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Interannual Variability of Landfast Ice Thickness in the Canadian High Arctic, 1950-89

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ABSTRACT. A physical one-dimensional heat transfer model of fast ice growth was used to investigate the interannual variability of maximum fast ice thickness at four sites in the High Arctic over the period 1950-89. The insulating role of snow cover was found to be the most important factor, explaining 30-60% of the variance in maximum ice thickness values. Other snow-related processes such as slushing and density variations were estimated to explain a further 15-30% of the variance. In contrast, annual variation in air temperatures explained less than 4% of the variance in maximum ice thickness. No evidence was found for the systematic ice thinning trend anticipated from greenhouse gas-induced global warming. However, recent ice thinning and thickening trends at two sites (Alert and Resolute) are consistent with changes in the average depth of snow covering the ice and may be explained by changes in cyclone frequencies. A response surface sensitivity analysis following Fowler and de Freitas (1990) indicated the High Arctic landfast ice regime would be more sensitive to air temperature variations under a warmer, snowier environment.

Key words: landfast ice, snow, interannual variability, climate change, Canadian High Arctic

RÉSUMÉ. On s'est servi d'un modèle physique de transfert unidimensionnel de chaleur de la croissance de la banquise côtière pour étudier la variabilité interannuelle de l'épaisseur maximale de la banquise côtière à quatre stations de l'Arctique septentrional au cours de la période allant de 1950 à 1989. Le rôle d'isolant de la couche de neige s'est révélé le facteur le plus important, répondant pour 30 à 60 p. 100 de l'écart observé dans les épaisseurs maximales de glace. On estime qu'une autre partie (15 à 30 p. 100) de l'écart découle d'autres processus liés à la neige, comme la variation de la densité et la gadoue. En revanche, la variation annuelle des températures de l'air est intervenue pour moins de 4 p. 100 de l'écart observé dans les épaisseurs maximales de la glace. On n'a relevé aucune tendance à l'amincissement systématique de la glace, tendance prévue du fait du réchauffement du globe provoqué par les gaz à effet de serre. Toutefois, les récentes tendances à l'amincissement et à l'épaississement enregistrées à deux stations (Alert et Resolute) sont compatibles avec la hauteur moyenne de la neige qui recouvre la glace. Ce fait tient peut-être à la modification de la fréquence des cyclones. D'après une analyse de la réaction de surface exécutée suivant la méthode de Fowler et de Freitas (1990), le régime de la glace côtière de l'Arctique septentrional est plus sensible à la variation de la température de l'air dans un milieu plus neigeux et plus chaud.

Mots clés: banquise côtière, neige, variabilité interannuelle, changement climatique, Arctique septentrional canadien

Traduit par Daniel Pokorn.

INTRODUCTION

It was recently reported by Wadhams (1990) that ice thickness data from submarine cruises in the Arctic Basin indicated a significant decrease in mean ice thickness north of Greenland between 1976 and 1987. As Wadhams (1990) points out, while ice thinning is an expected early consequence of greenhouse warming, it is not possible from two sets of measurements taken 11 years apart to determine whether the observed thinning is part of a progressive trend or simply a manifestation of the inherent variability of the system. Unfortunately, there are few if any data sets containing systematic long-term information on sea-ice thickness variations over the major ice-covered oceans of the globe. However, landfast ice thickness records at several sites in the Canadian High Arctic are now approaching 40 years in length. While these data cannot be extrapolated to the offshore sea-ice environment, they can nevertheless provide useful information on interannual variability in ice thickness and can be used to investigate the presence of the ice thinning noted by Wadhams (1990) and the ice thinning trend projected to accompany greenhouse gas-induced global warming by most Atmospheric General Circulation Models (GCM).

SITE SELECTION

Four sites (Alert Inlet, Eureka, Mould Bay and Resolute) in the Canadian Arctic Islands were selected for study. The rationale for selecting these particular sites was that they had the longest available periods of record and were located in a region where the greenhouse gas-induced climate warming signal is expected to be the greatest based on GCM output and historical analogues. The sites are well distributed throughout the Canadian Arctic Archipelago (Fig. 1) and are adjacent to the area of ice thinning noted by Wadhams (1990). Isachsen, on Axel Heiberg Island, would have been a valuable addition to the investigation. Unfortunately, this station was closed in 1978. Data from a fifth site at Dumbell Lake, close to Alert, were used as a quality control check for Alert Inlet.

DATA

Ice thickness and corresponding on-ice snow depth measurements have been made regularly at many coastal and inland locations throughout Canada since about 1950. In general, thickness measurements are taken once per week, starting after freeze-up when ice is safe to walk on and continuing until break-up or when the ice becomes unsafe. Ice thickness data are collected manually, and a degree of judgment is required when selecting measurement sites and taking measurements (particularly in certain locations in the Arctic where multi-year ice can be embedded in the landfast ice). Observers are requested to ensure that measurements are taken at sites where the depth of water is greater than the maximum ice thickness expected for the year and to drill new holes for each measurement (MANICE, 1989). The measurement process does involve a degree of subjectivity, however, and data quality is likely to vary somewhat. Potential sources of error in the measurements include changes in measurement locations, changes in personnel and disturbances within the measurement area. In spite of these problems, the data represent one of the few available sources of continuous ice thickness measurements in the Arctic.

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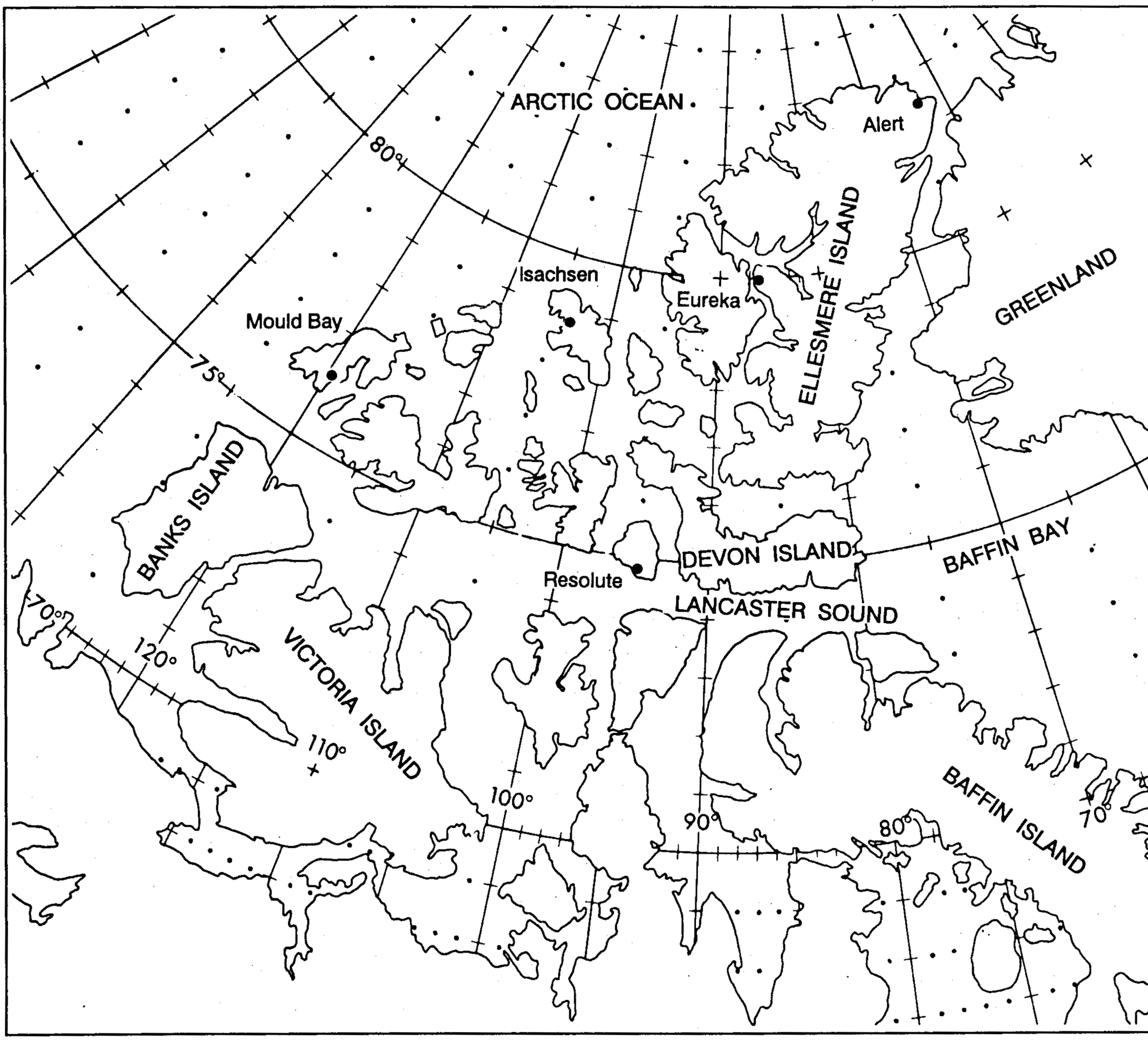

FIG. 1. Location map of the Canadian Arctic Islands showing the locations of the ice thickness measurement sites referenced in the text.

