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The Sensitivity of the Arctic Climate System to Snowfall:
Evidence from the Canadian High Arctic

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ABSTRACT

The sensitivity of the Arctic climate system to increasing snowfall was investigated using climate and landfast ice data from the Canadian High Arctic. Analysis of ice freeze-up and break-up data from several sites showed that additional snowfall in the fall period was associated with delayed freeze-up, while additional snowfall in the spring period was associated with earlier break-up. The observed net effect of additional snowfall was, therefore, to increase the open water period. Analysis of snowfall-temperature sensitivity revealed significant variability at seasonal and interdecadal time scales, consistent with the concept of a self-sustaining climate cycle in the Arctic as proposed by Mysak et al. (1990). Simplified energy balance models of the Arctic climate system such as Ledley (1993) do not include many of the processes and feedbacks required to simulate this variability, and the evidence suggests this may result in an exaggerated cooling response to increased precipitation.

Key words: Arctic climate, snowfall, freeze-up/break-up

INTRODUCTION

General Circulation Model simulations of the global climate for a doubled-CO_2 scenario typically show an amplified polar warming associated with a positive feedback from melting snow and ice. Much of this response is related to a strong positive climate feedback mechanism generally referred to as the "snow/ice albedo feedback" (Curry et al., 1994). However, recent research has indicated there may also be a number of important negative feedback loops in polar regions. For example, ice extent, cyclone movement and precipitation changes have been linked together into a negative feedback loop in the Arctic (Zakharov, 1990; Mysak et al., 1990) whereby decreased ice extent eventually results (through increased cyclone frequencies and precipitation) in a positive fresh water balance in the Arctic Ocean, and higher ice extent. Curry et al. (1994) show that the magnitude of the sea ice albedo feedback is critically dependent on physical processes such as melt-ponding, leads, divergence, and the temperature and salinity dependence of the thermal conductivity and specific heat capacity of ice. They also demonstrate that models which correctly replicate the current ice thickness climate of the polar regions may contain an incorrect ice-albedo feedback if important physical processes, such as melt ponding, are not included.

The results of modelling and empirical studies suggest that Arctic warming is associated with increased precipitation. Ledley (1991) showed that the addition of snow at the ice surface introduces a number of competing effects into the climate system: (1) snow acts as an insulator, keeping sea ice warm and thin; (2) snow has a lower volumetric specific heat and heat of fusion than sea ice, causing it to cool, warm, and melt more readily than ice; and (3) snow has a higher albedo than sea ice. Ledley found that the first two effects resulted in less energy being needed to melt sea ice, which resulted in longer ice-free periods during the summer. The third effect

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caused a reduction in absorbed solar radiation, and a cooling of the climate system. According to Ledley (1991), this third effect is dominant, so the addition of snow results in a cooling of the climate.

Ledley (1993) used a coupled energy balance climate-thermodynamic sea ice model (subsequently referred to as CCSI) to further investigate the impact of changes in precipitation rate on sea ice and climate. The results showed that the general effect of a thin layer of snow on the sea ice surface was to thin the sea ice. However, as precipitation increased, it eventually reached a point where it survived the summer season, contributing to a thickening of the sea ice, a cooling of the climate system from a higher surface albedo, and less turbulent heat transfer from the ocean to the atmosphere. One particularly interesting model result was that the addition of snow delayed break-up and caused earlier formation of new ice, thus reducing the period of open water. These findings imply the existence of a strong negative feedback mechanism in the Arctic to the warming and increased snowfall expected from an enhanced greenhouse effect.

The objective of this paper is to provide further insight into the sensitivity of the Arctic climate system to changing precipitation. In particular, the paper will focus on the relationship between air temperature and snowfall, and the role of snowfall in the freeze-up/break-up process. This represents an extension of previous work (Brown and Cote, 1992) which highlighted the dominant role of snow cover in the annual variability of maximum fast ice thickness.

DATA

The climate data used in this study consisted of monthly values of total snowfall and mean daily temperature observed at climate and synoptic stations in the Canadian Arctic. The snowfall data are obtained from ruler measurements of fresh snowfall. These data are likely to underestimate precipitation in the Arctic because of high frequencies of trace snowfall amounts (Metcalfe and Goodison, 1993). However, the measurement method has been applied consistently over the entire period of record.

