in 1984, 1988, and 1996. Some years, however, experienced an earlier-than-average consolidation: in 1986, more than 90% of the study area consolidated two to five weeks earlier than average. Over the 21-year period, these negative anomalies were not as prominent as the positive anomalies.

Like the breakup patterns, the consolidation patterns on a yearly basis were highly variable. For most years, some areas within M’Clintock Channel experienced an earlier breakup, while other areas in the same year experienced a

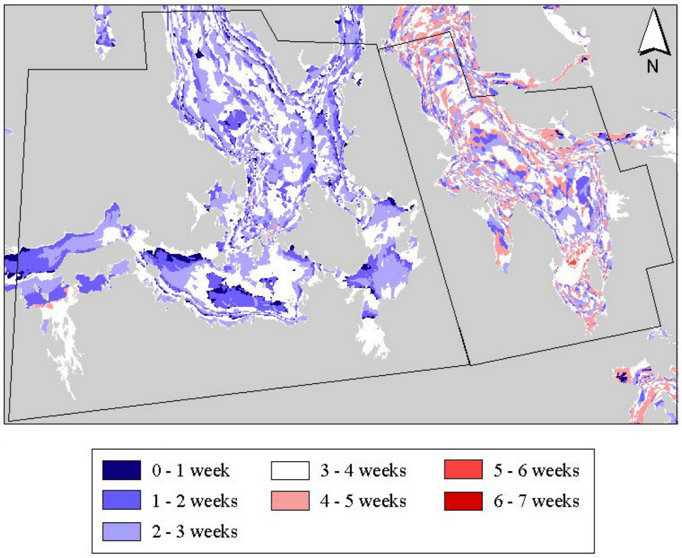

FIG. 5. Interannual variability in breakup dates for the M'Clintock Channel and Gulf of Boothia study areas over the 21-year study period (1980–2000).

later breakup. However, while the yearly breakup anomalies did not exhibit the occurrence of only earlier- or only later-than-average breakups, consolidation anomalies did exhibit this pattern in a number of years. For instance, most of the study area in 1986 experienced an earlier-than-average consolidation (the remaining area was not different from the average case), while for 1984 and 1988, consolidation was later than average for most of the study area (with the remaining area not different from average). However, the earlier or later consolidation pattern in those years was not matched by a corresponding earlier or later breakup.

Breakup and Consolidation Patterns: Gulf of Boothia

Average breakup within the Gulf of Boothia occurred over a 10-week period, concurrent with the pattern in M'Clintock Channel (from 9 July to 10 September). Breakup in this area began on average along the eastern coast of the Gulf of Boothia, along the southern coast of Pelly Bay, and in the northern section of the study area (Fig. 4). Breakup progressed away from the coasts and southward into the Gulf of Boothia. The last area to have ice concentration fall below 30% was the southern Gulf of Boothia. A significant portion of the study area (on average approximately 19%), located in the southern portion, did not break up.

The timing and distribution of breakup in the Gulf of Boothia were highly variable over the 21-year study period. For the entire study area, there was a zero- to seven-week variability in the breakup dates over the 21 years, two weeks greater than the breakup variability within MC (Fig. 5). Most of the study area, however, exhibited a two- to five-week variability. Of particular importance was the highly variable area in the northern portion of Committee Bay, which had a variability of more than six weeks. There were also regions throughout the study area that showed low variability in the breakup dates (between zero and one week). Spatially, there was no consistent pattern in the variability of breakup dates. This would suggest that the Gulf of Boothia was (and is) a very dynamic area.

Consolidation within the Gulf of Boothia on average occurred over a four-week period (from 3–9 September to 1–7 October), compared to the six weeks required for the M'Clintock Channel area (Fig. 6). The consolidation commenced in the southern section of the study area (southern Gulf of Boothia and northern Committee Bay) and progressed northward in a step fashion (Fig. 6). The last areas to consolidate were the first areas to break up, namely, Pelly Bay and the northern section of the study area. In this study area, the largest area consolidated during the week of 24–30 September.