Values of maximum ice thickness and mean on-ice snow depth were extracted from the weekly ice and snow thickness data at the four sites selected. Although measurements are available from the mid-1940s, the number of weekly observations is highly variable in earlier years. Annual values were only used in this study where there were sufficient weekly data throughout the ice season to ensure the mean snow depth and maximum ice thickness were well defined. This process resulted in the rejection of much of the data prior to about 1955. Accumulated freezing degree-day (ΣFDD) totals (base 0°C) for each ice season were obtained from Cote (1992) to investigate interannual variability in winter temperatures.

Characteristics of Fast Ice Regime

The main characteristics of the fast ice regime at each site are summarized in Table 1 and Figure 2. Permanent ice first forms in late August to mid-September and exhibits an approximately linear growth throughout the ice season, reaching a maximum thickness of about 2 m by late May. Ice breakup occurs rather rapidly after May, with ice typically reported to be unsafe for traffic by about mid-June and complete clearing of ice by late-July to mid-August (Cote, 1990). As this study is concerned with annual variability in maximum ice thickness, the main period of interest extends from September to late May.

The dominant period of snowfall in the High Arctic is from August to October (Fig. 3). However, in open areas like lakes and landfast ice, the wind continuously redistributes this snow throughout the ice growth season, resulting in an approximately linear growth of snow depth over time (Fig. 4). The effect of the higher winds at Resolute (Table 1) can be clearly seen by comparing Figures 3 and 4. The action of the wind and snow aging produce an increase in snow density throughout the ice season. Data from Woo and Heron (1989) for one year at Char Lake near Resolute show a rapid increase in snow density from 100 to 250 kg·m^{-3} in the initial period of ice growth, followed by a gradual increase from 250 to 400 kg·m^{-3} over the remainder of the ice growth period. Mean on-ice snow depths are in the order of 20 cm at all four sites. However, the most important point about snow depth is its considerably greater interannual variability compared to ΣFDD. This is clearly demonstrated by the values of the coefficient of variation (COV — a measure of relative dispersion defined by the ratio of the standard deviation to the mean) for snow depth, which are an order of magnitude greater than those for ΣFDD (Table 1). Given the well-documented sensitivity of ice thickness to snow depth (e.g., Holtsmark, 1955; Jacobs *et al.*, 1975; Maykut, 1978), the COV values in Table 1 suggest that snow depth is likely to exert a much greater role in ice thickness variability than ΣFDD. This role is systematically evaluated with a physical model of fast ice growth in a later section of this paper.

Another process affecting ice growth is water infiltration of the snow layer ("slushing") initiated by snow loading. A heavy layer of snow depresses the ice sheet below water level. Provided the ice temperature is warm enough for brine pockets to interconnect, water will migrate up the brine channels into the surface snow layer (Weeks and Lee, 1958). The formation of slush increases ice thickness, but more important, it changes the thermal properties of the surface layer. Weeks and Lee (1958) found the thermal conductivity of slush-ice to be 10-75 times that of snow. Ice growth under a layer of slush will therefore be greater than ice growth under a snow layer, and it is conceivable that a single slush formation event early in the ice season could have important consequences for ice formation during the entire ice growth period.

The potential for slush formation can be estimated from the hydrostatic balance. According to Ackley *et al.* (1990), flooding may occur when the ratio h_s/h_i exceeds $100/\rho_s$ (kg·m^{-3}). To investigate flooding potential at the High Arctic sites, h_s/h_i

TABLE 1. Fast ice characteristics at four High Arctic sites

	Alert	Eureka	Mould Bay	Resolute
Years studied	1956-87	1952-89	1954-89	1952-89
Mean max. ice thickness (cm)	201.8	229.7	203.6	200.2
s.d. (cm)	22.0	20.9	18.7	21.4
COV	0.109	0.091	0.092	0.107
Mean snow depth (cm)	18.5	16.0	25.1	21.6
s.d. (cm)	6.8	5.7	9.3	9.6
COV	0.368	0.354	0.370	0.445
Mean ΣFDD (base 0°C)	−6809.9	−7514.4	−6665.0	−6251.4
s.d.	221.7	336.2	264.0	301.6
COV (abs. value)	0.033	0.044	0.040	0.048
Mean date of first permanent ice[1]	Aug 30	Sep 08	Sep 08	Sep 19
Mean date of maximum ice[2]	May 31	May 25	May 29	May 28
Mean T_{air} at first permanent ice[3]	−3.8	−5.0	−4.3	−6.3
Mean JFM wind speed (km·h^{-1})[4]	9.4	10.0	14.0	20.4
Est. mean snow density (kg·m^{-3})[5]	338	360	405	412
Est. mean slushing potential (%)	3.4	0.3	1.0	1.51

[1]From Cote (1990).
[2]Computed from date when maximum ice thickness for a season first encountered.
[3]Interpolated from 1951-80 monthly mean air temperature normals.
[4]From Maxwell (1980).
[5]Estimated from ice growth model.

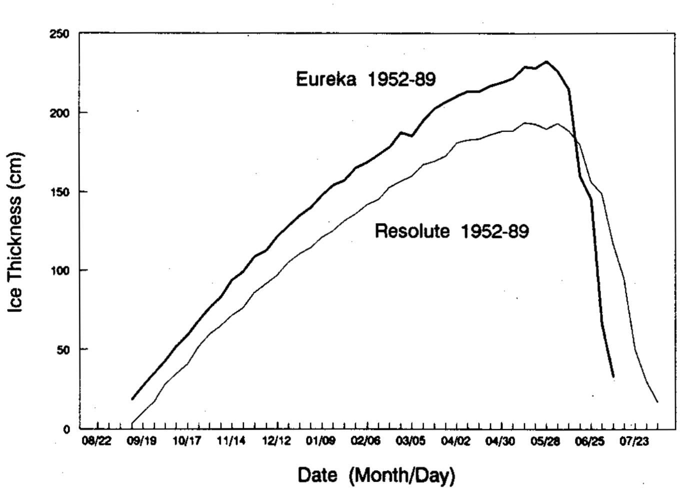

FIG. 2. Mean weekly values of measured ice thickness at Eureka and Resolute (Alert and Mould Bay data closely follow the Resolute curve).

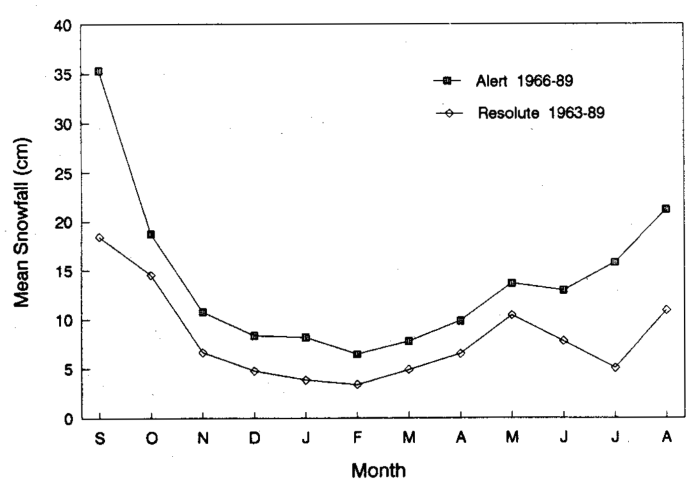

FIG. 3. Mean monthly nipher gauge snowfall at Alert (1966-89) and Resolute (1963-89). Note that the months are rearranged to coincide with the ice growth season.

was computed for all paired values of ice thickness and snow depth at the four sites. Because flooding is most likely to occur when the ice temperature is warm enough to allow upward brine flow, potential flooding was assumed to only occur in the early period of ice growth up till the end of October. Assuming a typical value for ρ_s of 300 kg·m^{-3}, potential flooding conditions exist where $h_s/h_i > 0.33$. The frequency of ratios exceeding 0.33 in the early ice growth period is shown in Table 1 expressed as a percentage of all h_s/h_i values. This ranged from a low of 0.25% at Eureka to a value of 3.4% at Alert Inlet. While these values are low, they suggest that potential slushing conditions can be encountered anywhere in the High Arctic landfast ice regime and that there is likely to be considerable spatial variability in slushing potential.