Freeze-up/break-up data were obtained from the AES Ice Centre for stations in the high Arctic which also had weekly ice thickness measurements. These data consist of dates of first permanent ice (FPI - date on which new ice first formed on the water surface and did not melt completely), complete freeze over (CFO - earliest date on which the water body is completely covered by ice), and water clear of ice (WCI - earliest date water is completely free of all floating ice). The data also include additional information such as the date when ice was safe/unsafe for traffic, and whether ice break-up was incomplete. Unfortunately, the latter information was found to be frequently missing when the WCI date was missing, making it difficult to know whether ice had cleared or not. The database is subjective, by definition, and variables such as CFO and WCI probably have rather low signal-to-noise ratios in the high Arctic where interannual variability in freeze-up/break-up dates is rather small.

Monthly mean cloud cover data were obtained from Resolute, Eureka and Alert for inclusion in multiple regression analysis of freeze-up/break-up data. These data were derived from synoptic observations of cloud cover taken every 3 or 6 hours. Maximum fast ice thickness data were derived from the digital database of weekly fast ice thickness data maintained at the AES Ice Centre.

METHOD OF ANALYSIS

The snowfall-temperature relationship (ΔSfall/ΔT) was analyzed on a regional basis for the Canadian High Arctic, which was defined for this study as the area of Canada north of 70°N. This included the eight stations shown in Figure 1. Analysis of seasonal variability in ΔSfall/ΔT was carried out by computing monthly values of ΔSfall/ΔT from linear regression analysis of total monthly snowfall and mean monthly air temperature for each station with at least 25 years of data in the period 1961-90. Monthly station values were then averaged over the study area to obtain a regional average. The units in this analysis were cm/°C. Interannual variability in ΔSfall/ΔT was investigated by constructing regionally-averaged time-series of seasonal snowfall and air temperature anomalies. To take account of variability in local climates across the study area, station temperature and precipitation data were converted to standardized anomalies (z_i) with respect to a 1961-80 reference period following Palutikof et al. (1984):