The timing and distribution of consolidation in the Gulf of Boothia showed little variability over the 21-year study period. From 1980 to 2000, the yearly consolidation date for each pixel varied between zero and three weeks (Fig. 7). This was considerably less than the variability in breakup for the same area, but similar to the variability in consolidation within M'Clintock Channel. A small portion of the area had a zero- to one-week variation in the consolidation date; however, for most of the area, consolidation varied by one to three weeks (Fig. 7). There also appeared to be more spatial homogeneity in the annual variability associated with the consolidation dates. A significantly large area in the center of the study area exhibited an interannual variability between one and two weeks. As well, the southern portion of the study area was generally more variable than the aforementioned area, with interannual variability of two to three weeks.

Analysis of the breakup anomalies for the Gulf of Boothia revealed findings different from those for M'Clintock Channel. In particular, breakup for a significant portion of the study area differed from the average pattern. The anomaly histograms for most years were bimodal, with a mode around zero weeks and another significant mode in the large positive values (values greater than 30 weeks). This suggested that in a particular year, a large portion of the study area experienced breakup later than average or did not break up when expected according to the average pattern. These positive anomalies were spatially extensive for most years within the first part of the study period (from 1980 to 1992). For instance, in 1982, more than 50% of the study area did not break up when, according to the average pattern, breakup should have occurred. After 1992, the large positive anomalies were not so widespread. From 1996 to 2000, as well as in 1985, the study area also exhibited more negative anomalies. Other years before 1996 did not show as many negative anomalies.

The consolidation anomalies for the Gulf of Boothia were not as extensive in either space or time as the anomalies for breakup within this area. For any given year, consolidation anomalies varied by zero to seven weeks

