Influence of the Arctic Circumpolar Vortex on the Mass Balance of Canadian High Arctic Glaciers

ALEX S. GARDNER AND MARTIN SHARP

Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada

(Manuscript received 25 July 2006, in final form 15 November 2006)

ABSTRACT

Variability in July mean surface air temperatures from 1963 to 2003 accounted for 62% of the variance in the regional annual glacier mass balance signal for the Canadian High Arctic. A regime shift to more negative regional glacier mass balance occurred between 1986 and 1987, and is linked to a coincident shift from lower to higher mean July air temperatures. Both the interannual changes and the regime shifts in regional glacier mass balance and July air temperatures are related to variations in the position and strength of the July circumpolar vortex. In years when the July vortex is "strong" and its center is located in the Western Hemisphere, positive mass balance anomalies prevail. In contrast, highly negative mass balance anomalies occur when the July circumpolar vortex is either weak or strong without elongation over the Canadian High Arctic, and its center is located in the Eastern Hemisphere. The occurrence of westerly positioned July vortices has decreased by 40% since 1987. The associated shift to a dominantly easterly positioned July vortex was associated with an increased frequency of tropospheric ridging over the Canadian High Arctic, higher surface air temperatures, and more negative regional glacier mass balance.

1. Introduction

Global climate models consistently predict that climate warming associated with increasing atmospheric concentrations of greenhouse gases will be largest in northern high latitudes (Houghton et al. 2001; Johannessen et al. 2004). The response of Arctic glaciers, ice caps, and ice sheets to this warming may therefore be a significant influence on the eustatic component of global sea level rise. In the long term, changes in the volume of the Greenland Ice Sheet are likely to have the greatest impact on sea level, but in the short term (the next century or so) contributions from ice caps and glaciers may be more significant (Meier 1984; Houghton et al. 2001; Raper and Braithwaite 2006). There is therefore considerable interest in characterizing the mass balance of these smaller ice masses and their relationship to climate trends and variability (Cogley et al. 1996; Dowdeswell et al. 1997; Dyurgerov and Meier 1997, 2000; McCabe et al. 2000; Braithwaite and Raper 2002; Hagen et al. 2003; Dyurgerov and Meier 2005; Dyurgerov and McCabe 2006).

In this paper, ~40-yr records of the surface mass balance of four ice masses in the Canadian High Arctic (>75°N) and their relationship to regional temperature trends and Arctic atmospheric circulation changes are analyzed. The Canadian High Arctic is a region of particular importance for this type of study because it contains the largest area of land ice in the world outside Greenland and Antarctica, and has the highest density of long-term glacier mass balance records in the Arctic.

The records used come from four ice masses in the Queen Elizabeth Islands (QEI), Nunavut, Canada: Devon Island Ice Cap, Meighen Ice Cap, Melville Island South Ice Cap (Koerner 2002; Dyurgerov and Meier 2005), and White Glacier, on Axel Heiberg Island (Cogley et al. 1996; Dyurgerov and Meier 2005) (Fig. 1). All four glaciers are located in the "polar desert" climatic region, where annual precipitation is often <200 mm, with minimal interannual variability. Surface air temperatures (SATs) over glaciers in this region only exceed the freezing temperature during two–three months of the year. For the four glaciers examined, variability in summer (June–August) mass balance accounts for 93%–98% of the variation in annual mass balance. This indicates that summer melt has

Corresponding author address: Alex Gardner, Department of Earth and Atmospheric Sciences, University of Alberta, 1-16B Earth Sciences Building, Edmonton, AB T6G 2E3, Canada.
E-mail: alexg@ualberta.ca

DOI: 10.1175/JCLI4268.1

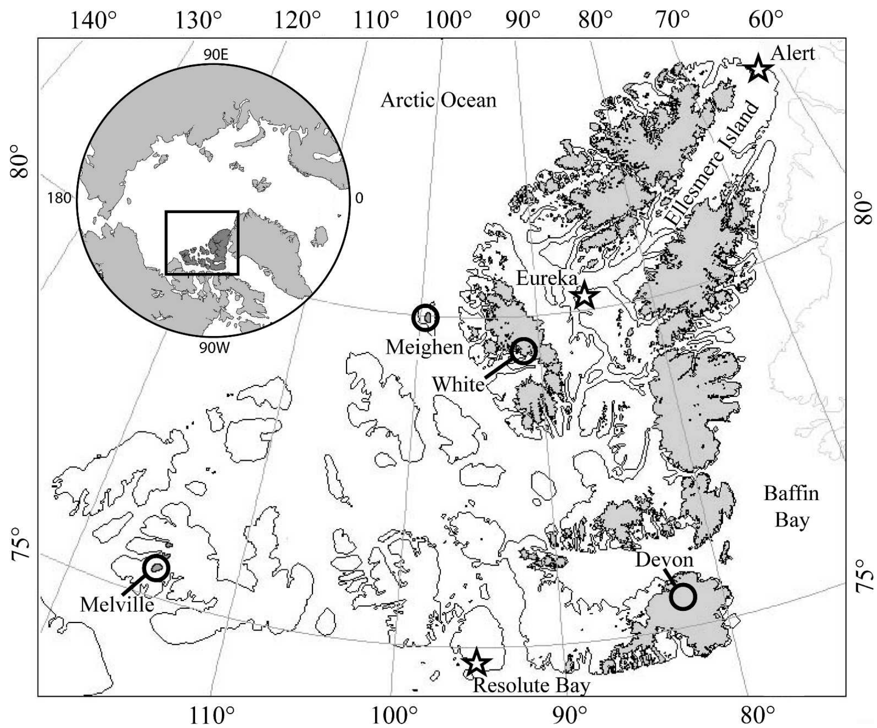

FIG. 1. Canadian High Arctic: Locations at which long term glacier mass balance records have been collected (circles) and locations of long term Environment Canada meteorological stations (stars).

a dominant influence on variability in both the summer and annual mass balances. This allows variability in annual mass balance to be used as a measure of summer climate influences on glaciers and ice caps in the Canadian High Arctic.

Previous studies of glacier mass balance in the Canadian High Arctic (Meier 1984; Alt 1987; Dowdeswell et al. 1997; Dyurgerov and Meier 1999; Braun et al. 2004; Dyurgerov and McCabe 2006) have documented trends in mass balance, but only Alt (1987) has attempted to explain the variability in annual mass balance in terms of synoptic-scale climatic forcing. Building on previous studies of synoptic climate controls on the mass balance of the Devon Island (Alt 1978) and Meighen Ice Caps (Alt 1979), Alt (1987) identified the synoptic conditions associated with extreme mass balance years on three ice masses in the QEI: the Meighen Ice Cap, Devon Island Ice Cap, and White Glacier. By examining surface and upper-air synoptic charts and climatic parameters over a 16-yr period (1960–76), Alt identified the following three sets of synoptic conditions associated with extreme mass balance years:

(i) high melt conditions, associated with the intrusion of a ridge from the south into the QEI at all levels in the troposphere;
(ii) melt suppression conditions, associated with the maintenance of a deep, cold trough across Ellesmere Island; and
(iii) summer snow accumulation conditions, which occur when cold polar lows track south and southeast across the QEI from the Arctic Ocean.