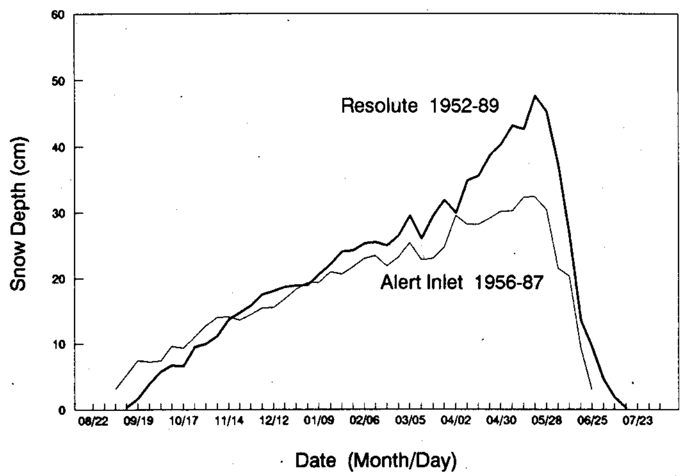

FIG. 4. Mean weekly values of measured on-ice snow depth at Alert Inlet and Resolute Bay.

Interannual Variability in Ice Thickness, Snow Depth and Freezing Degree-Days

Interannual variability in maximum ice thickness, snow depth and ΣFDD values at each of the four sites is shown in Figures 5 and 6. A five-term binomial filter was applied to the data to highlight longer time scale variability. As a first step, a linear regression analysis was performed on the data to identify the presence of first order trends in the time series (Table 2). In addition, 1980s' data were compared to a common 1961-80 reference period (Table 3) to determine the statistical significance of changes occurring in a decade that experienced the warmest global temperatures this century (Kerr, 1990). A longer reference period, say 1951-80, would have been preferred in this analysis, but there were insufficient data at all four sites during the 1950s.

Eureka and Mould Bay showed no evidence of significant trends or recent changes in maximum ice thickness or snow depth. Alert, however, displayed evidence of a trend toward

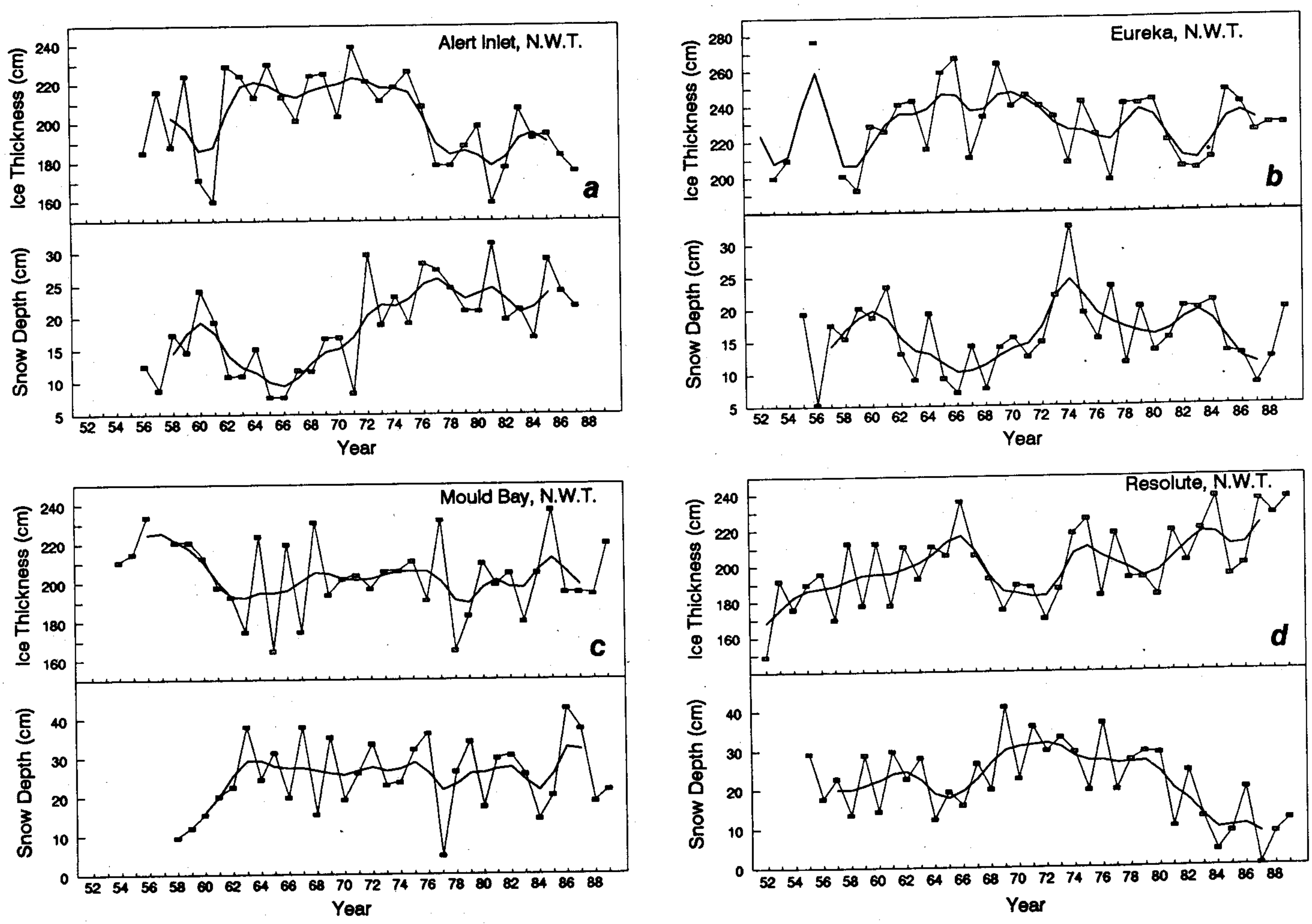

FIG. 5. Annual variation in maximum landfast ice thickness and mean on-ice snow depth for a) Alert Inlet, b) Eureka, c) Mould Bay and d) Resolute Bay. The solid curve is the result of applying a five-term binomial filter.