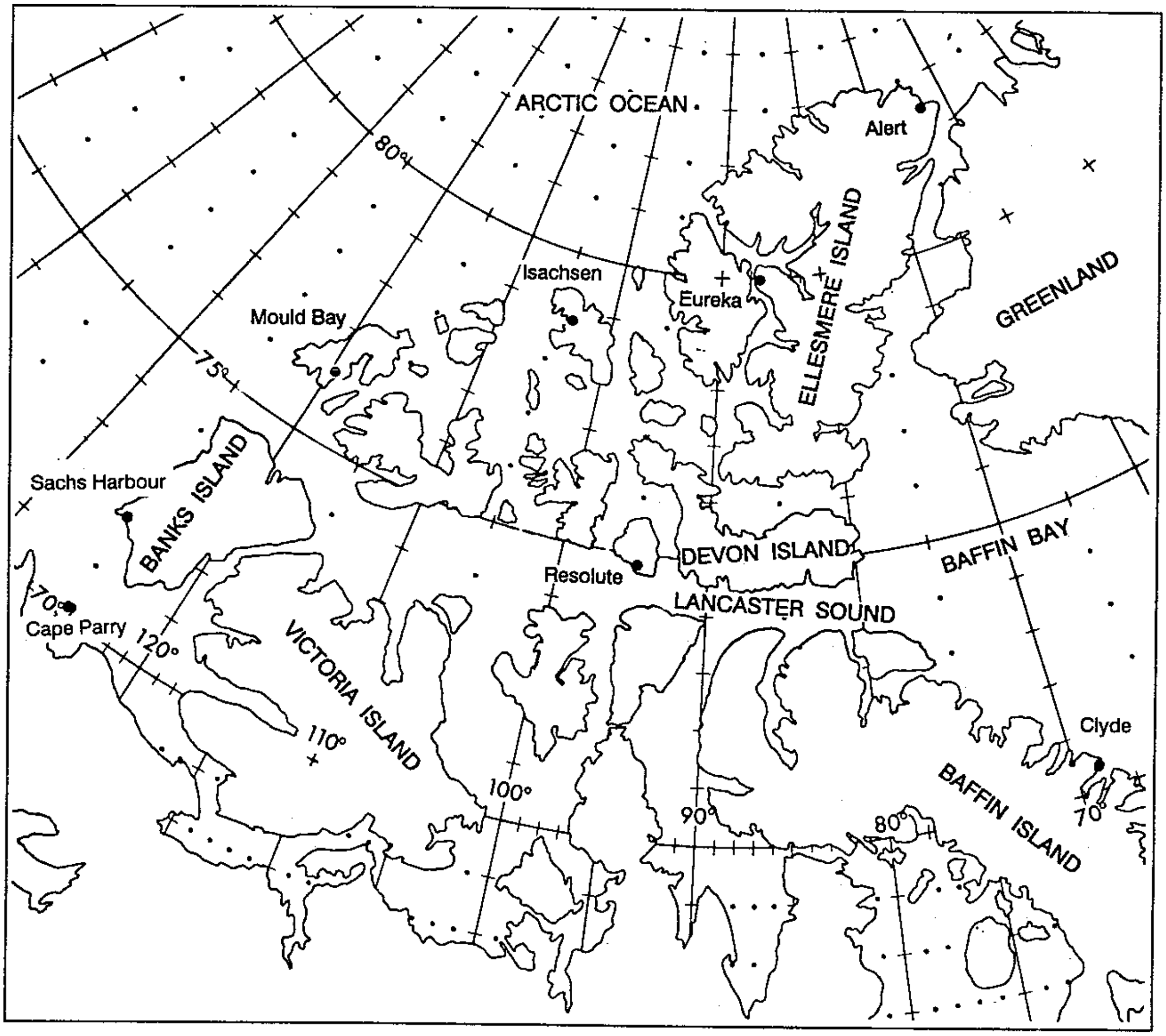

Figure 1. Study area showing location of stations included in the analysis.

$$z_i = (x_i - x_{ref}) / s_{ref}$$

where x_i is the observed data in year i, and x_{ref} and s_{ref} are the reference period mean and standard deviation. Standardized anomalies were then averaged over all stations in the study area to derive regionally-averaged anomaly series for regression analysis. The data were averaged over the entire ice growth year (August-July), and for the fall (August-January) and spring (February-July) half-year periods. Plots of annual variability in regional snowfall and temperature are shown in Figure 2. The units for ΔSfall/ΔT computed with these data are dimensionless since both snowfall and temperature are normalized.

Freeze-up/break-up relationships were investigated at Resolute, Eureka and Alert. These three stations provide a N-S transect covering 1100 km from 75° to 83°N. In addition, two of these stations (Alert and Resolute) were observed by Brown and Cote (1992) to have experienced quite different trends in maximum ice thickness and snow cover over the last 20 years. Stepwise multiple linear regression was used to investigate the sensitivity of CFO, WCI and the period of open water (OPEN) to May-October monthly values of mean air temperature (T5 to T10), snowfall (S5 to S10), cloud cover (CL5 to CL10), maximum ice thickness prior to break-up (IMAX), and total annual snowfall (STOT) over the previous ice growth season (August-July). These variables were selected on the basis of regression results obtained by Da Silva (1985) for Canadian Arctic stations, and recommendations provided by Skinner (1986). Skinner (1992) considered CFO to be more reliable than FPI. To investigate this, both FPI and CFO were included in the analysis, along with the corresponding two definitions of the duration of the open water season i.e. OPEN1 (CFO-WCI) and OPEN2 (FPI-WCI). Unfortunately, only a small number of complete break-up cases were documented at Alert (11 cases), which significantly reduced the number of degrees of freedom at that site. A summary of the data is provided in Table 1.

SNOWFALL-TEMPERATURE RELATIONSHIP

In Ledley's (1993) CCSI model, the snowfall-rate is defined as a function of surface air temperature such that as temperature decreases, the snowfall rate decreases (i.e. ΔSfall/ΔT is positive). In the CCSI model, this assumption results in any warming being counteracted by an enhanced albedo feedback from increased snowfall. One of the reasons the model is considered to be so sensitive to additional precipitation is because it employs a rather simple specification of surface albedo (snow albedo ranges from 0.84 to 0.74 over the melt period), and there is no treatment of melt ponds. According to Curry et al. (1994), this process contributes significantly to a *positive* feedback in response to warming. In addition, the minimum summer ice albedo used in the CCSI model (0.51) appears to be high compared to recently published data from Robinson et al. (1992) which show that mean area-averaged surface albedo decreases to values of under 0.45 in summer over the Arctic basin. Semtner (1976) showed his sea ice model to be highly sensitive to a decrease in summer albedo, with a 0.1 drop causing substantial reductions in ice thickness (the thermodynamic sea ice model used in the CCSI model is based on Semtner, 1976).