These three situations were related to differences in the position and shape of the July 500-mbar circumpolar vortex (Alt 1987). This midtropospheric feature consists of a cyclonic system with strong winds rotating counterclockwise about the cold polar air mass in its center, and is widely recognized as being the dominant factor in Arctic summer atmospheric circulation (Maxwell 1980). Unlike the stratospheric circumpolar vortex, which breaks down in summer, the tropospheric vortex, although weaker in summer, is present year-round (Serreze and Barry 2005). On a daily time scale, the July 500-mbar circumpolar vortex can split into several centers, spawning smaller cyclones that often move in a westerly direction around the pole. On a monthly time scale, the July mean polar vortex is most often characterized by a single, well-defined annular geopotential low with its center located between 80° and 90°N or by two weaker cyclonic systems with one system located near the pole and the other located over Baffin Bay.

Glaciers in the Canadian High Arctic have experienced a sharp reduction in mass balance since the late 1980s (Dyurgerov and McCabe 2006). In the work presented here, we investigate whether the relationships recognized by Alt (1987) can be used to explain this marked change in regional glacier surface mass balance. In particular, this research aims to characterize the interannual variability in the July 500-mbar circumpolar vortex and to define its relationship to both interannual and longer-term changes in the mass balance of glaciers in the Canadian High Arctic.

2. Methods

Long-term (1963–2003) mass balance records for the four target ice masses in the Canadian High Arctic were obtained from syntheses of global glacier mass balance (Dyurgerov 2002; Dyurgerov and Meier 2005). Missing mass balance records for White Glacier and the Devon Island Ice Cap from 2002 and 2003 were obtained from the World Glacier Monitoring Service (IAHS/UNESCO 2005) and R. M. Koerner (2006, personal communication), respectively. Glacier mass balance measurements are made by monitoring a network of stakes drilled into the glacier ice and firn in both the accumulation and ablation areas. Measurements are made in spring, before the onset of summer melt. In the ablation area, the required measurements include the change in stake height, and the depth and density of the snowpack overlying glacier ice. In the accumulation area, snow depth is measured to the dense melt surface formed at the end of the previous summer and, in addition to measurements of stake height and snow density, it is necessary to estimate the fraction of summer melt retained by refreezing within the snowpack and underlying firn. This is accomplished by measuring ice accumulation in buried collection trays, and average snow densities. Cogley et al. (1996) estimated the error in annual glacier mass balance measured at each stake on White Glacier to be ±200-mm water equivalent. This single stake error can be used as a conservative estimate of the error in whole glacier mass balance estimates for all monitored glaciers in the Canadian High Arctic (Cogley and Adams 1998). These measurements document the surface mass balance and do not account for mass loss resulting from glacier calving or basal melt, which may be significant in some cases (Burgess et al. 2005). For a more detailed description of the physical characteristics and methods used to determine the surface mass balance of each of the four glaciers, see Koerner (1996, 2002) and Cogley et al. (1996).

Nonrotated principal component analysis (PCA) was used to extract the primary modes of variance from standardized time series of the four mass balance records. Time series were standardized by subtracting the mean of the series from each value and dividing the resulting values by the standard deviation of the series. Because this study is concerned with long-term changes in mass balance, the individual mass balance records were not detrended prior to PCA (Venegas 2001). To select modes for further analysis, the Kaiser criterion (Kaiser 1960) was used, which excludes any factors with an eigenvalue of less than one, thereby excluding any factors that explain less variance than a single original variable. Because the first principal component (PC1) explains 53% of the variance in the original four mass balance time series and is the only component with an eigenvalue greater than one, all other principal components were excluded.

A sequential algorithm developed for the detection of climate regime shifts from empirical data (Rodionov 2004) was used to determine whether and when any significant shifts in the mean of the PC1 anomalies occurred. Unlike commonly used confirmatory statistical methods for identifying climate regime shifts, such as those employed by Mantua et al. (1997), which require an a priori hypothesis about the timing of the shift, this method allows for the automatic detection of discontinuities in the time series. Another advantage of this method is that it can detect regime shifts toward the end of a time series, which is not the case for other automatic detection methods. Only regime shifts detected using a cutoff length of 20 years and having a probability level $p \leq 0.05$ were considered. A Huber parameter (Huber 1964) of two was used to reduce the weighting of outliers that deviate by more than two standard deviations from the expected mean value of a new regime when calculating the regime shift. The red noise component of the time series to which this technique was applied was removed prior to applying the regime shift detection algorithm by "prewhitening" the time series (Rodionov 2006). The autoregressive parameter used in the prewhitening procedure was calculated using the method of inverse proportionality with four corrections (IPN4), with a subsample size of 10 (Rodionov 2006). Using these criteria, only one regime shift was detected.

The magnitude of glacier ablation, and thus the annual surface mass balance of glaciers in the Canadian High Arctic, depends on the energy balance at the glacier surface. Quantifying the historical net surface energy balance for this data-sparse region is extremely difficult. For this reason, the relationship between glacier mass balance and near-surface air temperatures (a commonly used proxy for the surface energy balance) was examined to investigate surface climate–glacier in-

TABLE 1. Principal component analysis of four Canadian High Arctic glacier mass balance records (1963–2003).

			Component loading			
Component	Eigenvalue	% of variance	White Glacier	Devon Ice Cap	Melville Island Ice Cap	Meighen Ice Cap
1	2.13	53.30	0.71	0.75	0.81	0.64
2	0.85	21.22	−0.53	0.30	−0.30	0.62
3	0.58	14.53	0.29	−0.12	−0.12	0.45

teractions. SAT records were obtained for local Environment Canada meteorological stations (available at http://www.climate.weatheroffice.ec.gc.ca). Because only three meteorological stations in the Canadian High Arctic (Alert, Eureka, and Resolute Bay; Fig. 1) have continuous SAT records over the period of study (1963–2003), gridded 850-mbar air temperatures from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) climate reanalysis (Kalnay et al. 1996; Kistler et al. 2001; available at http://www.cdc.noaa.gov) were also utilized. These were used to provide a more location-independent measure of regional-scale temperature and to investigate the spatial pattern of temperature changes. The 850-mbar pressure level (≈2 km above sea level) NCEP–NCAR-reanalyzed atmospheric temperatures were used in place of reanalyzed SATs because they are less affected by the spectrally defined topography used in the NCEP–NCAR climate reanalysis (Kalnay et al. 1996). This topography is too coarsely resolved to capture the complex orography of the Canadian High Arctic. An additional reason for selecting the 850-mbar pressure level was to reduce possible SAT biases resulting from erroneously defined snow cover within the NCEP–NCAR reanalysis model (Kanamitsu et al. 2002). SAT measurements from the three meteorological stations located in the region of interest were compared with mean monthly 850-mbar NCEP–NCAR air temperatures from the respective overlying grid cells to determine the degree of agreement between the records.