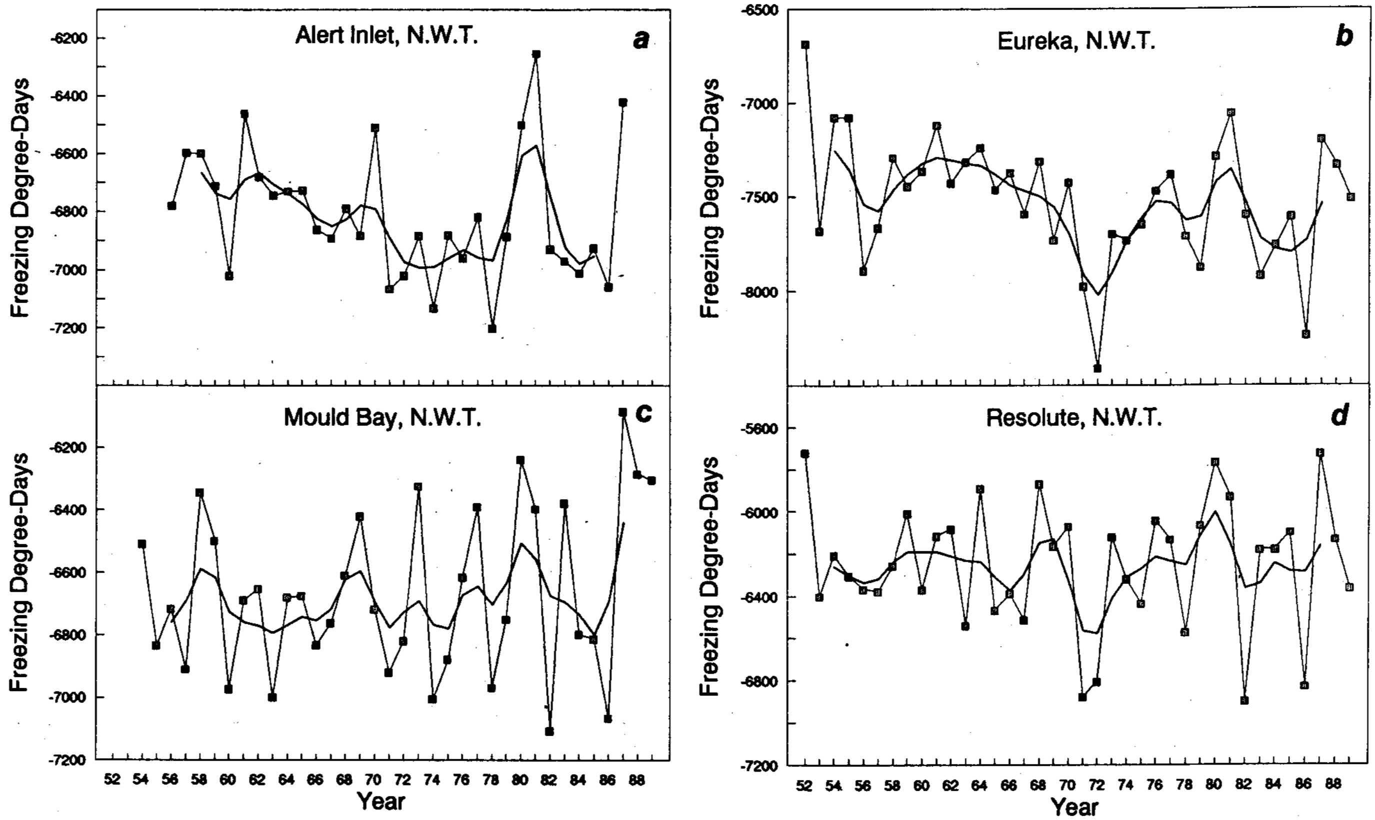

FIG. 6. Annual variation in accumulated freezing degree-days (base 0°C) for a) Alert Inlet, b) Eureka, c) Mould Bay and d) Resolute Bay. The solid curve is the result of applying a five-term binomial filter.

lower ice thickness values, while Resolute exhibited an opposing trend toward thicker ice. In both cases, these changes were associated with corresponding changes in snow depth consistent with the insulating role of snow. The Alert and Resolute trends are mainly the result of recent changes, as seen in Figure 5 and confirmed statistically in Table 3. The rather abrupt change in ice thickness values at Alert after 1976 is suggestive of a possible discontinuity in the data. Fortunately, an ice thickness measurement program is also carried out at a lake site (Upper Dumbell Lake) close to Alert. The Dumbell Lake anomalies (not shown) were significantly correlated with those at Alert ($r = 0.66$ for ice thickness, and $r = 0.57$ for snow depth) and exhibited the same changes after 1976. Moreover, the fact that a lake site exhibited the same response as Alert Inlet provides strong evidence that the observed decrease in ice thickness is not related to changes in ocean heat flux or salinity. The presence of landfast and lake ice thickness monitoring sites in close proximity is extremely valuable for verifying the homogeneity of data and for assessing the importance of ocean heat flux and salinity effects.

There was no second ice observing site to verify the opposite trend in snow cover and ice thickness observed at Resolute Bay. It was possible, nevertheless, to compare the on-ice snow depth data with end of month snow depth measurements taken at the Resolute weather observing station. The two series (not shown) were significantly correlated ($r = 0.40$), and a post-1968 trend toward decreasing snow cover was evident at both sites. Concerns have been expressed by a number of individuals that ice thickness measurements from Resolute Bay are contaminated by effluent discharge from the village and that this is responsible for the observed increases in ice thickness. Such skepticism seems unwarranted after taking

TABLE 2. Results of linear trend analysis

	Period	Ice ($cm \cdot yr^{-1}$)	Snow ($cm \cdot yr^{-1}$)	ΣFDD^1 ($\Sigma FDD \cdot yr^{-1}$)
Alert Inlet	1956-87	−0.71	+0.43*	−4.89
Alert (Dumbell Lake)	1957-87	−0.90*	+0.30	−3.08
Eureka	1952-89	−0.00	+0.04	−10.02*
Mould Bay	1954-89	−0.29	+0.20	+5.23
Resolute	1952-89	+0.99*	−0.33*	−0.70

*Linear trend significant at 95% level.
[1]Note ΣFDD defined negative so positive change indicates warming and vice versa.

TABLE 3. Change in 1980s' decade maximum ice thickness, mean snow depth and accumulated freezing degree-day totals compared to 1961-80 average

	Change (1980-89 minus 1961-80)		
	Ice (cm)	Snow (cm)	ΣFDD (base 0°C)
Alert Inlet[1]	−23.7*	5.6*	72.4
Alert (Dumbell Lake)[1,2]	−20.2*	1.5	
Eureka	−10.5	−0.3	9.8
Mould Bay	4.9	−0.3	149.8
Resolute	17.9*	−13.5*	51.4

[1]1980-87 period used.
[2]No temperature measurements made at Dumbell Lake site.
*Significant at 95% level.

a closer look at the data. First, the measuring site was only moved close to the village in 1986, several years after the observed increases in ice thickness. Second, the observed increase in thickness is consistent with the observed decrease in snow cover. However, the possibility for anthropogenic influences on ice measurements taken close to settlements cannot be dismissed entirely, and this should be an important consideration when observers select measurement sites.

The only site to display a significant temperature trend was Eureka, with a gradual cooling of $-10\ \Sigma\text{FDD}\cdot\text{yr}^{-1}$ over the last 40 years. The sign of the ΣFDD linear trend was negative at all the sites, with the exception of Mould Bay, which is consistent with the 1946-86 cooling trend over the eastern Arctic and northwest Atlantic noted by Jones *et al.* (1987). This trend appears to have halted during the 1980s, where the change in mean freezing degree-day totals indicates mean winter temperatures were slightly warmer than the 1961-80 average. Mould Bay showed the largest positive change in ΣFDD during the 1980s, which is consistent with the dichotomy in recent temperature trends between the eastern and western Arctic (Jones *et al.*, 1987).

The interannual variability of the data is characterized by large fluctuations from one year to the next. This noise completely dominates the temporal characteristics of the data, and computed autocorrelation functions showed no significant lagged correlations, with the exception of mean snow depths at Alert and Resolute, where there was evidence of a biennial oscillation. In order to investigate the significance of longer term periodicities, the data were low-pass filtered with a five-term binomial filter. Frequency spectra of the low-pass filtered annual values were computed, and the significance of spectral peaks were tested by comparing the normalized cumulative sum of periodogram ordinates against the 95% Kolmogorov-Smirnov bounds for a uniform distribution. This tests whether the time series is random or not. Significant spectral peaks of 8-10 years were found in maximum ice thickness at Alert Inlet, Mould Bay and Resolute, while decadal or near decadal (10-14 year) cycles were found in snow depth at Alert Inlet, Eureka and Resolute. These fluctuations are consistent with the 8- to 12-year variability in oceanographic conditions noted in the Beaufort Sea by Fissel and Melling (1990) and also with the decadal internal variability of the North Atlantic air-ice-ocean system (Mysak *et al.*, 1990; Weaver and Sarachik, 1991). Significant 5-year cycles were found in ΣFDD at Alert, Eureka and Resolute and in ice thickness data at Eureka. These results are consistent with 4- to 6-year cycles in ice severity in the western Arctic (Barnett, 1980; Mysak and Manak, 1989), and 5- to 6-year cycles in sea-surface temperatures and sea-level fluctuations in the northeast Pacific (Mysak, 1986). Mysak and Manak (1989) suggested that the 4- to 6-year cycle may be related to the interannual variability in North Pacific sea-level pressures.

Spatial Variability

To investigate the spatial dimension of the observed interannual variability, correlations were computed among all four stations for maximum ice thickness, mean snow depth and ΣFDD (Table 4). Apart from the ΣFDD correlations, which were all significant, only one snow depth spatial correlation (Alert and Eureka) was statistically significant. These results confirm the conclusion of Jacobs (1989) that snowfall and snow depth data contain such high levels of spatial variability and/or measurement error that interpolation/extrapolation cannot be reliably carried out over even mesoscale distances. This conclusion would seem to apply equally well to landfast ice thickness data.

There is some indication from the sign and magnitude of the spatial correlations that the two northern sites, Alert and Eureka, share a different regional climate than Resolute or Mould Bay. This regional grouping is consistent with climatic regions I and V of the Canadian Arctic Islands (Maxwell, 1981). The main factor responsible for the different regimes is the rugged mountains of Ellesmere Island, which reduce the influence of cyclonic systems moving in from the Beaufort Sea and Baffin Bay.