Table 1. Ice freeze-up/break-up statistics for the 1961-90 period. WCI and CFO are in Julian days, while OPEN1 is in days. Nobs is the total number of observations available at each site.

	Resolute			*Alert*			*Eureka*		
	WCI	CFO	OPEN1	WCI	CFO	OPEN1	WCI	CFO	OPEN1
Mean	217.1	273.9	57.6	211.3	250.3	42.4	210.8	259.5	49.0
SD	10.8	10.2	15.1	11.0	7.9	13.6	14.8	6.5	18.3
Nobs	23	35	19	12	28	11	23	36	20

The assumption that ΔSfall/ΔT is positive was investigated by looking at both seasonal and secular variability in ΔSfall/ΔT. Seasonal variability in ΔSfall/ΔT was computed from linear regression analysis of monthly snowfall and mean air temperature data for months where snowfall was non-zero. The results were averaged over all stations in the Canadian High Arctic (north of 70°N), and also for the eastern Arctic (60-90°N, 50-90°W) to look at regional variability in the mean values. Analysis of the frequency distributions of monthly total snowfall data at Alert and Resolute showed that the data were, for the most part, normally distributed.

Mean monthly values of ΔSfall/ΔT (Fig. 3) revealed evidence of a clear seasonal shift in ΔSfall/ΔT from negative values in the August-September period, to positive values in the November-April period in both regions. The

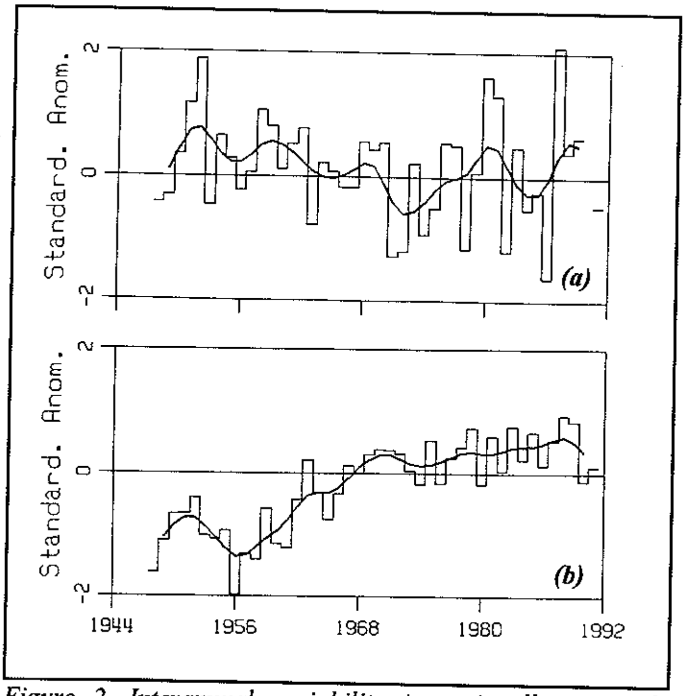

Figure 2. Interannual variability in regionally-averaged, normalized values of (a) annual mean air temperature and (b) total annual snowfall. The heavy line is the result of passing a 9-term binomial filter.

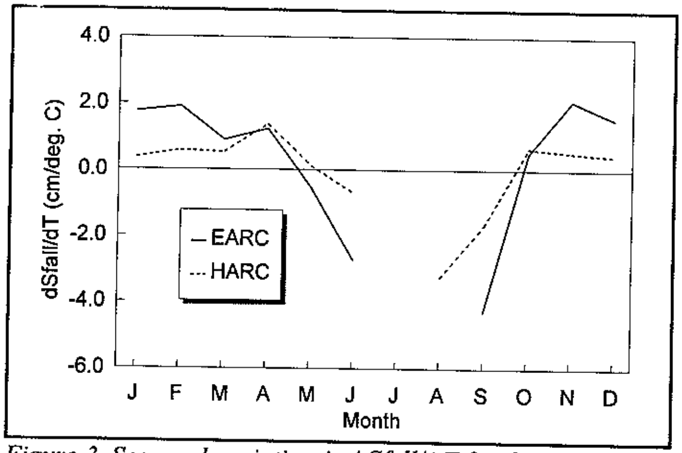

Figure 3. Seasonal variation in $\Delta Sfall/\Delta T$ for the High Arctic (HARC) and Eastern Arctic (EARC) regions for the 1961-90 period.