Both regional glacier mass balance and air temperatures were examined in relation to interannual variations in the position and strength of the circumpolar vortex. The location and standardized magnitude of the absolute minimum July NCEP–NCAR 500-mbar geopotential height north of the equator were used to characterize the center location and strength of the circumpolar vortex. The time series of minimum July 500-mbar geopotential height was standardized and inverted to provide a relative index of vortex strength. Years with positive strength indices have relatively low absolute minimum July 500-mbar geopotential heights with strong cyclonic circulation and were classified as years with a strong July vortex. In contrast, years with negative strength indices have relatively high absolute minimum July 500-mbar geopotential heights with weak cyclonic circulation and were referred to as years with a weak July vortex. Locations of July 500-mbar vortices were divided into three regional groups. We then investigated the relationships between the strength and position of the circumpolar vortex and the regional glacier mass balance.

To study the causes of the reduction in regional glacier mass balance in the late 1980s, differences between the NCEP–NCAR reanalysis fields for 850-mbar temperature and 500-mbar geopotential height for the years prior to and after 1987 were examined.

All correlation values presented in this paper are expressed in terms of r, Pearson's product-moment coefficient of correlation. The significance of the correlations was determined using a two-tailed Student's t test with the null hypothesis that the time series are uncorrelated ($r = 0$). All r values quoted are significant at the 0.05 level.

3. Results

a. Glacier mass balance

The four annual surface mass balance records, spanning the 41 yr from 1963 to 2003, are not well correlated with each other ($r = 0.23$–0.52), but they nevertheless display strong underlying similarities. PC1 of these records has an eigenvalue of 2.13 and accounts for 53% of the variance across the four time series (Table 1). The loadings of the four mass balance time series on PC1 are similar in magnitude and sign, ranging between 0.64 and 0.81, suggesting that PC1 identifies a regional climatic influence on glacier mass balance. The standardized PC1 was therefore taken as a measure of the regional mass balance history of Canadian High Arctic glaciers for the period of 1963–2003, and is hereafter referred to as the *regional glacier mass balance*. Individual standardized glacier mass balance records are compared with PC1 in Fig. 2. Over the period of 1961–2003, PC1 has a weak but significant linear trend to-

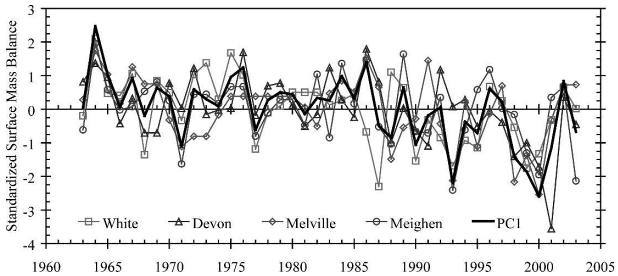

FIG. 2. Annual mass balance records from individual glaciers expressed as standardized anomalies with the first principal component (PC1) plotted in bold.

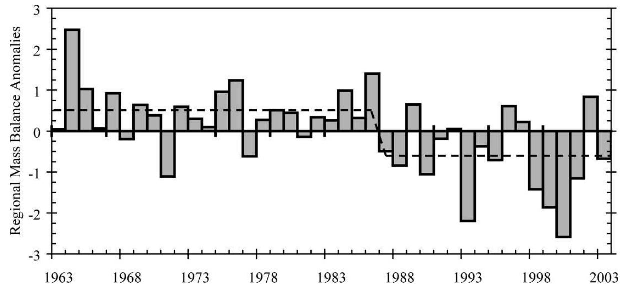

FIG. 3. Standardized anomalies of the first principal component (PC1) of the four glacier mass balance records. Inferred mass balance regimes are represented by a dashed line.

ward more negative regional glacier mass balance anomalies ($r^2 = 0.27$).

Applying the regime shifts detection algorithm outlined in section 2, only one regime shift was detected in the regional glacier mass balance signal. This occurred between 1986 and 1987 (Fig. 3), in agreement with the findings of Dyurgerov and McCabe (2006). This method of regime shift detection is most sensitive to the user-defined variables of cutoff length and probability level. To determine the robustness of the identified regime shift, similar analyses were conducted using other cutoff lengths. For all cutoff lengths between 12 and 30 years, a 1986–87 regime shift in the mean of the regional glacier mass balance signal was detected. A significant difference in mean between the periods of 1963–86 and 1987–2003 is also found when using the traditional two-tailed Student's t-test method, assuming unequal variance. The 24-yr period prior to 1987 contains only 4 years with negative mass balance anomalies and has a mean standardized regional glacier mass balance anomaly of 0.46 with no linear trend. In contrast, the 17-yr period after 1987 includes 12 years with negative mass balance anomalies, and has a mean standardized anomaly of -0.66. While there are too few points to identify a significant trend in the later 17-yr period, there is a tendency toward increasingly negative anomalies toward the end of the series, with 4 of the 5 most negative mass balance anomaly years in the entire 41-yr period occurring during the last 6 years of record (Fig. 3).

b. Air temperature

Interannual variability in Canadian High Arctic annual glacier mass balance is governed almost entirely by variation in summer glacier surface melt, which occurs mainly in the month of July (Wang et al. 2005). For this reason, only the relationships between regional annual mass balance and summer air temperatures were investigated. Average June, July, August, and summer (June–August) SATs for Alert, Eureka, and Resolute Bay were correlated with the regional glacier mass balance signal. Of the 12 SAT series, only June, July, and summer SATs from Eureka and Resolute Bay are significantly correlated with the regional glacier mass balance. On average, July SATs from Eureka and Resolute Bay account for 56%, 44%, and 26% more variance in the regional glacier mass balance than mean August, June, and summer SATs, respectively. In addition, when average July SATs from Eureka or Resolute Bay were used to model regional glacier mass balance, there were no significant correlations between the linear regression residuals and any June, August, or summer SAT series. This strong relationship between Canadian High Arctic glacier mass balance and mean July temperature has long been recognized (Bradley and England 1978; Dowdeswell 1995). Because the majority of the variance in the Canadian High Arctic regional glacier mass balance signal is captured in the July SATs from Eureka and Resolute Bay, and there is minimal correlation with the SATs from the neighboring months, we focus solely on July atmospheric variables in the remainder of this analysis.

The average July SATs from Eureka and Resolute Bay are highly correlated ($r = 0.85$), however, no significant correlation exist between these two records and July SATs from Alert. This suggests that northern Ellesmere Island SATs may be influenced by different synoptic conditions than those that affect the more southern parts of the Canadian Arctic Archipelago. The implications of this for the glacier mass balance of the region will be discussed in section 5.