Possible Mechanisms for Observed Snow Depth Variations at Resolute and Alert

Providing reasons for the observed recent trends in snow depth at Resolute and Alert is difficult because of the complex factors affecting snow deposition on the ground. However, an obvious starting point would be to look for changes in snowfall amount. Comparison of October-May total snowfall and mean snow depth anomalies at Alert and Resolute for periods after nipher gauges were installed yielded a significant correlation for Resolute (1963-89) of 0.50, but a somewhat lower, not statistically significant correlation of 0.34 for Alert (1966-89). Woo *et al.* (1983) found no significant correlations between snowfall and snow depth at Mould Bay, Resolute and Eureka. However, Jacobs (1989) indicated he had obtained significant relationships between total winter snowfall and maximum snow depth for five Baffin Island stations. The different results are probably related to site factors, as well as the different lengths of data employed when computing correlations. At any rate, the above results indicate that changes in measured snowfall amount explain some of observed variance in snow depth at the two sites, but that much of the variance (75%) is still unexplained.

After change in snowfall amount, wind and local topography are probably the most important factors controlling local snow cover distribution. It is well known (e.g., Komarov, as cited by Maxwell, 1980:361) that the rate of snow transport over open, flat areas is particularly sensitive to changes in wind speed. Analysis of mean winter (JFM) wind speeds

TABLE 4. Spatial correlation of variables; distances between stations (km) are given below the leading diagonal

	Resolute			Mould Bay			Eureka			Alert		
	Ice	Snow	ΣFDD	Ice	Snow	ΣFDD	Ice	Snow	ΣFDD	Ice	Snow	ΣFDD
Resolute	—	—	—	.08	.26	.69*	–.14	.17	.63*	–.22	–.10	.59*
Mould Bay		694		—	—	—	–.09	–.28	.38*	–.07	.04	.57*
Eureka		625			860		—	—	—	.25	.35*	.69*
Alert		1091			1279			481		—	—	—

*Correlations significant at 95% level.

showed no evidence of any changes at Resolute. However, a significant trend toward lower winter wind speeds was observed at Alert, which accounted for a 4 $km \cdot h^{-1}$ reduction in mean winter wind speeds over the 1953-90 period. Lower wind speeds could contribute to the recently observed thinner ice at Alert through less packing of the snow and a resultant lowering of average snow densities.

A possible synoptic origin for the observed changes in snow cover at the two sites was investigated by looking at the frequency of cyclones (duration ≥ 24 h) during the months of October and November, which account for a large proportion of the total annual snowfall. Six-hourly surface pressure analysis fields on a 381 km grid from Fleet Numerical Oceanography Center (FNOC) were input to an automated surface pressure tracking system (SPASM, 1985) and the frequency of lows computed over a grid of circles with radius 230 km. To verify the automated technique and the pressure data set, computed cyclone frequencies were compared to storm frequencies derived from manual interpretation by Serreze and Barry (1988). The spatial pattern produced by the automated method agreed well with the manual analysis, although cyclone frequencies were slightly higher in all areas, particularly over the Barents Sea and Baffin Bay. As the latter feature has been observed in other studies (e.g., Keegan, 1958; Maxwell, 1980), it was concluded that the automated technique and the data were suitable for investigating changes in cyclonic activity.

Cyclone frequencies were computed for the recent 1980-89 decade and compared to the 1961-80 reference period (Fig. 7). A change in the 1980s' pattern that could explain the decreased snow depth at Resolute is an apparent eastward shift and anticlockwise rotation of the Baffin Bay storm track about the centre of Baffin Bay. This may reflect a deepening of the upper trough over the eastern Arctic, which is consistent with the observed cooling trend in the eastern Arctic (J.B. Maxwell, pers. comm. 1991). These changes resulted in an approximate 25% reduction in the number of lows reaching the Resolute area in the 1980s compared to the earlier 20-year period.

A feature of the 1980s' pattern that may explain the increased snow depths at Alert is a noticeable doubling in the frequency of lows north of Ellesmere Island and Greenland. Analysis of individual storm tracks indicated that 50% of the storms in this area were of local origin and of relatively short duration. This feature was noted to persist throughout the winter and may be a manifestation of the thinner ice conditions indicated by Wadhams (1990). However, it is also possible that the greater frequency of storms in this area may simply be an artifact of the increased number of drifting buoys deployed in the Arctic during the 1980s as part of the Arctic Ocean Buoy Program (Untersteiner and Thorndike, 1982).

Modelling Interannual Variability in Fast Ice Thickness

The factors responsible for the observed interannual variability in maximum ice thickness can be investigated by constructing a physical model of the ice growth process. One of two approaches is usually taken in modelling ice growth: the physical approach based on the theory of heat transfer (e.g., Jacobs *et al.*, 1975; Maykut, 1978; Woo and Heron, 1989), or empirical treatments correlating ice growth to accumulated degree-days below the freezing temperature of water (e.g., Zubov, 1945; Billelo, 1961). The problem with the empirical approach is that it requires a long period of data to compute coefficients with some degree of confidence, and the empirical coefficients are only valid for specific locations. In contrast, a physically based model can be applied at any location, and it is possible to look at the sensitivity of ice growth to changes in the individual controlling variables such as air temperature, snow depth, snow density and water salinity.

As outlined by Woo and Heron (1989), High Arctic fast ice growth is the simplest case to model because of the tremendous heat loss in the winter. The first several snowfalls may be incorporated in the ice, but the rapid growth of ice means there is little potential for slushing of subsequent snowfalls, and "black" ice constitutes the largest portion of the ice cover (Woo and Heron, 1989). The ocean heat flux, so important for modelling sea ice, can be ignored at landfast ice sites where the ocean heat flux is negligible after the water column has been cooled to the freezing point of sea water and ice formation has started (Prinsenberg, 1992). Since there is little solar radiation input over the ice growth period to complicate the surface energy balance, ice growth can be predicted very successfully from a one-dimensional heat flow equation following Jacobs *et al.* (1975):

$$dh_i/dt = \frac{(T_w - T_s)}{\rho_i \, L_f \, (h_i/k_i + h_s/k_s)}$$

where T_w = freezing temperature of sea water (°C); T_s = temperature of surface of snow (°C); k_i = thermal conductivity of ice ($W \cdot m^{-1} \cdot °C^{-1}$); h_i = ice thickness (m); k_s = thermal conductivity of snow ($W \cdot m^{-1} \cdot °C^{-1}$); h_s = snow depth (m); ρ_i = ice density ($kg \cdot m^{-3}$); and L_f = latent heat of fusion ($J \cdot kg^{-1}$).

In the model, T_s was estimated from mean monthly air temperature data that were fitted with a cubic spline to allow interpolation of daily values. T_w was estimated from Stallabrass (1980) as

$$T_w = -0.002 - 0.0524\,S - 6.0 \cdot 10^{-5}\,S^2 \ (°C),$$

where S is the sea surface salinity in parts per thousand. A value for S of 32 parts per thousand was assumed in the model. ρ_i was taken to be 910 $kg \cdot m^{-3}$ and k_s was estimated from snow density, ρ_s, following Woo and Heron (1989) by

$$k_s = 2.84 \cdot 10^{-6} \rho_s^{\,2} \qquad (W \cdot m^{-1} \cdot °C^{-1}).$$

k_i was estimated from the mean ice temperature (T_i) and salinity (S_i) following Untersteiner (1961):

$$k_i = 2.03 + 0.117\, S_i/(T_i - 273) \qquad (W \cdot m^{-1} \cdot °K^{-1}),$$

subject to the restriction that k_i = 1.32 $W \cdot m^{-1} \cdot °K^{-1}$ when the ice temperature exceeds 272°K (Miller, 1981). The mean ice temperature was estimated from $(T_{is} + T_w)/2$, where the temperature at the ice/snow interface, T_{is}, was approximated following Maykut (1978) by

$$T_{is} = (T_s + \zeta T_w)/(1 + \zeta) \qquad (°C)$$

where $\zeta \equiv k_i h_s / k_s h_i$ and an initial value of 1.38 was assumed for k_i based on typical values estimated for Canadian arctic landfast ice sites by Prinsenberg (1992). Mean ice salinity, S_i, in parts per thousand was estimated from the empirical relationships obtained by Cox and Weeks (1974):

$$S_i = 14.24 - 19.39\, h_i \qquad h_i \le 0.4 \text{ m},$$
$$S_i = 7.88 - 1.59\, h_i \qquad h_i > 0.4 \text{ m}.$$