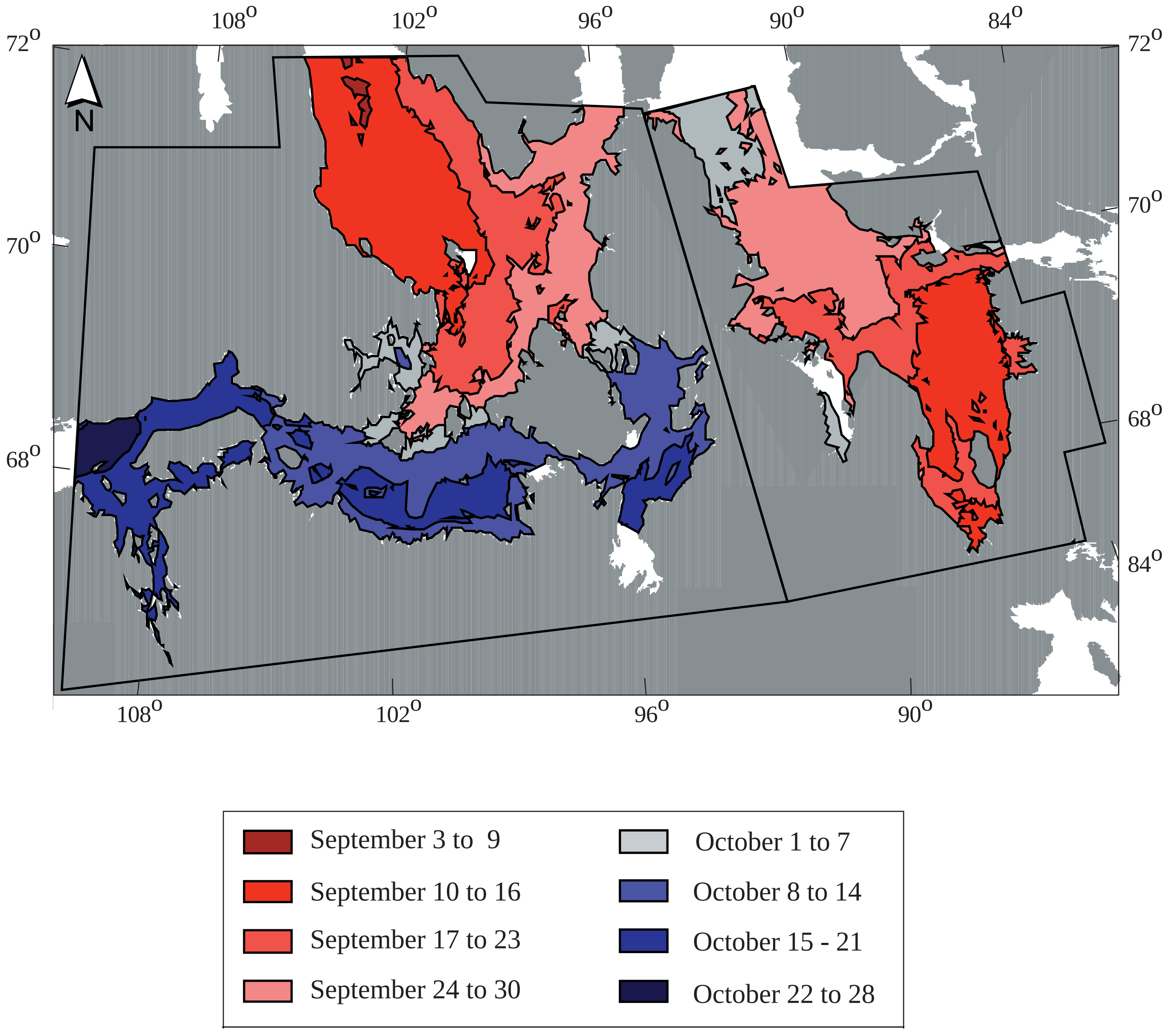

FIG. 6. Average consolidation dates for the M’Clintock Channel and Gulf of Boothia study areas over the period 1980–2000.

from the average date, on a pixel-by-pixel basis. The anomaly patterns over the 21-year study period did show some interannual variability. For instance, consolidation anomalies in 1985 were negatively skewed, as a large portion of the study area experienced later-than-average consolidation. However, in the previous year, most of the area had experienced similar-to-average consolidation, and in 1986 both positive and negative anomalies were present throughout the study area. The analysis of the consolidation anomalies for 1998 indicated that, like M’Clintock Channel, the entire Gulf of Boothia study area experienced a later-than-average consolidation (two to seven weeks later) in that year.

The consolidation anomalies, in general, appeared within confined sub-areas of each region (i.e., they were restricted spatially). The consolidation anomalies (both positive and negative) were concentrated in most years within the central portion of the study area. However, for some years—notably 1985, 1998, and 1984—these anomalies also extended into the northern and most southern portions of the study area. In 1985 and 1998, consolidation in most of the study area was two to five weeks later than average. If 1984 can be considered an “average” year in terms of consolidation, anomalies indicate that for the entire study area, consolidation occurred within one week (before or after) the average date of consolidation.

M’Clintock Channel Sea Ice Type Analysis

Analysis of variance of the mean percent coverage for the four ice types over the five-year study period indicated that rough first-year sea ice had the largest fraction (44%),

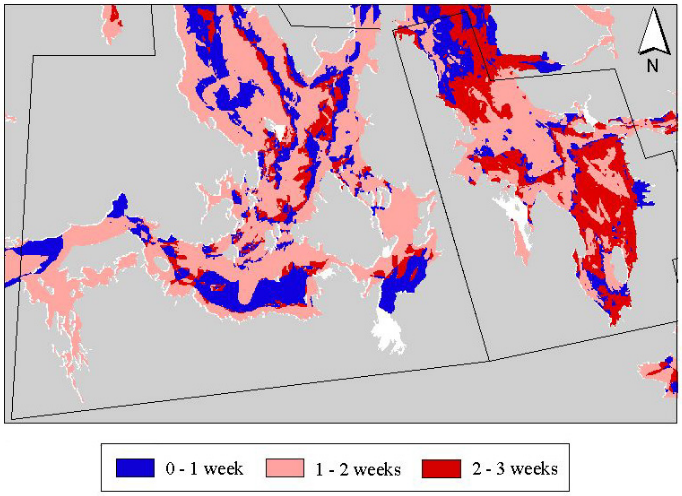

FIG. 7. Interannual variability in consolidation dates for the M'Clintock Channel and Gulf of Boothia study areas over the 21-year study period (1980 to 2000).