The average July SATs from both Eureka and Resolute Bay were correlated with the 850-mbar temperatures in the $2.5° \times 2.5°$ reanalysis grid cell located directly over each station. Reanalysis 850-mbar air temperatures and station SATs are reasonably well correlated ($r = 0.65$–0.87). To estimate how well regional variability in station-derived SATs is captured by the NCEP–NCAR 850-mbar air temperatures, these

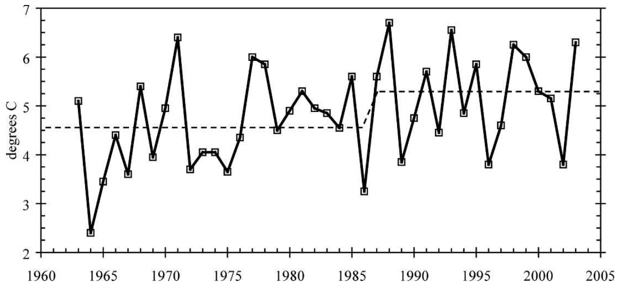

FIG. 4. Regional mean July station derived surface air temperature (SAT), taken as the average temperature observed at the Environment Canada meteorological stations of Eureka and Resolute Bay. The dashed line displays the two significant temperature regimes.

temperatures (averaged over the region of interest: 75°–80°N, 75°–115°W) were correlated with the average Eureka and Resolute Bay July temperature (r = 0.82).

The average Eureka/Resolute Bay SATs are highly correlated with the regional glacier mass balance (PC1) (r = 0.79). July SATs also show a significant regime shift from cooler to warmer temperatures between 1986 and 1987, with a 1°C increase in mean July SAT between earlier and later time periods (Fig. 4). The SAT series also contains a weakly significant linear trend toward warmer temperatures (r^2 = 0.13). This shift in regional temperature corresponds with the 1987 acceleration in the rate of annual glacier mass loss identified in section 3a. A similar shift is found in the regionally averaged NCEP–NCAR 850-mbar air temperatures.

It should be noted that in the 15 yr prior to 1963 (the first year of record used in this study) mean July SATs taken from the Environment Canada meteorological stations of Resolute Bay and Eureka were 1°C warmer than those in the period of 1963–86. The difference between the two is statistically significant and has previously been documented by Bradley and England (1978).

c. 500-mbar Arctic circumpolar vortex

For all years examined, the center locations of the July circumpolar vortices were grouped into the following three sectors (Fig. 5a): sector I: 75°–90°N, 0°–180°E; sector II: 75°–90°N, 0°–180°W, and sector III: 60°–75°N, 90°–60°W. To show the relationship between the position and strength of the circumpolar vortex and the mass balance of Canadian High Arctic glaciers, the relative vortex strength (standardized and inverted minimum Northern Hemisphere July 500-mbar geopotential height) and the Canadian High Arctic regional glacier mass balance signal (PC1) have been grouped by the sector in which the vortex center is located and sorted from the strongest to the weakest strength vortex within that group (Fig. 5b).

For sector I vortices there is a well-defined linear relationship between vortex strength and regional glacier mass balance, wherein strong vortices result in moderately positive mass balance anomalies and weak vortices result in extremely negative mass balance anomalies. A similar relationship exists for sector II vortices, except that strong vortices produce extremely positive mass balance anomalies and weak vortices produce neutral to moderately negative mass balance anomalies. As for sector III vortices, there is little variation in vortex strength or regional glacier mass balance, with both indices close to neutral. If the extreme year of 1993 (discussed further in section 4) is excluded from the analysis, there are statistically significant relationships between vortex strength and regional glacier mass balance for both Eastern (sector I) and Western (sectors II and III) Hemisphere–centered vortices.

Looking solely at the relationship between vortex location and regional glacier mass balance, 67% of all negative mass balance anomalies exceeding one standard deviation from the mean occurred during years when the vortex was located in the Eastern Hemisphere. Of all positive mass balance anomalies exceeding one standard deviation from the mean, 67% occurred during years when the vortex was located in the Western Hemisphere. In 18 of the 24 yr prior to the 1987 decrease in regional glacier mass balance, the July vortex center was located in the Western Hemisphere. In contrast, the July vortex was centered in the Western Hemisphere in only 6 of the 17 yr between 1987 and 2003. Analysis of the NCEP–NCAR climate reanalysis data available for the 15 yr prior to 1963 shows an equal distribution of Eastern and Western Hemisphere–centered vortices.

d. 1987–2003 atmospheric anomalies

To examine atmospheric differences between the time periods before and after the 1987 shift in regional glacier mass balance, the differences between the 1963–86 and 1987–2003 mean July NCEP–NCAR 850-mbar atmospheric temperature and 500-mbar geopotential height anomalies were determined. Relative to 1963–86, the mean 1987–2003 July 850-mbar temperature increased by 1°–2°C over the Canadian High Arctic, Siberia, and the Barents Sea and decreased by 1°–2°C over the Kara and Labrador Seas (Fig. 6a). The mean July 500-mbar geopotential height shows a similar pat-