The latent heat of fusion was estimated from

$$L_f = 3.335 \cdot 10^5 + (2.113 \cdot 10^3 - 11.0\, T_w)\, T_w \qquad (J \cdot kg^{-1}).$$

A simple model of this sort is unable to predict the onset of freeze-up. It was therefore assumed, based on the data presented in Table 1, that a permanent ice cover was established when the mean air temperature fell below –5°C. Ice growth was then computed until the mean air temperature warmed to

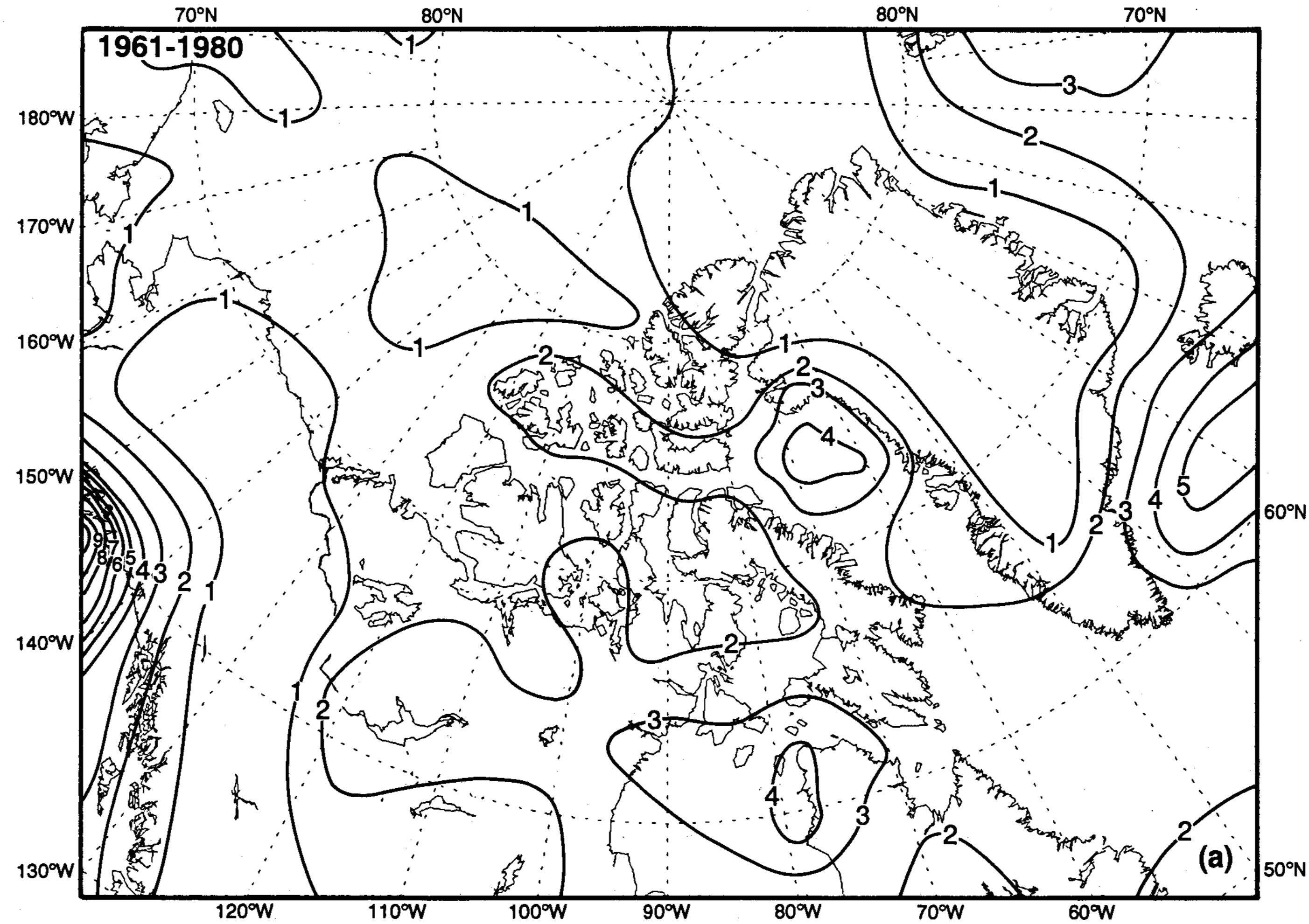

FIG. 7. Percentage frequency of all lows with duration ≥ 24 h in October and November for A) 1961-80 and B) 1980-89. Frequencies were derived using an automated method (SPASM, 1985) with 6-hourly sea-level pressure data from FNOC.

T_w. The realism of these assumptions was tested by comparing the estimated dates for first permanent ice and maximum ice thickness computed from 1951-80 mean monthly temperature normals, with the corresponding observed average dates given in Cote (1990). In all cases the estimated dates were within five days of the observed averages. Snow depth was assumed to grow linearly in the model from zero snow at the start of the ice season to a value of twice the average snow depth at the time of maximum ice thickness. This replicates the approximately linear growth of snow depth observed in Figure 4.

MODEL RESULTS

To investigate the importance of air temperature and snow depth variations in explaining interannual variability in maximum ice thickness, the ice growth model was run in three configurations: 1) interannual variation permitted in snow depth, air temperature held constant; 2) interannual variation permitted in air temperature, snow depth held constant; and 3) interannual variation permitted in both air temperature and snow depth.

The model was first run in configuration (3) to calibrate the model for each site. This was achieved by iteratively varying snow density until there was less than a 0.1 cm difference between the observed and predicted mean maximum ice thickness. The calibration process also provides a test of the model physics in that unrealistic snow densities would indicate problems with the model implementation. The empirically tuned average snow densities ranged from 338 $kg{\cdot}m^{-3}$ at Alert to 412 $kg{\cdot}m^{-3}$ at Resolute, with snow density increasing with increasing mean winter wind speed (Table 1). These values are not unreasonable and compare favourably with the Char Lake snow density data presented by Woo and Heron (1989). It was also encouraging to discover the model yielded identical estimated snow density values for Dumbell Lake and Alert Inlet: these sites are close to each other but have very different salinities (0 versus 32 parts per thousand). This was considered additional evidence of the robustness of the physics employed in the model.

In configuration (1), mean monthly temperatures were taken from published climatic normals for the period 1951-80 (AES, 1982) and daily values interpolated using a cubic spline fit as outlined previously. In configuration (2), the mean on-ice snow depth values shown in Table 1 were used. Monthly mean air temperature data from the Digital Archive of Canadian Climatological Data (AES) were used in the cubic spline interpolation scheme to obtain daily temperature data for configurations (2) and (3). The results of the model runs are summarized in Table 5 and plots of observed and predicted maximum ice thickness are shown in Figure 8 for the four sites.