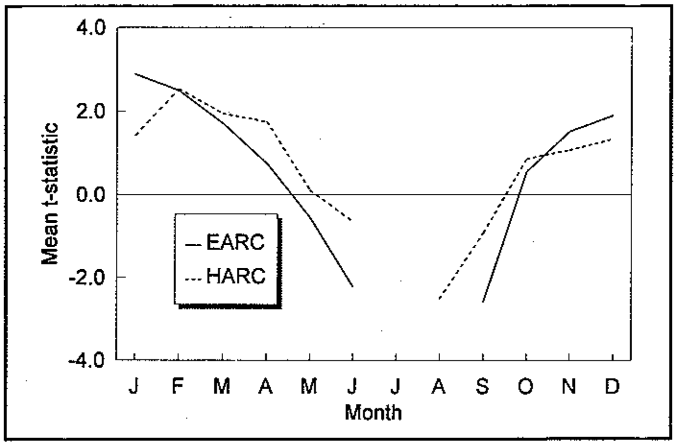

Figure 4. Seasonal variation in the average t-statistic corresponding to the ΔSfall/ΔT results presented in Fig. 3.

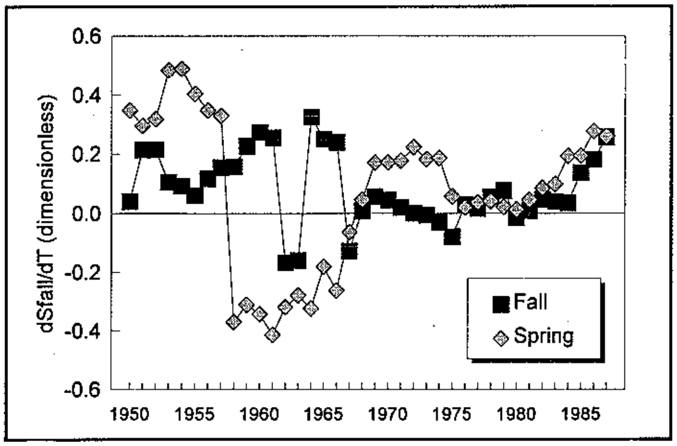

Figure 5. Secular variability in ΔSfall/ΔT for the High Arctic as computed from a running 11-year block of data. ΔSfall/ΔT is dimensionless in this instance, as both air temperature and snowfall are normalized.

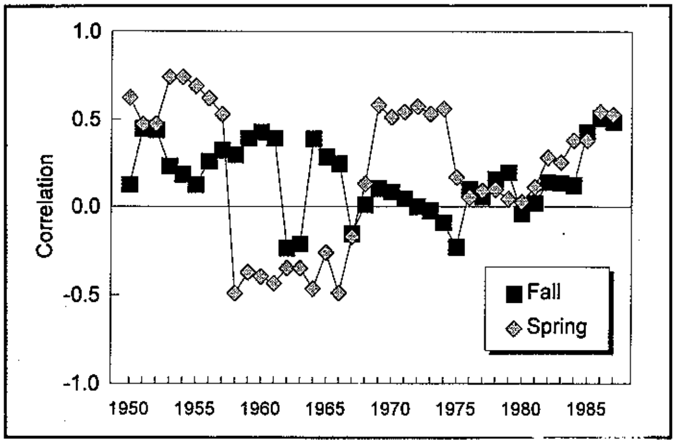

Figure 6. Secular variability in the correlation of snowfall and air temperature for the High Arctic as computed from a running 11-year block of data. Correlations > ±0.53 are significant at the 0.05 level.

eastern Arctic region displayed a higher sensitivity than the high Arctic, which reflects its closer proximity to the Baffin Bay cyclone track. It should be emphasized that the sensitivities are very low over most of the year, and investigation of mean slope *t*-statistics (Fig. 4) revealed that snowfall and temperature were only significantly correlated ($t > \pm 2.0$) in August-September and January-February. However, the large negative values of ΔSfall/ΔT displayed in August-September in both areas is important because this period accounts for ~30% of total annual snowfall in the high Arctic. This is also the time of year when snowfall has the strongest insulating effect on ice growth (Maykut, 1978).