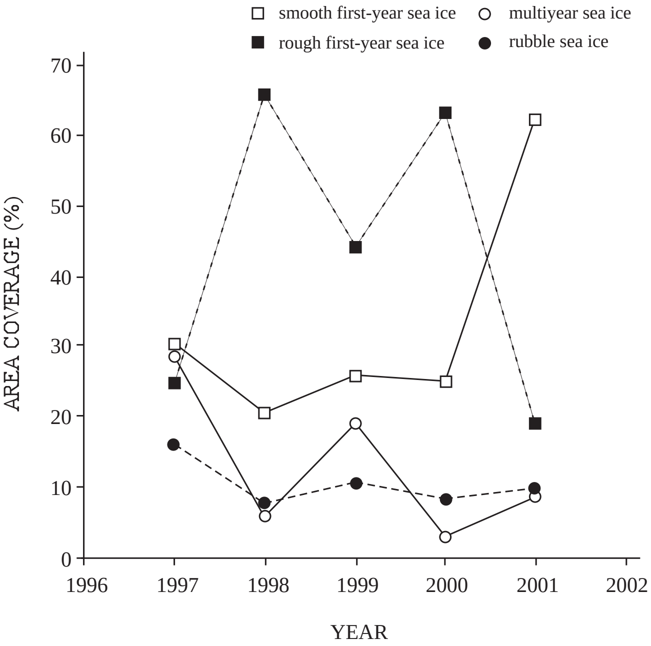

FIG. 8. Relative areal fractions of smooth first-year, rough first-year, rubble, and multiyear sea ice within M'Clintock Channel (standardized to the 1997 satellite coverage).

while smooth first-year sea ice (33%) had a greater fraction than rubble (11%) and multiyear sea ice (13%). The first-year ice classes covered most of the study area (average 85% for the five years), confirming the fraction for first-year sea ice derived from the weekly winter ice charts.

The relative areal fractions of ice types showed considerable interannual variability over the study period. During the winter of 1997, smooth first-year, rough first-year, and multiyear sea ice had similar ice concentrations, between 25% and 30% of the study area (Fig. 8). During the period from 1998 to 2000, there was a greater difference in the relative proportions of the various types of sea ice.

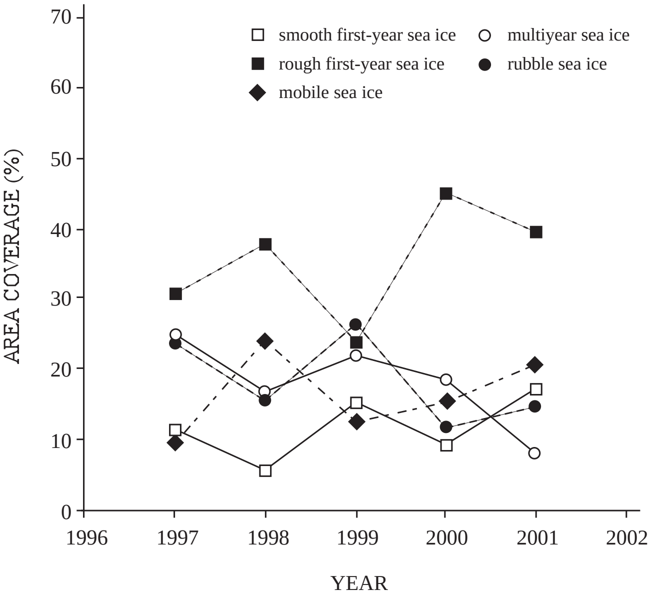

FIG. 9. Relative areal fractions of smooth first-year, rough first-year, rubble, mobile and multiyear sea ice within the Gulf of Boothia (standardized to the 1997 satellite coverage).

Rough first-year sea ice was the most abundant ice type within M'Clintock Channel, covering between 45% and 66% of the study area (Fig. 8). During this period, rubble and multiyear ice each covered less than 20% of the study area. In 1999, the proportion of multiyear sea ice increased to approximately 19%, from 5% the previous year. The remaining area in these years was covered by smooth first-year ice. In 2001, while the proportions of multiyear and rubble sea ice remained similar to those of the previous year (less than 10% each), the proportions of smooth and rough first-year ice changed significantly, with a dramatic increase in the proportion of smooth first-year sea ice and a comparable decrease in the proportion of rough first-year sea ice (Fig. 8).

The spatial pattern of the ice types within M'Clintock Channel was also highly variable. Between 1997 and 1999, Franklin Strait was predominantly covered by multiyear sea ice, with small areas of smooth first-year sea ice. In later years, this area was dominated by rubble (in 2000) and smooth first-year sea ice (in 2001). M'Clintock Channel was also variable, with different ice types covering the area from year to year. In 1997, the area was dominated by multiyear and rubble sea ice. The following year, the same area had no multiyear sea ice, small amounts of rubble and smooth first-year sea ice, and large amounts of rough first-year sea ice. We speculate that this change was due to the anomalously low sea ice concentrations in the Canadian Basin (Jeffers et al., 2001), which reduced the source for flux of multiyear sea ice into this region.