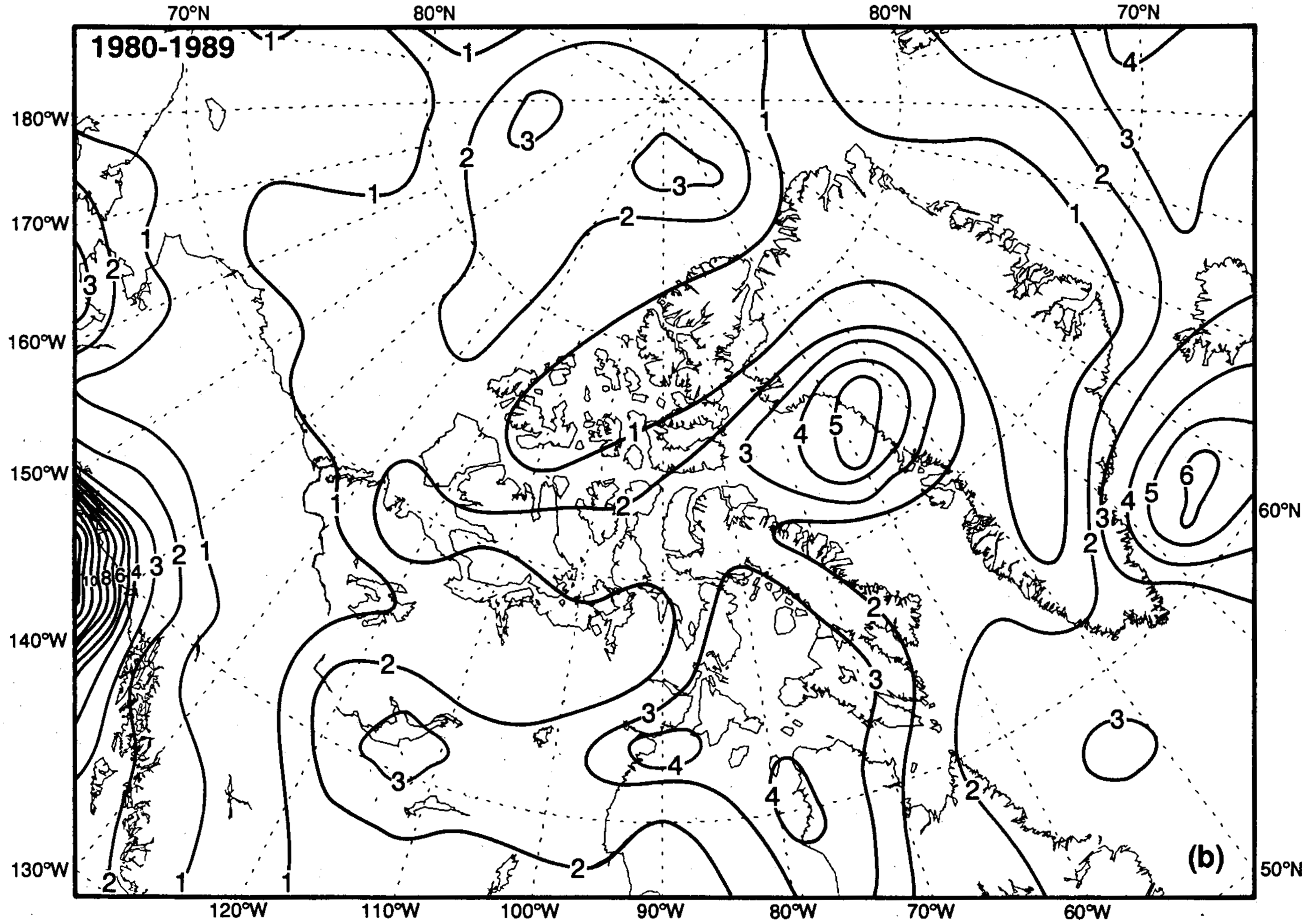

FIG. 7B.

It is clear from Table 5 that annual variation in snow depth is the main factor responsible for annual ice thickness variability. Snow depth variations alone account for almost all of the variance able to be explained by the model, highlighting the dominant insulating effect of snow in the Canadian High Arctic landfast ice environment. In contrast, the model configuration where only air temperature varied accounted for, at most, only 4% of the variance. On the surface, this result appears somewhat surprising given the well-demonstrated relationships between accumulated freezing degree-days and the thickness of landfast ice. However, it should be noted that these relationships are *climatological*, while this investigation is concerned with the factors responsible for *interannual variability* in ice thickness. An examination of climatological relationships between ΣFDD and ice thickness (e.g., Parker, 1987) reveals considerable scatter about fitted curves, with the scatter typically growing with time during the ice season. Thus, while the mean air temperature and snow depth are important factors in determining the average ice thickness for a given site, annual variability in snow cover is the key factor determining interannual variability in maximum ice thickness in the Canadian High Arctic.

From Figure 8 it can be seen that the model was able to reproduce the general features of the interannual variability in maximum ice thickness at all four sites. The root mean squared error (*rmse*) was close to 15 cm at Resolute, Mould Bay and Eureka, but it was noticeably higher (18 cm) at the Alert sites. The main reason for the poorer performance at Alert Inlet was the systematic underprediction of ice thickness during the first half of the 1970s and 1972 in particular. Similar

TABLE 5. Ice growth model performance statistics (cm)

		Air temp fixed		Snow depth fixed		Both varied	
	No. yrs	*rmse*[1]	*r*	*rmse*	*r*	*rrmse*	*r*
Alert Inlet	32	19.3	0.56	21.3	0.19	18.4	0.61
Alert (Dumbell Lake)	29	19.1	0.55	19.2	0.14	18.4	0.58
Eureka	32	15.7	0.65	20.5	0.20	14.9	0.70
Mould Bay	31	15.8	0.65	19.4	0.00	15.6	0.66
Resolute	34	14.2	0.75	21.7	0.02	13.7	0.75

[1]Root mean squared error.

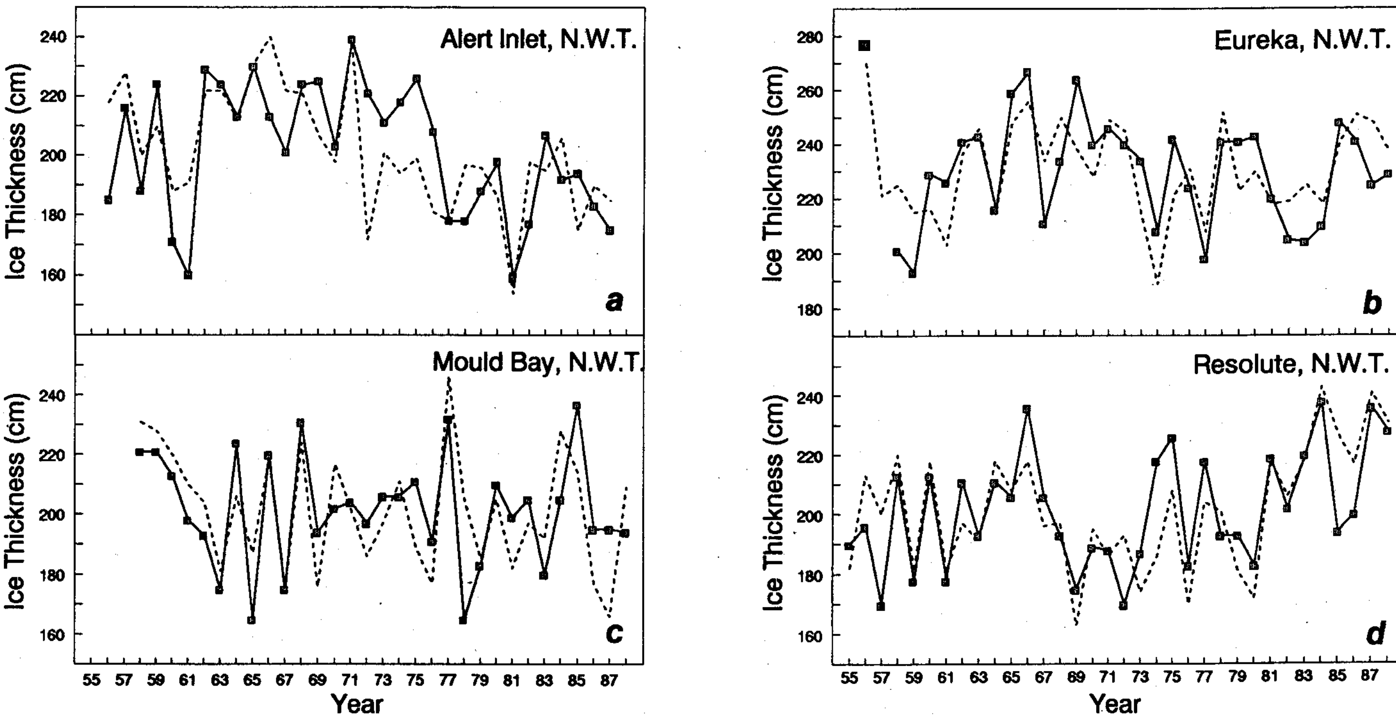

FIG. 8. Comparison of observed (solid) and predicted (dashed) maximum fast ice thickness at a) Alert Inlet, b) Eureka, c) Mould Bay and d) Resolute Bay.

large model underpredictions were also observed at Dumbell Lake, which precludes changes in ocean heat flux or salinity as a possible explanation. Inspection of the snow data for this period indicated significant amounts of snow on the ice early in the growth season. For example, 30 cm of snow was measured on the ice at Alert Inlet in early October 1972, and snow depths of 10-15 cm were measured in September 1973 and 1974. These findings suggest that early heavy snow accumulations on the ice promoted slushing events, which altered the thermal properties of the surface layer. It now becomes evident that *seasonal* variations in snow depth have important implications for interannual variation in ice thickness and that the linear snow growth profile assumed in the model is an oversimplification.

To check whether there was any systematic source unaccounted for by the model, a spectral analysis of model residuals (observed minus predicted) was carried out following the method outlined earlier. While all of the residual series were random at a 95% confidence interval, there was evidence of a five-year cycle in the residuals at several at the sites. Correlation of model residuals with ΣFDD and mean snow depth revealed a significant positive correlation with mean snow depth at both Alert sites, Mould Bay and Resolute. The correlations explained an additional 14-30% of the variance in maximum ice thickness. The positive correlation with snow depth suggests the snow-related variance not included in the model may be related to infiltration of water into the snow layer.

