The Mass Balance of Circum-Arctic Glaciers and Recent Climate Change

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The sum of winter accumulation and summer losses of mass from glaciers and ice sheets (net surface mass balance) varies with changing climate. In the Arctic, glaciers and ice caps, excluding the Greenland Ice Sheet, cover about 275,000 km² of both the widely glacierized archipelagos of the Canadian, Norwegian, and Russian High Arctic and the area north of about 60°N in Alaska, Iceland, and Scandinavia. Since the 1940s, surface mass balance time-series of varying length have been acquired from more than 40 Arctic ice caps and glaciers. Most Arctic glaciers have experienced predominantly negative net surface mass balance over the past few decades. There is no uniform recent trend in mass balance for the entire Arctic, although some regional trends occur. Examples are the increasingly negative mass balances for northern...
INTRODUCTION

The winter inputs and summer losses of mass from the ice sheets, ice caps, and glaciers covering more than 2 million km$^2$ of the polar North vary in response to climate change and affect global sea level as increments of water are released to the oceans or stored in solid form. This area includes the 1.8 million km$^2$ of ice on Greenland, together with the glaciers and ice caps that cover about 275,000 km$^2$ in the extensively glacierized archipelagos of the High Arctic and north of about 60°N within continental North America, Europe, and Iceland (Dowdeswell, 1995) (Fig. 1).

Climate change in the Arctic over the past few hundred years was dominated by the generally cool Little Ice Age and subsequent warming of up to several degrees marking the termination of this cold period (e.g., Grove, 1988). These changes are documented in the oxygen isotopic and melt-layer signals from ice cores and from the few long time series of direct meteorological observations available from the circumpolar region. Time-dependent General Circulation Model (GCM) simulations of future climatic response to increasing proportions of anthropogenically introduced “greenhouse gases” in the atmosphere have also predicted that Arctic regions will experience enhanced warming relative to lower latitudes (e.g., Stufler et al., 1989; Washington and Meehl, 1989; Cattle and Thomson, 1993).

The aims of this paper are (a) to document the net mass balance of ice masses throughout the Arctic and to identify any trends in these measurements over the past few decades and (b) to outline recent climate records from Arctic stations and to discuss the links between glacier mass balance and recent climate change in the Arctic.

FIELD MEASUREMENTS OF GLACIER MASS BALANCE

The sum of gains and losses of mass over an entire ice mass, from the end of one summer melt season to the end of the next, is known as net surface mass balance (Østrem and Brugman, 1991). This net balance provides an integrated record of glacier–climate interactions. Consequently, measurements of glacier mass balance are of significance as a measure of climate change in the extensively ice-covered Arctic, where other forms of data are sparse. In addition, the winter snow accumulation component of the annual net balance may be considered a more accurate record of trends in solid precipitation than that provided by standard snowfall measurement techniques.

Since the 1940s, surface mass balance time-series of varying length have been acquired from a number of Arctic glaciers and ice caps (Fig. 1a). The values we discuss are from field measurements, usually derived from extensive stake arrays covering glacier accumulation and ablation zones. They do not include basal melting, which is small or nonexistent, or mass loss by iceberg calving, which does not apply to glaciers terminating on land. The mass balance of the Greenland Ice Sheet is difficult to measure using direct field techniques due to its vast area and the large uncertainties in iceberg production. Satellite radar altimeter and airborne laser alimeter investigations are now under way to assess whether the ice sheet is growing or decaying (e.g., Zwally et al., 1989; Thomas et al., 1995; Wingham, 1995).

DISTRIBUTION AND LENGTH OF ARCTIC MASS-BALANCE DATASETS

Time-series data are available on the mass balances of more than 40 glaciers and ice caps in the Arctic. Ice masses from high Arctic latitudes include examples from the Canadian Arctic islands, the Svalbard and Russian Severnaya Zemlya archipelagos, and the Russian Urals. For lower latitudes within the Arctic, net mass balance data from Alaska, Iceland, Norway, and Sweden are available. These data cover the bulk of the ice-covered Arctic outside Greenland, from 100°E to 150°W (Fig. 1a). However, mass-balance datasets from a number of glaciers are fragmentary, often representing a limited number of years. The longest continuous record, back to 1945–1946, is from Storglaciären in Northern Sweden (Holmlund et al., 1996).

Measurements of net mass balance from 18 Arctic glaciers (Figs. 2 and 3) were selected (a) for their spatial coverage of the major areas of the Arctic (Fig. 1a) and (b) for the long time-series provided by a number of the datasets. Ten sets of net balance measurements contain more than 20 years of data, and two are more than 40 years long.

TRENDS IN THE MASS BALANCE OF ARCTIC GLACIERS

The Arctic net mass balance records can be divided into two groups. The first are for those glaciers located in the High Arctic, above about 70°N, and distributed mainly in the high latitude archipelagos of the Canadian Queen Elizabeth islands, Norwegian Svalbard, and Russian Severnaya Zemlya in the Eurasian sector (Fig. 1a). The second are those glaciers at lower Arctic latitudes, between approximately 60° and 70°N, and located in the continental areas of Alaska and Scandinavia and the island of Iceland (Fig. 1a). The net mass balance datasets for these higher- and lower-latitude Arctic glaciers are shown in Figures 2 and 3, respectively.
Of the 18 glaciers shown in Figures 2 and 3, 83% have a negative mean net mass balance. Almost 80% of the mass balance time series also have a positive trend, toward a less negative mass balance. However, the interannual variability in the records for many glaciers is high (Figs. 2 and 3), and the measurement errors usually are poorly known.