Gulf of Boothia Sea Ice Type Analysis

Upon examination of the SAR data in the GB region we discovered that a fifth type of ice class was evident.

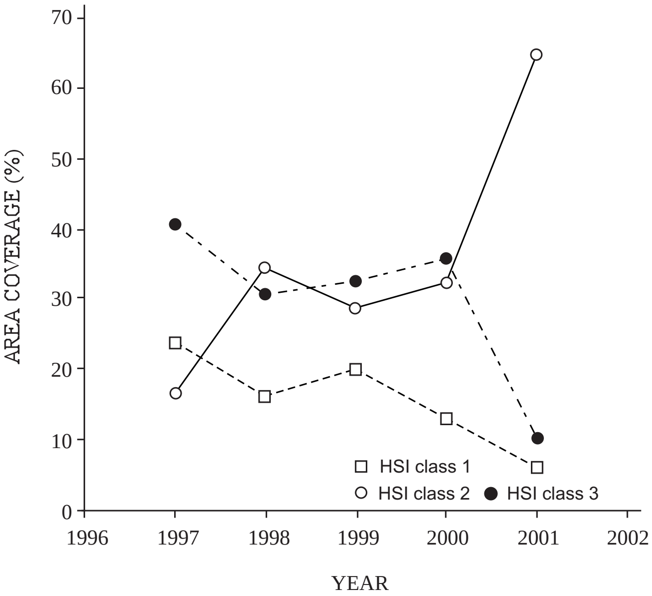

FIG. 10. Relative areal fractions of habitat suitability index (HSI) classes 1, 2, and 3 within M'Clintock Channel.

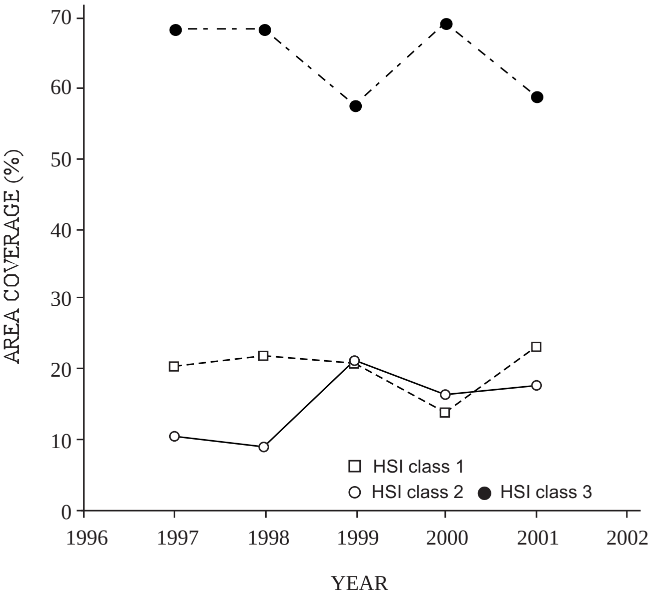

FIG. 11. Relative areal fractions of habitat suitability index (HSI) classes 1, 2, and 3 within the Gulf of Boothia.

Through spectral signature analysis of the SAR data (confirmed through discussions with S. Atkinson, pers. comm. 2002), we classified this fifth type as highly mobile, young, deformed sea ice conglomerated with small pieces of older, larger floes.

For the five-year study period, analysis of the means for the five ice types suggests that the relative proportions of ice types were similar, except for rough first-year sea ice. The proportions of smooth first-year, rubble, multiyear and mobile ice were similar for the five years (average fractions were computed to be 12%, 18%, 18%, and 16% respectively). The same analysis indicated that the average relative areal fraction of rough first-year sea ice was larger than the average for the other ice types (average proportion was 36%) (Fig. 9). Over the study period, first-year ice types covered the majority of the area, varying between 40% in 1999 and 57% in 2001 (Fig. 9). This analysis confirmed the finding from the weekly digital ice charts, as it did for M'Clintock Channel.

The spatial pattern of the various ice types in the Gulf of Boothia was fairly consistent over the study period. The southern portion of the study area in Committee Bay was dominated by mobile sea ice from 1997 to 2001. As well, rough ice was consistently present in the northern section of the Gulf of Boothia, and multiyear and rubble sea ice covered the western edge of the Gulf of Boothia for all five years. The central portion of the study area was not as consistent in terms of the ice type coverage, with some years dominated by rough first-year sea ice and other years by multiyear or rubble sea ice.