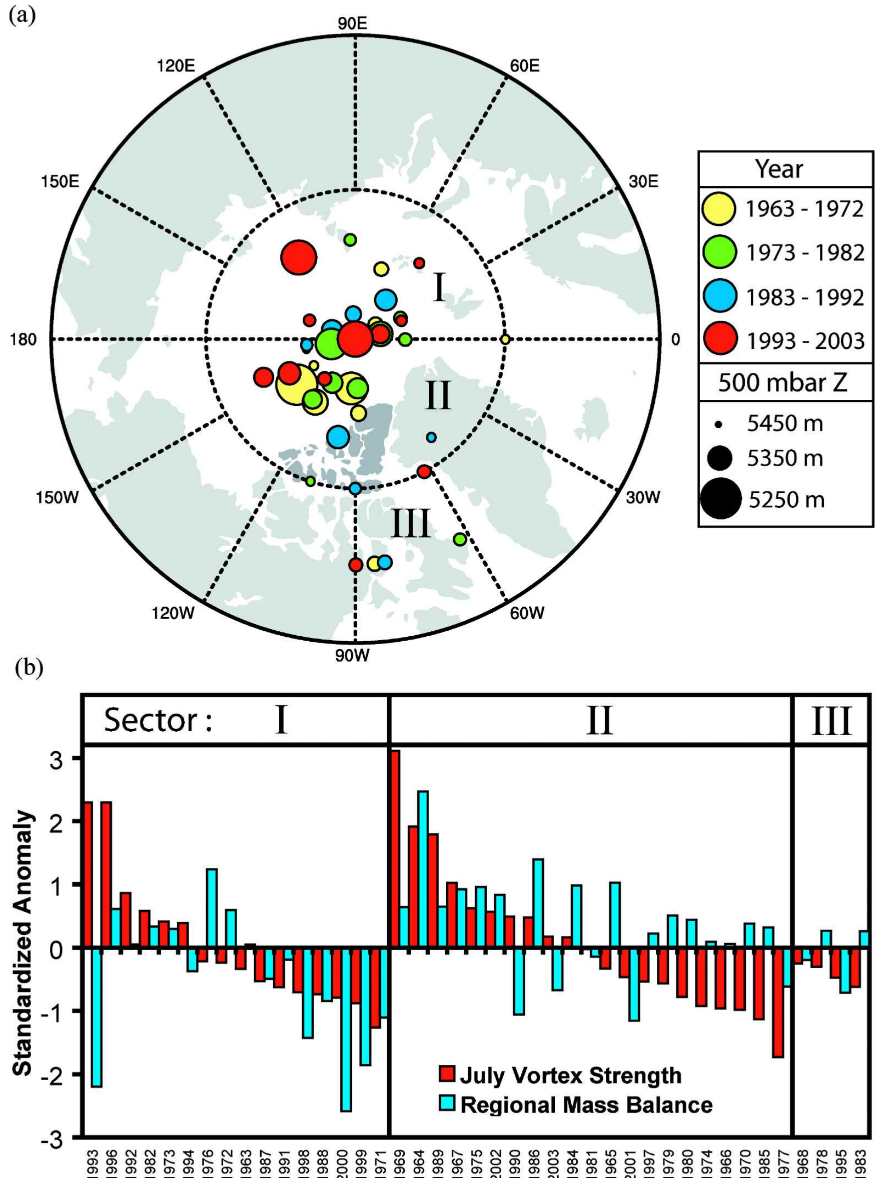

FIG. 5. (a) Sector boundaries and July 500-mbar Arctic circumpolar vortex center location and strength, defined as the location and magnitude of the minimum Northern Hemisphere 500-mbar geopotential height. Years of anomalously low (high) minimum geopotential heights are classified as years with a "strong" ("weak") circumpolar vortex. (b) Inverse of the standardized minimum Northern Hemisphere 500-mbar geopotential height (vortex strength) and Canadian high Arctic regional glacier mass balance (PC1) grouped by year into the sectors in which the vortex center is located and sorted by vortex strength.

tern, with increases in geopotential height over regions where there was atmospheric warming and decreases in geopotential height over regions with atmospheric cooling (Fig. 6b). The 1987–2003 decrease in mean July 500-mbar geopotential height in the region bounded by 75°–90°N, 0°–180°E and the increase in 500-mbar geopotential height in the region bounded by 75°–90°N, 0°–180°W reflects the increasing tendency for the July circumpolar vortex to be centered in the Eastern Hemisphere during the period of 1987–2003.

A time series (1963–2003) of mean area-weighted July 500-mbar geopotential height over the region 70°–85°N, 75°–115°W was created to determine whether there were any significant regime shifts in mean 500-mbar geopotential height over the Canadian Arctic and whether they corresponded with the abrupt change in

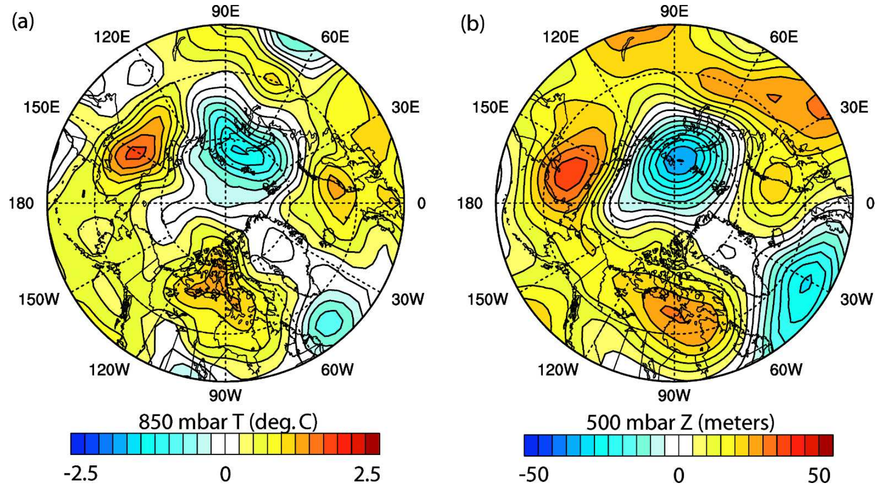

FIG. 6. Mean July 1987–2003 (a) 850-mbar air temperature (T) and (b) NCEP/NCAR 500-mbar geopotential height anomalies based on a 1963–86 base period.

regional glacier mass balance. No significant shift or trend was identified. Regional 500-mbar geopotential heights are however highly correlated with the time series of regional glacier mass balance ($r = 0.66$).

4. Discussion

On a hemispheric scale, both Angell (1998, 2006) and Frauenfeld and Davis (2003) have shown that variability in the extent of the summer midtropospheric Arctic circumpolar vortex, as defined by the 700–300-mbar geopotential height contour that consistently falls within the primary baroclinic zone, is significantly correlated with variability in Northern Hemisphere mid- to lower-tropospheric temperatures. Alt (1987) showed that interannual changes in the shape, strength, and position of the July 500-mbar Arctic circumpolar vortex have a strong influence on Canadian High Arctic regional glacier surface mass balance.

To illustrate the influence of both vortex strength and position on the regional glacier mass balance, July vortices were categorized into four types: I-A, I-B, II-A, II-B, and III. The first, type I-A, includes years when the July 500-mbar circumpolar vortex was strong and its center was located in the Eastern Hemisphere. This type included all years with July vortices that had centers located in sector I with positive strength anomalies. For type-I-A years it was most common for the area of low geopotential height surrounding the vortex center to extend into Baffin Bay (1973, 1982, 1992, 1994, 1996, and 2003). July 1992 exemplifies the regional influence of vortices with these characteristics (Fig. 7a). Under these conditions, the regional influence of continental high pressure systems over the Canadian High Arctic during July is greater than in years when a strong July vortex is located in the Western Hemisphere (type II-A). In type-I-A years, average July temperatures result in neutral regional glacier mass balance anomalies.

In years when the July vortex is either weak (negative strength anomaly) and centered in the Eastern Hemisphere (type-I-B conditions: 1963, 1971, 1972, 1976, 1987, 1988, 1991, 1998, 1999, and 2000) or is strong but the region of lowest geopotential height is not elongated over the Canadian High Arctic (1993) (Fig. 7b), the Canadian High Arctic becomes almost thermally homogeneous with continental North America. This results in anomalously warm July SATs and extremely negative regional glacier mass balance. The 11 yr with these characteristics contain 4 of the 5 warmest years in the 41-yr record and 6 of the 8 most negative regional glacier mass balance years. Type-I-B conditions compare well with Alt's (1987) synoptic analog for an extreme melt year (1962), when there was an anomalously high percentage of open water in the Queen Elizabeth Islands channels and a cloud cover minimum. Type-I-B vortices were identified either as having centers located in sector I with negative strength anomalies or as having centers located in sector I with the area of low geopotential heights constrained strictly to the Eastern Hemisphere with positive strength anomalies.