Secular variation in ΔSfall/ΔT was investigated by performing the regression analysis with running 11 year blocks of the normalized regional snowfall and temperature data. The 11 year period was chosen *a priori* in light of the known decadal variability in the Arctic climate system (Mysak et al., 1990). The results (Fig. 5) show clear evidence of decadal variability, particularly in the spring half of the snow and ice cover year. There is also some evidence that the seasonal responses were out of phase prior to 1975. The cyclical variation in the sign of the relationship is even more apparent in the correlation results (Fig. 6). Recent analysis of historical variability in ΔSfall/ΔT over the continental interior of North America (Brown et al., in press, 1994) revealed no evidence of cyclical variations (ΔSfall/ΔT was consistently negative).

Mysak et al. (1990) proposed a negative feedback loop for the Arctic linking cyclogenesis, precipitation, runoff, salinity, sea ice extent, oceanic stability, convective overturning, poleward oceanic heat transport and heat flux into the atmosphere. They estimated that this loop would have an approximately 20 year cycle, and that each state (high/low precipitation) would last approximately 5-9 years. The spring correlation results appear to fit the timing of this conceptual model of a self-sustaining climate cycle in the Arctic. However, there is little evidence of decadal variation in regional snowfall over the high Arctic (Fig. 2), and analysis of interannual variability in cyclone frequency over the Mackenzie Basin (Bjornsson et al., in prep., 1994) revealed no evidence of significant decadal variation. The main features observed were a significant upward trend in cyclone frequency over the last 40 years (which fits in with the observed increase in total snowfall), and significant variability at periods of 4-5 years, which appears to be linked, in part, to Pacific sea-surface temperature variability. While the available evidence suggests the Mysak et al. (1990) feedback loop is not completely adequate, the cyclical variations in precipitation-temperature relationships observed in this study are consistent with some form of decadal climate oscillation in the Arctic.

FREEZE-UP/BREAK-UP SENSITIVITY

Statistically significant (0.05 level) variables selected from the step-wise, multiple linear regression analysis are summarized in Table 2 in decreasing order of significance. The presentation of regression equations, as is the usual practice, has been expressly avoided here in light of the limited amount of data included in the analysis, the site-specific nature of regression equations, and because the purpose of this paper is to investigate sensitivity rather than demonstrate a predictive capability. The units used in the regression analysis were °C*10 for monthly mean temperature, cm*10 for monthly snowfall, cm for total annual snowfall and maximum ice thickness, and 10ths for cloud cover. FPI, CFO, and WCI were expressed as Julian days, while OPEN1 and OPEN2 were defined as days.

It is evident from the results that all the variables selected for the regression analysis are important in explaining interannual variability in freeze-up/break-up in the high Arctic. However, considerable local variation in the relative importance of the variables is also apparent. Nevertheless, there are a number of generalizations which can be made.

First, based on the amount of variance explained by the regression analysis, CFO is less noisy than FPI, which confirms the subjective assessment of Skinner (1992).

Second, air temperature and snowfall are consistently important factors in both freeze-up and break-up at all sites. The important role of air temperature has been documented in numerous empirical investigations of ice freeze-up and break-up in the Arctic (see Skinner (1992) for a review). The role of snowfall, however, has received less attention.

Third, cloud cover is only a significant factor in break-up, and the sensitivity of break-up to cloud cover is observed to change sign during the melt season, i.e. above-average cloud cover early in the melt season (May) is associated with

Table 2. Summary of significant (0.05 level) multiple regression coefficients.

Parameter	*Resolute*		*Eureka*		*Alert*	
FPI	T8	0.44	CL7	2.73	T8	0.39
	S10	0.04	T9	0.13	IMAX	-0.14
			IMAX	-0.13		
	$r^2 = 0.32$		$r^2 = 0.41$		$r^2 = 0.50$	
CFO	T8	1.15	T9	0.18	T8	0.32
	S8	0.10	IMAX	-0.17	T9	0.23
	IMAX	0.20	S8	0.07	STOT	-0.06
	$r^2 = 0.51$		$r^2 = 0.71$		$r^2 = 0.58$	
WCI	T6	-0.38	T6	-0.52	S8	-0.07
	STOT	-0.28	CL7	7.42	T6	-0.37
	CL5	-5.07			S7	-0.05
	IMAX	0.19				
	$r^2 = 0.64$		$r^2 = 0.58$		$r^2 = 0.61$	
OPEN1 (WCI-CFO)	T7	0.71	T6	0.68	S7	0.16
	CL5	6.91	CL7	-8.88	S8	0.12
	CL8	-9.33			T7	0.83
	STOT	0.17				
	$r^2 = 0.74$		$r^2 = 0.65$		$r^2 = 0.74$	
OPEN2 (WCI-FPI)	STOT	0.37	T6	0.50	S8	0.17
	T7	0.74	T7	0.82	S7	0.17
	T8	0.60				
	$r^2 = 0.69$		$r^2 = 0.60$		$r^2 = 0.62$	