Ringed Seal Habitat in M'Clintock Channel

Throughout the five-year study period, ringed seal HSI classes 2 and 3 dominated M'Clintock Channel, together covering more than 60% of the study area (Fig. 10). In 2001, more than 65% of the study area was classified as HSI class 2. Throughout the study period, less than 31% of the study area was classified as HSI class 1 (Fig. 10). Statistical analysis of the trend in the proportion of the study area covered by the first HSI class indicated a significant decrease of this habitat class over the five years (r = -0.90, $p < 0.05$, n = 5). Trends for the other two habitat classes were not statistically different from zero. With such a limited number of years, we strongly urge caution in interpreting the significance of this result.

Within M'Clintock Channel, there was significant interannual variability in the habitat classes. HSI classes 2 and 3 had the most interannual variability, especially between 1997 and 1998 and between 2000 and 2001 (Fig. 10). The change in the proportion of the study area for these two habitat classes was greater than 20%. The interannual variability for HSI class 1 was much lower: less than 7% per year (Fig. 10). For this habitat class, most years experienced a decrease in the area covered. In 1999, there was a 3% increase in the area dominated by HSI class 1. The opposite trends in interannual variability were apparent for HSI classes 2 and 3, which showed an increase in extent for most years.

Ringed Seal Habitat in the Gulf of Boothia

The three habitat classes in the Gulf of Boothia were more distinct in their coverage than in the M'Clintock Channel area. From 1997 to 2001, HSI class 3 dominated the Gulf of Boothia study area (more than 57% in every year) (Fig. 11). Correlation analysis of the three HSI classes over the study period indicated that the proportion of the study area dominated by each class did not change in a statistically meaningful way.

The interannual variability in the proportion of the study area covered by each habitat class was much smaller than in the M'Clintock Channel area. For each class, the change in the proportion of the study area covered was less than 13% (Fig. 11). For HSI class 1, the change from 1997 to 1999 was not significant, with decreases in the coverage of less than 2%. Between 1999 and 2001, the magnitude of change increased (-7% from 1999 to 2000 and +9% from 2001 to 2000). For HSI classes 2 and 3, the interannual variability changed direction annually, with decreases in one year and increases in the next year. The patterns of the variability were opposite for these two classes (Fig. 11).

Generally, HSI classes 1 and 2 within the Gulf of Boothia area were located within the southern and western portions of the study area. Consistently throughout the five-year study period, a significant portion of Committee Bay and the southern end of Gulf of Boothia were classified as HSI class 1 for ringed seals. This is partly due to the location of the floe edge in this area. However, in 1997 and 1999, a significant area in the northern section of the study area, classified in other years as HSI class 3, was also classified as HSI classes 1 and 2.

Correlation analysis indicated that no trend was present for the HSI classes over the five-year study period. The only HSI class to exhibit a statistically significant trend was HSI class 1 for M'Clintock Channel (r = -0.90, $p < 0.05$, n = 5). This result suggested that the proportion of sea ice area classified as HSI class 1 decreased significantly from 1997 to 2001. As previously stated, we advise caution in interpreting this result because the analysis was based on only five years of data.

DISCUSSION AND CONCLUSION

There is a growing awareness that the polar regions are among the first areas on the planet to respond to climate variability or change. The enhanced warming of the planet will manifest itself in significant changes in both dynamic and thermodynamic processes operating across the ocean–sea ice–atmosphere interface. Thermodynamic processes control the growth and ablation of ice. Dynamic processes control snow catchment topography and thus give rise to suitable conditions for ringed seals and polar bears. The interaction of dynamic and thermodynamic processes can lead to complex changes in the physical ice environment and associated higher trophic level habitats.

The objectives of this research were twofold: 1) to examine sea ice conditions within the M'Clintock Channel and Gulf of Boothia polar bear management areas over the past 21 years (1980–2000), and 2) to examine ringed seal habitat in the same regions from 1997 to 2001.