For years when the July 500-mbar vortex is strong and centered in the Western Hemisphere (type-II-A conditions) cyclonic conditions prevail over the Canadian High Arctic. July 1964 (Fig. 7c) was selected as a

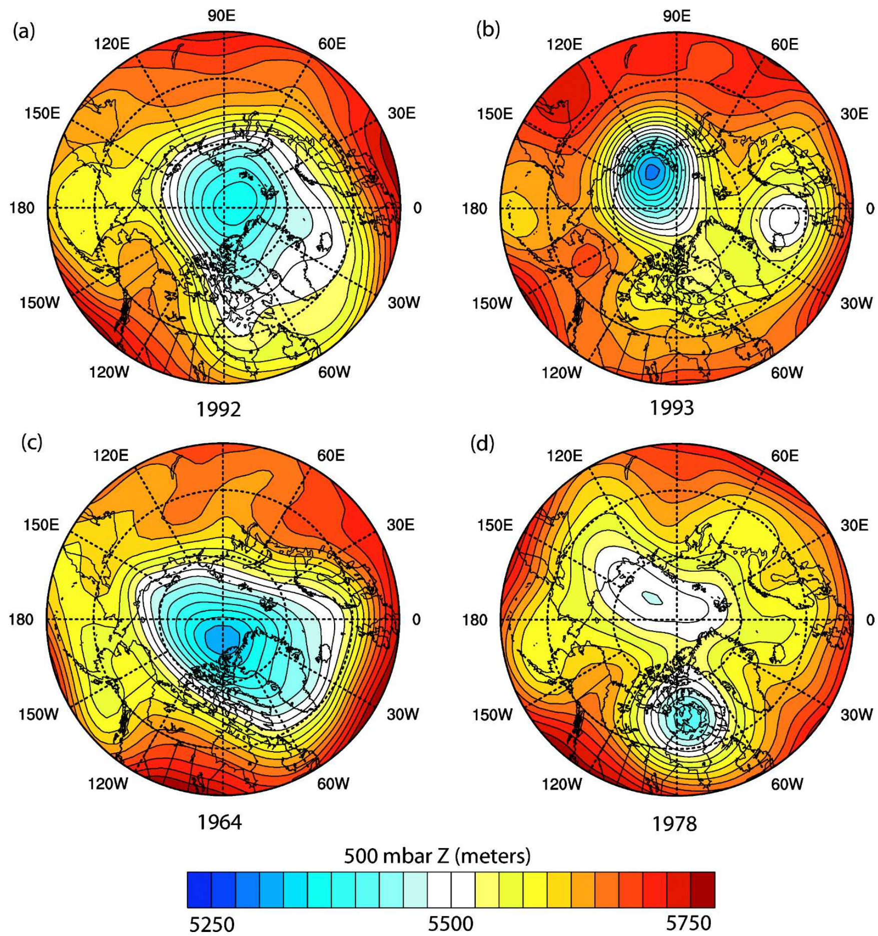

FIG. 7. Mean July NCEP/NCAR 500-mbar geopotential height for 1992, 1993, 1964, and 1976 (a)–(d), representative examples of type-I-A, -I-B, -II-A, and -III July vortex types.

representative year with these vortex characteristics. During this year, strong cyclonic conditions prevented North American high pressure ridges from extending northward over the Canadian High Arctic, keeping July SATs exceptionally low. Cold SATs, in turn, resulted in below-average glacier ablation rates and highly positive annual glacier mass balance anomalies. Also, 1964 was a year of above-average summer precipitation, which resulted from a succession of barotropic cyclones that transported Arctic Ocean moisture southward and deposited snow over the Canadian high Arctic (Alt 1987). Of the 41 yr investigated, 1964 had the coldest mean July SAT, and the most positive annual regional glacier mass balance. Similar July vortex characteristics prevailed during 9 out of the 41 yr investigated (1964, 1967, 1969, 1975, 1984, 1986, 1989, 1990, and 2002). Out of these 9 yr, 8 were among the 10 most positive mass balance years on record. All years with vortex centers located in sector II with positive strength anomalies were grouped in this category.

In years when the July circumpolar vortex is located in the Western Hemisphere but the vortex strength is decreased (higher minimum geopotential height) (type-II-B conditions: 1965, 1966, 1970, 1974, 1977, 1979, 1980, 1981, 1985, 1997, and 2001), the circumpolar vortex does not so effectively block warm North American continental air from moving into the Canadian High Arctic. These conditions result in average regional SATs and neutral regional glacier mass balance anomalies. All vortices with centers located in sector II and having negative strength anomalies where placed in this category.

The last grouping of July vortices consists of years when there are two 500-mbar geopotential minima, the strongest of which (lowest geopotential height) is located in sector III. The two minima are located to the south of, and to the north of, the Canadian High Arctic (type III: 1968, 1978, 1983, and 1995). The 500-mbar geopotential height contours for 1978, a representative year, are shown in Fig. 7d. These vortex characteristics are associated with above-average July SATs and below-average Canadian High Arctic regional glacier mass balance.

Analysis of the NCEP–NCAR climate reanalysis data for the 15-yr period prior to 1963 shows a much higher occurrence (40%) of type-I-B vortices, which are associated with extreme melt conditions, and a reduced occurrence (20%) of type-II-B vortices, which are associated with average glacier mass balance conditions, relative to the period of 1963–86. This suggests that the period of 1948–62 closely resembles the 1987–2003 period, when there was a more negative glacier mass balance regime. This is also consistent with the above-average July SATs observed during this period.

Analysis of July mean precipitation records from the Environment Canada meteorological stations at Eureka and Resolute Bay shows that in years when the vortex is strong and located in the Western Hemisphere (type II-A) there is a nearly threefold increase (~20 mm) in total July precipitation compared to years when the vortex is either weak and located in the Eastern Hemisphere (type I-B), or located to the south of the Canadian High Arctic (type III). During type-I-B and -III years average regional July SATs measured at Eureka and Resolute Bay, both of which are located at elevations near sea level, are 5.6°C, compared to 3.8°C for type-II-A years. Assuming a cooling factor of 3°C for SATs over glaciers, as was done by Atkinson and Gajewski (2002) when estimating high-resolution summer SATs for the Canadian Arctic Archipelago, this lowers the mean July sea level SATs over glaciers to 2.6° and 0.8°C for type-I-B-III and -I-A years, respectively. Because type-II-A years have mean July temperatures near 0°C, it is likely that more of the precipitation will fall as snow during type-II-A years than in type-II-B and -III years. Thus, the influence of vortex characteristics on summer precipitation in the Canadian High Arctic likely amplifies the thermally driven response of regional glacier mass balance to changes in the strength and location of the July 500-mbar circumpolar vortex.

Comparing the mean July 500-mbar geopotential heights in the 24-yr period prior to the 1987 shift in regional glacier mass balance with those in the following 17 yr (Fig. 6b), there is a large decrease (40 m) in mean geopotential height on the eastern side of the Arctic Ocean and a large increase (30 m) on the western side. This is consistent with Angell's (1998, 2006) conclusion that the summer circumpolar vortex adopted a more easterly position in the latter part of the period of 1963–2001.

In more general terms, when the mean July 500-mbar vortex is located in the Western Hemisphere the mass of cold polar air is more frequently situated over the Canadian High Arctic and warm high pressure ridges that build over continental Canada are more effectively blocked from moving northward over this region. When the mean July vortex is centered in the Eastern Hemisphere, warm continental high pressure ridges are not so effectively blocked from pushing northward and the Canadian High Arctic becomes more thermally homogeneous with continental North America. In terms of the influence of vortex characteristics on the Canadian High Arctic glacier mass balance, only 17% of years between 1963 and 1986 had easterly positioned type-I-B July vortices, which result in extreme glacier melt conditions. In the 17 yr that followed, 41% of the years had type-I-B July vortices and the overall occurrence of westerly positioned July vortices (types II-A, II-B, III) decreased by 40%.