Unfortunately, ice and snow data are not recorded regularly enough in the early part of the ice growth season to permit a detailed investigation of the interannual variability in the flooding criteria presented earlier. However, decadal variation in flooding potential was computed to gain some idea of the temporal variability. The results in Table 6 clearly indicate that potential flooding conditions can exhibit considerable temporal variability. The effect of the trend toward lower

TABLE. 6. Decadal variation in flooding potential (%)

	Alert Inlet	Eureka	Mould Bay	Resolute
1950-59	2.2	0.0	0.0	3.3
1960-69	4.3	0.0	0.0	2.3
1970-79	4.2	0.3	2.5	1.3
1980-89	1.6	0.6	0.6	0.0

snow depths at Resolute is clearly visible as a corresponding trend to lower flooding potential, and the 1960s and 1970s show up as periods of higher flooding potential at Alert. The flooding potential at Alert Inlet during the 1972-76 period of poor model performance was 5.5%. These results further highlight the important role of snow cover and snow cover processes in determining interannual variability in landfast ice thickness: the combined influence of snow processes is estimated to explain around 70% of the variance in maximum landfast ice thickness.

Landfast Ice Thickness under a Changed Climate

The above model can be used to investigate how the High Arctic landfast ice regime may respond to changes in air temperature and precipitation that are anticipated to result from greenhouse gas-induced global warming. Climate change impact assessments typically employ scenarios (plausible future climate states derived from historical analogues, instrumental data or GCM output) as input to a model or transfer function. Fowler and de Freitas (1990) argue that an inherent weakness of the scenario approach is that it can obscure the inherent sensitivity of biophysical and societal systems. They prefer the use of a "response surface," which represents the sensitivity of a process to changes in driving variables. A response surface is defined as a two-dimensional representation of a three-variable data set showing the effect of changes in one response variable to joint changes in two driving climate variables. This is essentially a form of sensitivity analysis that has been widely used in hydrological modelling but only rarely used in climate change impact assessment (Fowler and de Freitas, 1990).

A response surface of maximum fast ice growth was constructed in Figure 9 using the base climate for Alert. Alert mean monthly air temperature data for the period 1951-80 were used, and the mean snow density was set at 338 $kg \cdot m^{-3}$. Temperature changes were assumed to be uniform over all months. Changing air temperature in the model has the combined effect of modifying the length of the ice growth season, as well as the rate of heat loss through the ice-snow layer. Mean snow depth was varied in 5 cm increments from 0 to 40 cm. The large solid box represents the modelled fast ice regime at Alert based on the maximum range in mean snow depth and air temperatures observed over the period 1956-87. The current climate is estimated to produce a mean maximum ice thickness of 196 cm, varying over a range of 159-241 cm. The observed mean maximum ice thickness at Alert is 202 cm, with a range of 159-239 cm. This compares very favourably with the model. The solid lines represent isopleths of maximum ice thickness for 150, 200 and 250 cm. The near vertical slope for low snow depth values reflects the initial strong sensitivity of ice growth to the addition of snow. This sensitivity decreases somewhat for additional snow, but the overall steepness indicates a strong snow depth dependence (compared to a horizontal line, which would indicate maximum ice thickness was only temperature dependent).

A significant advantage of a response surface is its flexibility. For example, a number of different scenarios can be investigated on a single diagram, and scenarios can be readily updated. Most important, the response surface will show if the sensitivity of the response variable is changed under a new climatic regime. This is demonstrated in Figure 9, where an arbitrary 3°C warming and 25% increase in precipitation are assumed. If we assume that climate variability does not change under the new climate, the dashed boxes represent the new fast ice regime for Alert. For the above scenario the model indicates a 16% decrease in mean maximum ice thickness from 196 to 165 cm and a new range in maximum ice thickness of 132-205 cm. We can also see from the response curves that the new fast ice regime is, on average, more sensitive to air temperature variations than the base climate. The latter important information cannot be derived from individual scenarios results. The predicted ice growth season decreased approximately five days per °C increase in mean annual air temperature. It should be stressed that these results pertain to landfast ice and that the model does not account for important processes such as slushing. Snow cover effects are less important in offshore pack ice, where much of the snow is blown into leads (S. Prinsenberg, pers. comm. 1991). However, for highly consolidated and multi-year ice, changes in snow cover could still be expected to play a significant role in modifying through-ice heat transfer. With respect to slushing, it could be hypothesized that slushing potential may increase under a warmer, snowier arctic climate, and the subsequent modification of surface thermal properties would offset, to some extent, a shorter ice season and warmer temperatures. Landfast ice thickness may therefore be less sensitive to climatic fluctuations than indicated by the response surface in Figure 9.

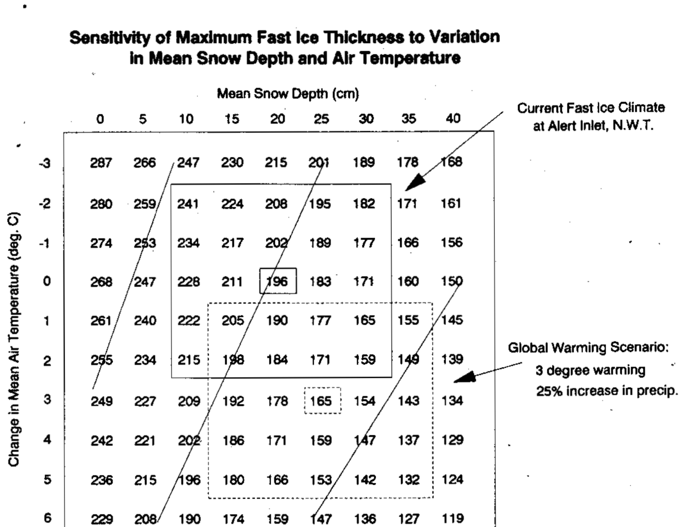

FIG. 9. Response surface of maximum fast ice thickness at Alert following Fowler and de Freitas (1990).

CONCLUSIONS

The main conclusion of this study is that the interannual variability of maximum landfast ice thickness in the High Arctic is closely tied to annual and decadal-scale variations in snow depth. The dominant snow effect was insulation, but snow load-induced flooding of the ice surface was also found to be an important process, even in sites as far north as Alert. The failure of a simple one-dimensional heat flow model at Alert in 1972 emphasized the fact that seasonal variation in snow cover has important consequences for the interannual variability of ice thickness. Further efforts to model interannual variability in landfast ice thickness will need to take slush formation and seasonal changes in snow density into account.

The large temporal and spatial variability of landfast ice thickness, taken together with its observed dependence on seasonal and decadal-scale fluctuations in snow accumulation, suggests landfast ice thickness is an unlikely candidate for early detection of any global warming signal. It was thus hardly surprising that little evidence was found for a systematic ice thinning trend in landfast ice thickness in the Canadian High Arctic, especially in light of the relatively short history of ice thickness and snow depth measurements. However, continued monitoring of landfast ice thickness is critical for further understanding of the internal variability of the arctic climate system. The use of landfast and lake ice thickness monitoring sites in close proximity, such as Alert Inlet and Dumbell Lake, is considered extremely valuable for verifying the homogeneity of data and for assessing the importance of ocean heat flux and salinity effects.

These landfast ice results cannot readily be extrapolated to the offshore sea-ice regime. However, the 4-6 and 8-10 year cycles observed in the landfast ice thickness data have also been observed in arctic sea-ice extent (Mysak and Manak, 1989) and in Beaufort Sea oceanographic conditions (Fissel and Melling, 1990). It is therefore not inconceivable that fluctuations on these scales will also be found in arctic sea-ice thickness. This observation reinforces the conclusion of Wadhams (1990) on the need for more extensive long-term monitoring of arctic ice thickness if a thinning trend is to be separated from the interannual variability of the sea-ice system.

Ice extent, cyclone movement and precipitation changes have recently been linked together into a negative feedback loop for the Arctic (e.g., Zakharov, 1990; Mysak *et al.*, 1990) whereby decreased ice extent eventually results (through increased cyclone frequencies and precipitation) in a positive freshwater balance in the Arctic Ocean and in higher ice extents. The main role of precipitation in this loop is the freshening of the Arctic Ocean. The results of this investigation indicate that fluctuations in landfast ice thickness may also be tied into this precipitation-driven cycle. While such feedback mechanisms are highly speculative in nature, they serve to highlight the sensitivity of the arctic basin and adjacent waters to precipitation variation.

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