Overview of Sea Ice Conditions

The winter ice conditions within the two study areas suggested that large interannual variability existed within the various ice types examined (first-year, thick, and thin ice classes). However, this variability was greater for the Gulf of Boothia than for M'Clintock Channel. First-year ice types dominated the latter area throughout the 21-year study period, while within the Gulf of Boothia, thick ice types dominated in several years. No trends in the individual ice classes were found over the 21-year period for M'Clintock Channel, suggesting no large change in the proportions of the three ice classes from 1980 to 2000.

Fast ice and vast floes, on average, dominated both study areas over the study period. More than 75% of the M'Clintock Channel area contained fast ice and an additional 16% of the area contained vast floes, while the mean proportions of the two floe sizes were more similar for the Gulf of Boothia. As with the proportions of ice types, there was considerable interannual variability in the various floe sizes. As well, no trend over the study period was found for any floe size class within either study area.

Breakup and Consolidation Patterns

Average breakup and consolidation patterns with the two study areas were considerably different. Breakup within M'Clintock Channel originated in the southern part of the study area and progressed northward, while breakup began in the northern portion of the Gulf of Boothia area and progressed southward. The breakup of the most significant area in M'Clintock Channel occurred early in the season, while in the Gulf of Boothia, more breakup, in terms of area, occurred towards the end of the period. A large area in the Gulf of Boothia did not break up (in the southern portion of the study area), while a significantly smaller area in the M'Clintock Channel did not experience breakup on average. The annual variability in breakup was similar (varying by two to four weeks) in the two study areas. Another difference between the two areas was shown in the anomalies of breakup dates. The distribution of the breakup anomalies for the M'Clintock Channel area was centered on the zero anomaly (indicating little or no difference between dates), while for the Gulf of Boothia, the distribution of anomalies was bimodal and suggested a later-than-average breakup (first mode) or years where complete breakup of the sea ice did not occur (second mode).

Similar differences were found for the consolidation patterns within the two study areas. The spatial patterns of ice consolidation were opposite for the two areas: M'Clintock Channel consolidation began in the northern sections and progressed southward, while for the Gulf of Boothia, the consolidation originated in the southern portion and progressed northward. Additionally, the Gulf of Boothia area consolidated at a more rapid rate than M'Clintock Channel. Anomalies suggest considerable variability in the annual consolidation dates for both study areas.

The processes that lead to consolidation and breakup are a combination of atmospheric and oceanic forcing. An important distinction occurs between the two areas, in that the Gulf of Boothia is linked directly to Lancaster Sound. For example, when the polynya is open in Lancaster Sound, ice is able to move into the Gulf of Boothia via Prince Regent Inlet. This means that the percent of coverage and types of sea ice in GB will be correlated to changes in Baffin Bay and Lancaster Sound sea ice. On the other hand, the MC sea ice is more closely coupled to the presence (and types) of sea ice in the Beaufort Sea. When the Central Arctic pack ice moves against the Archipelago coast, multiyear ice can (and does) advect into McClure Strait and from there into the northern portion of M'Clintock Channel. This means that the presence of multiyear ice in the MC region will likely be related to dynamic processes associated with the Beaufort Gyre. Synoptically, Baffin Bay and the Beaufort Sea ice conditions respond to very different oceanic and atmospheric forcing. Although the details of these sea ice teleconnections are, at best, speculative, we feel this relationship warrants further investigation, since hemispheric changes in sea ice forced by climate change could mean very different responses in the MC and GB regions.

Areal Fractions and Spatial Patterns of Ice Types

Analysis of the ice types derived from the satellite data produced findings similar to those obtained from the weekly ice charts. First-year ice types dominated M'Clintock Channel (covering on average 85% of the study area), with considerable interannual and spatial variability. The proportions of the ice types within the Gulf of Boothia area were not different over the five-year study period; however, some interannual variability existed within this period. This area showed small spatial variability in the various ice types.

Ringed Seal Habitat Suitability Index

A ringed seal habitat suitability index (HSI) based on the classification of the satellite data was devised for each year from 1997 to 2001. Within both study areas, the HSI classes 2 and 3 dominated over the five-year study period. There was a statistically significant decrease in the proportion of HSI class 1 within the M'Clintock Channel area; however, we interpret this finding with caution, as the trend is based on data for only five years. No other habitat class for either area exhibited a statistically significant trend. Both areas showed interannual variability in the proportion of the habitat classes; however, the variability was smaller for the Gulf of Boothia.