In section 3d it was shown that regional July 500-mbar geopotential heights are significantly correlated with the regional glacier mass balance, but the regional 500-mbar geopotential height time series does not show the 1986–87 regime shift identified in both the air temperature and regional glacier mass balance time series. This suggests that it is not solely the absolute change in July 500-mbar height over the region that resulted in the inferred 1986–87 shift in regional glacier mass balance, but rather the combination of changes in the strength and position of the July circumpolar vortex. This can be illustrated by comparing regional July 500-mbar geopotential heights during type-I-A and -II-B vortex years. During type-I-A vortex years (strong vortex centered in the Eastern Hemisphere), regional July 500-mbar geopotential heights over the Canadian High Arctic are on average 0.32 standard deviations below the 41-yr mean. During type-II-B vortex years (weak vortex centered in the Western Hemisphere) regional 500-mbar geopotential heights over the Canadian High Arctic are on average 0.40 standard deviations greater than for type-I-A vortex years. Despite the higher regional 500-mbar geopotential heights for years with type-II-B vortices, there is little difference in the regional glacier balance or station-derived July SATs between years with type-II-B vortices and years with type-I-A vortices. This suggests that the combination of vortex position and strength must be accounted for when describing the relationship between the circumpolar vortex and the regional glacier mass balance.

The absence of significant correlations between the regional glacier mass balance record and the July temperature record from Alert (Fig. 1), and between the Alert and Resolute Bay/Eureka July temperature records suggests that mass balance variations of glaciers located in northern Ellesmere Island might differ from the pattern depicted by the regional glacier mass balance signal (PC1) of the four existing mass balance records for the Canadian High Arctic, and therefore their relationships with the July 500-mbar vortex may differ from those presented here.

Other climate regime shifts that have previously been identified and shown to influence climate in Arctic regions are briefly examined. One of the most well known climate regime shifts is the 1976 shift in North Pacific sea surface temperatures, which is commonly referred to as the 1976 shift in the Pacific decadal oscillation (PDO; Mantua et al. 1997). By inspection of Fig. 3, it can clearly be seen that the shift in PDO had little if any impact on the regional glacier mass balance of the Canadian High Arctic. Additional statistical analysis of the relationship between monthly and annual PDO indices [taken as the first empirical orthogonal function (EOF) of Pacific sea surface temperatures poleward of 20°N; information available at http://jisao.washington.edu/pdo/] shows no significant correlation between the PDO and the regional glacier mass balance. Another well-studied climate regime shift is the 1989 upward shift in the wintertime North Atlantic Oscillation (NAO; Hurrell 1995)/Arctic Oscillation (AO; Thompson and Wallace 1998) index, taken here as the first EOF of sea level pressure poleward of 20°N. The majority of the variability in the Canadian High Arctic regional glacier mass balance is governed by melt processes that occur during summer months, so it is not surprising that no significant correlation exists between the National Weather Service Climate Prediction Center's winter AO index (available at http://www.cpc.noaa.gov) and the regional glacier mass balance. The only significant correlation that exists between monthly AO indices and the regional glacier mass balance signal is for the month of July ($r = 0.42$). The July AO is also significantly correlated ($r = 0.50$) with the average area-weighted regional 500-mbar geopotential height and, like the regional 500-mbar geopotential height, the July AO does not contain a 1986–87 regime shift. Less well known regime shifts that did occur in 1987 affected central Arctic annual sea level pressures (Walsh et al. 1996) and Northern Hemisphere snow extent (Robinson and Frei 2000), suggesting that the inferred 1987 climate regime shift may have affected areas beyond the Canadian High Arctic.

5. Conclusions

A significant decrease in the Canadian High Arctic mean regional glacier mass balance anomaly, as represented by our 41-yr time series of the first principal component of four glacier mass balance records, was detected between 1986 and 1987. For the four glaciers examined, variability in summer mass balance determines variability in the annual glacier mass balance. Regional glacier mass balance is strongly correlated with July mean air temperature at Eureka and Resolute Bay and with the regionally averaged 850-mbar July temperature from the NCEP–NCAR climate reanalysis. Significant shifts to higher July mean temperatures after 1987 were found in both station-derived SATs and NCEP–NCAR 850-mbar temperatures.

Consistent with the findings of Alt (1987), interannual changes in the strength and position of the July 500-mbar circumpolar vortex exert a strong influence on Canadian High Arctic regional SATs and glacier mass balance. In general, when the July circumpolar vortex is strong and its center is located in the Western Hemisphere, positive mass balance anomalies prevail. In contrast, when the July circumpolar vortex is either weak or strong without elongation over the Canadian High Arctic, and the vortex center is located in the Eastern Hemisphere, highly negative mass balance anomalies prevail. Since the late 1980s there has been a significantly higher occurrence of July vortex types that produce anomalously high SATs over the Canadian High Arctic. This, in turn, has resulted in a sharp decrease in the regional glacier mass balance. The tendency for more easterly centered July circumpolar vortices is reflected in 1987–2003 anomalies in NCEP–NCAR 500-mbar geopotential heights (Fig. 6), which show a decrease of up to 40 m in mean geopotential height over the eastern side of the Arctic Ocean and an increase of up to 30 m in geopotential height over the Canadian Arctic relative to the 1963–87 period.

These findings highlight the importance of understanding the dynamics behind the climatic forcings that have resulted in accelerated glacier melt in the Canadian High Arctic and show that the observed changes in July mean SATs and glacier mass balance in the region are not appropriately characterized by simple linear trends. To identify the mechanisms behind the regional patterns of warming and mass balance change in the Canadian High Arctic, it is necessary to analyze the dominant synoptic-scale pressure systems and regional circulation patterns over the Arctic. The results presented here clearly show that changes in the strength and center position of the July 500-mbar circumpolar vortex have resulted in the acceleration of glacier ablation in the Canadian high Arctic since 1986–87. Further research is needed to determine what has caused these changes in the July 500-mbar circumpolar vortex.

Acknowledgments. This work was supported by NSERC (through a discovery grant to M. Sharp, and an undergraduate summer research award and Canada graduate scholarship to A. S. Gardner), the Alberta Ingenuity Fund (through a scholarship to A. S. Gardner), the Meteorological Service of Canada (through a scholarship supplement to A. S. Gardner), and by the Canadian Foundation for Climate and Atmospheric Sciences through the Polar Climate Stability Network. We gratefully acknowledge the sustained efforts of Roy Koerner, Peter Adams, Graham Cogley, Miles Ecclestone, and coworkers to produce long time series of surface mass balance measurements for glaciers and ice caps in the Queen Elizabeth Islands. We also thank Lindsey Nicholson and two anonymous reviewers for their comments and insights.

REFERENCES

Alt, B. T., 1978: Synoptic climate controls of mass balance variations on Devon Island Ice Cap. *Arct. Alp. Res.,* **10,** 61–80.

——, 1979: Investigation of summer synoptic climate controls on the mass balance of Meighen Ice Cap. *Atmos.–Ocean,* **17,** 181–199.