enhanced break-up and a longer open water period, while above-average cloud cover during July-August is associated with delayed break-up. The former response is likely linked to the advection of warm air (and cloud) from the south, with enhanced melt from warmer air temperatures and reduced radiative cooling. For example, Barry and Jacobs (1974) note that during the 1973 break-up season along eastern Baffin Island, there was frequent strong advection of warm air from the south which resulted in rapid ablation, even though there was an unusually heavy snowpack and high number of cloudy days. The inverse cloud cover response in the later part of the melt season is likely linked to a reduction of incoming solar radiation during the period of high insolation and strong radiative melting.

Fourth, while there is obviously considerable local variability in the importance of snowfall in the freeze-up/break-up process, snowfall appears to be associated with delayed freeze-up (positive relationships between snowfall and CFO at Resolute and Eureka) and earlier break-up (negative relationship between snowfall and WCI at Alert and Resolute). The former response is related to the high sensitivity of thin ice to snow cover (e.g. Jacobs et al., 1975). Heavy snowfall early in the period of ice formation greatly reduces the rate of ice formation, and increases potential for flooding, both of which retard the establishment of a complete ice cover. The link between snowfall and earlier break-up is likely related to the advection of warmer air from the south. The net effect of snowfall is, therefore, to *increase* the "open water" period as demonstrated by the positive relationships between snowfall and open water period at both Resolute and Alert. It would be inappropriate to generalize from these few sites to the entire Arctic Basin. However, the results are, for the most part, consistent with the physics of ice growth and the spring climate of the Arctic region, and suggest that the precipitation-albedo feedback in the CCSI model may be exaggerated.

Fifth, maximum ice thickness at the start of the melt season appears to be more important in freeze-up than break-up. This was something of a surprise since Bilello (1977) showed that ice decay rates were relatively constant from one year to the next, which should mean that the time required to completely melt ice is a strong function of the initial ice thickness. This hypothesized positive relationship between IMAX and WCI was only observed at Resolute. Negative relationships between IMAX and freeze-up statistics were observed at Eureka and Alert (heavy ice associated with earlier freeze-up) which could be explained through cooler summer water temperatures in years where ice was heavy.

CONCLUSIONS

A recent climate model simulation of the sensitivity of the Arctic to precipitation increases indicated that additional snow cooled the climate system, resulting in delayed ice melt, and earlier formation of new ice (Ledley, 1993). However, a sensitivity analysis of ice freeze-up and break-up data from several sites in the Canadian High Arctic did not support this response, at least for the range of values encountered over the last ~30 years. The observed data indicated that additional snowfall in the fall period was associated with delayed freeze-up, while additional snowfall in the spring period was associated with earlier break-up. The observed net effect of snowfall was, therefore, to increase the open water period, the opposite response to that suggested by the CCSI model.

The snowfall-temperature relationship employed in the CCSI model was considered to be a contributing factor to the strong cooling response of the model to increased precipitation. The relationship used in the model results in snowfall decreasing as temperature decreases ($\Delta Sfall/\Delta T$ is positive), which counteracts warming through the strong albedo feedback characterizing the model's response. Analysis of snowfall-temperature sensitivity in the Canadian High Arctic revealed that the sign and magnitude of $\Delta Sfall/\Delta T$ varied seasonally, and that it also exhibited strong inter-decadal variability, particularly in the spring half of the snow and ice cover year. These results are consistent with the concept of a self-sustaining climate cycle in the Arctic proposed by Mysak et al. (1990). The CCSI model is a simplified energy balance model which does not include many of the linkages of the fully-coupled atmosphere/sea ice/ocean system. In addition, it does not include key processes, such as melt-ponding, which Curry et al. (1994) showed to be of critical importance in determining ice-albedo feedback. Without these processes and linkages, it appears the CCSI model may exaggerate the cooling response of the Arctic to increased precipitation.

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