We view this work as a preliminary step in understanding the complex dynamic and thermodynamic processes that create specific "icescapes" in different parts of the Canadian Arctic Archipelago and, in turn, how these ice features are used as habitats for organisms at higher trophic levels, such as ringed seals and polar bears. It is important to consider how regions of the Archipelago are linked within the synoptic setting of the ocean–sea ice–atmosphere system. For example, the fact that multiyear sea ice arrives in the MC region from the Beaufort Sea is significant to how the "icescape" forms in this region and thus to how it relates to ringed seals and polar bears. The fact that the GB sea ice is instead advected from Lancaster Sound and Baffin Bay makes these two study regions potentially different in their response to Arctic climate change.

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REFERENCES

BARBER, D.G., PAPAKYRIAKOU, T.N., LEDREW, E.F., and SHOKR, M.E. 1995. An examination of the relation between the spring period evolution of the scattering coefficient (σ^o) and radiative fluxes over landfast sea-ice. International Journal of Remote Sensing 16(17):3343–3363.

FINLEY, K.J., MILLER, G.W., DAVIS, R.A., and KOSKI, W.R. 1983. A distinctive large breeding population of ringed seals (*Phoca hispida*) inhabiting the Baffin Bay pack ice. Arctic 36(2):162–173.

FISCHER, R., and AKAY, M. 1996. A comparison of analytical methods for the study of fractional Brownian motion. Annals of Biomedical Engineering 24(4):537–543.

FROST, K.J., LOWRY, L.F., GIBERT, J.R., and BURNS, J.J. 1983. Ringed seal monitoring: Relationships of distribution and abundance to habitat attributes and industrial activities. Final Report to the Outer Continental Shelf Environmental Assessment Program, Anchorage, RU No. 667.

HAMMILL, M.O., and SMITH, T.G. 1988. Factors affecting the distribution and abundance of ringed seal structures in Barrow Strait, NWT. Canadian Journal of Zoology 67:2212–2219.

IACOZZA, J., and BARBER, D.G. 1999. An examination of the distribution of snow on sea-ice. Atmosphere-Ocean 37(1): 21–51.

IPCC (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE). 2001. Climate Change 2001: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the IPCC Third Assessment Report. Edited by Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., and

Xiaosu, D. Cambridge, U.K.: Cambridge University Press. 944 p.

JEFFERS, S., AGNEW, T.A., ALT, B.T., DeABREU, R., and McCOURT, S. 2001. Investigating the anomalous sea-ice conditions in the Canadian High Arctic (Queen Elizabeth Islands) during summer 1998. Annals of Glaciology 33:507–512.

JOHANNESSEN, O.M., SHALINA, E.V., and MILES, M.W. 1999. Satellite evidence for an Arctic sea ice cover in transformation. Science 286(3):1937–1939.

NICHOLS, T.K. 1999. Development of a ringed seal (*Phoca hispida*) habitat suitability index for the Canadian High Arctic using synthetic aperture radar. M.A. thesis, University of Manitoba, Winnipeg. 221 p.

PARKINSON, C.L., CAVALIERI, D.J., GLOERSEN, P., ZWALLY, H.J., and COMISO, J.C. 1999. Arctic sea ice extents, areas and trends, 1978–1996. Journal of Geophysical Research 104(C9):20837–20856.

ROTHROCK, D.A., YU, Y., and MAYKUT, G.A. 1999. Thinning of the Arctic sea-ice cover. Geophysical Research Letters 26(23):3469–3472.

SMITH, T.G., and STIRLING, I. 1975. Ringed seals in James Bay and Hudson Bay: Population estimates and catch statistics. Arctic 28(3):170–182.

STIRLING, I., and DEROCHER, A.E. 1993. Possible impacts of climatic warming on polar bears. Arctic 46(3):240–245.

STIRLING, I., ANDRIASHEK, D., and CALVERT, W. 1993. Habitat preference of polar bears in the western Canadian Arctic in late winter and spring. Polar Record 29(168):13–24.

WELCH, H.E., and BERGMANN, M.A. 1989. Seasonal development of ice algae and its prediction from environmental factors near Resolute, N.W.T., Canada. Canadian Journal of Fisheries and Aquatic Sciences 46:1793–1804.

WMO (WORLD METEOROLOGICAL ORGANIZATION). 1970. Sea ice nomenclature. Report 259, Technical Paper 145, Geneva: WMO. 147 p., 8 supp.