——, 1987: Developing synoptic analogs for extreme mass balance conditions on Queen Elizabeth Island ice caps. *J. Climate Appl. Meteor.,* **26,** 1605–1623.

Angell, J. K., 1998: Contraction of the 300 mbar north circumpolar vortex during 1963–1997 and its movement into the Eastern Hemisphere. *J. Geophys. Res.,* **103,** 25 887–25 893.

——, 2006: Changes in the 300-mb north circumpolar vortex, 1963–2001. *J. Climate,* **19,** 2984–2994.

Atkinson, D. E., and K. Gajewski, 2002: High-resolution estimation of summer surface air temperature in the Canadian Arctic Archipelago. *J. Climate,* **15,** 3601–3614.

Bradley, R. S., and J. England, 1978: Recent climatic fluctuations of the Canadian high Arctic and their significance for glaciology. *Arct. Alp. Res.,* **10,** 715–731.

Braithwaite, R. J., and S. C. B. Raper, 2002: Glaciers and their contribution to sea level change. *Phys. Chem. Earth,* **27,** 1445–1454.

Braun, C., D. R. Hardy, and R. S. Bradley, 2004: Mass balance and area changes of four High Arctic plateau ice caps, 1959–2002. *Geogr. Ann.,* **86A,** 43–52.

Burgess, D. O., M. J. Sharp, D. W. F. Mair, J. A. Dowdeswell, and T. J. Benham, 2005: Flow dynamics and iceberg calving rates of Devon Ice Cap, Nunavut, Canada. *J. Glaciol.,* **51,** 219–230.

Cogley, J. G., and W. P. Adams, 1998: Mass balance of glaciers other than the ice sheets. *J. Glaciol.,* **44,** 315–325.

——, ——, M. A. Ecclestone, F. Jung-Rothenhäusler, and C. S. L. Ommanney, 1996: Mass balance of White Glacier, Axel Heiberg Island, NWT, Canada, 1960–91. *J. Glaciol.,* **42,** 548–563.

Dowdeswell, J. A., 1995: Glaciers in the high Arctic and recent environmental change. *Philos. Trans. Roy. Soc. London,* **352A,** 321–334.

——, and Coauthors, 1997: The mass balance of circum-Arctic glaciers and recent climate change. *Quat. Res.,* **48,** 1–14.

Dyurgerov, M. B., 2002: Glacier mass balance and regime: Data of measurements and analysis. INSTAAR, University of Colorado Occasional Paper 55, 268 pp.

——, and M. F. Meier, 1997: Year-to-year fluctuations of global mass balance of small glaciers and their contribution to sea-level changes. *Arct. Alp. Res.,* **29,** 392–402.

——, and ——, 1999: Analysis of winter and summer glacier mass balances. *Geogr. Ann.,* **81A,** 541–554.

——, and ——, 2000: Twentieth century climate change: Evidence from small glaciers. *Proc. Natl. Acad. Sci. USA,* **97,** 1406–1411.

——, and ——, 2005: Glaciers and the changing earth system: A 2004 snapshot. INSTAAR, University of Colorado Occasional Paper 58, 117 pp.

——, and G. J. McCabe, 2006: Associations between accelerated glacier mass wastage and increased summer temperature in coastal regions. *Arct. Antarct. Alp. Res.,* **38,** 190–197.

Frauenfeld, O. W., and R. E. Davis, 2003: Northern Hemisphere circumpolar vortex trends and climate change implications. *J. Geophys. Res.,* **108,** 4423, doi:10.1029/2002JD002958.

Hagen, J. O., K. Melvold, F. Pinglot, and J. A. Dowdeswell, 2003: On the net mass balance of the glaciers and ice caps in Svalbard, Norwegian Arctic. *Arct. Antarct. Alp. Res.,* **35,** 264–270.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. Van Der Linden, D. Xiaosu, K. Maskell, and C. A. Johnson, Eds., 2001: *Climate Change 2001: The Scientific Basis*. Cambridge University Press, 881 pp.

Huber, P. J., 1964: Robust estimation of location parameter. *Ann. Math. Stat.,* **35,** 73–101.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science,* **269,** 676–679.

IAHS/UNESCO, 2005: *Glacier Mass Balance Bulletin*. No. 8, 108 pp.

Johannessen, O. M., and Coauthors, 2004: Arctic climate change: Observed and modeled temperature and sea-ice variability. *Tellus,* **56A,** 559–560.

Kaiser, H. F., 1960: The application of electronic-computers to Factor-Analysis. *Educ. Psychol. Meas.,* **20,** 141–151.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S. K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter, 2002: NCEP–DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc.,* **83,** 1631–1643.

Kistler, R., and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.,* **82,** 247–267.

Koerner, R. M., 1996: Canadian Arctic. Report on Mass Balance of Arctic Glaciers, Working Group on Arctic Glaciology, International Arctic Science Committee Rep. 5, 5–8.

——, 2002: Glaciers of the Arctic Islands. Glaciers of the High Arctic Islands, USGS Professional Paper 1386-J-1, J111–J146.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.,* **78,** 1069–1079.

Maxwell, J. B., 1980: *The Climate of the Canadian Arctic Islands and Adjacent Waters: Climatological Studies No. 30.* Vol. 1, Atmospheric Environmental Services, Environment Canada, 532 pp.

McCabe, G. J., A. G. Fountain, and M. Dyurgerov, 2000: Variability in winter mass balance of Northern Hemisphere glaciers and relations with atmospheric circulation. *Arct. Antarct. Alp. Res.,* **32,** 64–72.

Meier, M. F., 1984: Contribution of small glaciers to global sea-level. *Science,* **226,** 1418–1421.

Raper, S. C. B., and R. J. Braithwaite, 2006: Low sea level rise projections from mountain glaciers and icecaps under global warming. *Nature,* **439,** 311–313.

Robinson, D. A., and A. Frei, 2000: Seasonal variability of Northern Hemisphere snow extent using visible satellite data. *Prof. Geogr.,* **52,** 307–315.

Rodionov, S. N., 2004: A sequential algorithm for testing climate regime shifts. *Geophys. Res. Lett.,* **31,** L09204, doi:10.1029/2004GL019448.

——, 2006: Use of prewhitening in climate regime shift detection. *Geophys. Res. Lett.,* **33,** L12707, doi:10.1029/2006GL025904.

Serreze, M. C., and R. G. Barry, 2005: *The Arctic Climate System*. 1st ed. Cambridge University Press, 385 pp.

Thompson, D. W. J., and J. M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.,* **25,** 1297–1300.

Venegas, S. A., 2001: Statistical methods for signal detection in climate. Danish Center for Earth System Science Rep. 2, 96 pp.

Walsh, J. E., W. L. Chapman, and T. L. Shy, 1996: Recent decrease of sea level pressure in the central Arctic. *J. Climate,* **9,** 480–486.

Wang, L., M. J. Sharp, B. Rivard, S. Marshall, and D. Burgess, 2005: Melt season duration on Canadian Arctic ice caps, 2000–2004. *Geophys. Res. Lett.,* **32,** L19502, doi:10.1029/2005GL023962.