High Arctic Glacier Mass Balance

The time series of net mass balance data for each of the high Arctic glaciers shown in Figure 2 has a negative mean, implying that mass has been lost over the period of observation. In Svalbard, for example, only 4 of the 46 measurements (<10%) of net mass balance show a positive annual increment (Fig. 2b). This is also typical for several other Svalbard ice masses for which mass balance data are available (Hagen and Liestøl, 1990). In the Canadian Arctic islands, more than 70% of balance years were negative (Fig. 2a). Mass balance data from the Vavilov Ice Dome in the Russian High Arctic are more variable, with large fluctuations about a marginally negative mean (Fig. 2c). Consistently negative glacier mass balance data have also been reported from Franz Josef Land ice masses (Grosswald and Krenke, 1962), although detailed mass balance measurements are difficult to obtain.

All these mass balance datasets have a relatively high interannual variability, although a number of the mean values are statistically different from zero and indicate a negative mass balance over the period of observation. Statistical analysis of these time series demonstrates that the approximately 30-yr-long records from White Glacier and the Meighen and Devon ice caps in the Canadian High Arctic are negative at a 95% level of significance (Cogley et al., 1995, 1996). Similarly, the consistently negative annual records of between 9 and 25 yr in length from Svalbard are each significantly different from zero at a 95% level of confidence (Cogley et al., 1995). Indeed, the reconstructed mass balance history of Austre Brøggerbreen in northwest Spitsbergen shows an average loss of 35 m of ice over the glacier surface in the last 80 yr (Lefaucheur and Hagen, 1990). The mass balance measurements from glaciers in the Russian Arctic have mean values which are not significantly different from zero (Fig. 2c). The Vavilov Ice Dome, on Severnaya Zemlya (Fig. 1a), may therefore be approximately in balance (Fig. 2c). The reconstructed mass balance history of Austre Brøggerbreen in northwest Spitsbergen shows an average loss of 35 m of ice over the glacier surface in the last 80 yr (Lefaucheur and Hagen, 1990). The mass balance measurements from glaciers in the Russian Arctic have mean values which are not significantly different from zero (Fig. 2c).

High Arctic Glacier Mass Balance

The mass balance measurements from glaciers in the Russian Arctic have mean values which are not signifi-

Statistically, Nigardsbreen in the western maritime sector of south Norway, with a mean positive mass balance of +0.47 m yr⁻¹ from more than 30 yr of measurements (Fig. 3c), has a mean balance significantly above zero (at the 95% level). It is, however, the only glacier of the 18 we illustrate in Figures 2 and 3 which has an unequivocally positive mass balance over the period of observation. Net mass balances for the two Icelandic glaciers, which are based on only short series of measurements, are indistinguishable from zero statistically (Fig. 3b). Storðalur, in a more continental setting than Nigardsbreen within southern Norway, and Storglaciären in northern Sweden are both significantly negative in mean annual balance (Cogley et al., 1995).

In Alaska, almost all the glaciers observed either are in a state of negative mass balance or have mass balances close to zero over the period of observation (Fig. 3a). Comparisons between U.S. Geological Survey topographic maps from the early 1950s and airborne laser altimeter measurements of changes in ice surface elevation at a number of glaciers across Alaska support this statement, except for

This conclusion is supported by detailed ice-stratigraphic studies at ice caps of relatively low summit elevation in the Canadian Arctic and Russian Franz Josef Land. The Canadian Meighen Ice Cap has lost an average of about 13 m of ice over its entire surface in the past 80 yr (Koerner and Paterson, 1974). Hayes Ice Dome in Franz Josef Land has ice throughout a shallow ice core, with no firm stratigraphy, implying that any accumulation at the crest is from superimposed ice (Thompson, L. G., personal communication, 1996). The altitude of both core sites is about 250 m, suggesting that low-elevation ice masses in both the Canadian and the Russian High Arctic may have experienced a generally negative annual mass balance over parts of the twentieth century (cf. Grosswald and Krenke, 1962). The analysis of digital Landsat satellite imagery of Franz Josef Land, acquired during late summer, demonstrates that a number of ice caps have spectral signatures similar to that of Hayes Ice Dome, with bare ice exposed even at the crest. The implication is that ice caps with summits at less than 250–300 m may have a negative net balance through much of Franz Josef Land (Grosswald and Krenke, 1962; Dowdeswell, 1995), unless substantial accumulation is taking place through superimposed ice formation (cf. Jonsson, 1982).
Worthington Glacier in the central Chugach Mountains, which has gained a glacier-wide average of $7 \pm 5$ m (water equivalent) since 1950 (Echelmeyer et al., 1996). McCall Glacier, in the Brooks Range of northern Alaska, has mean annual balances of $-0.13$, $-0.33$, and $-0.60$ m yr$^{-1}$ for the periods 1958–1971, 1972–1993, and 1993–1995, respectively. Comparison with ice thickness changes at 10 glaciers within a 30 km radius of McCall Glacier demonstrates that McCall Glacier is representative of the regional mass balance (Rabus et al., 1995). Thus, it is likely that the glaciers of northern Alaska have experienced a generally negative mass balance since the 1950s, with a trend toward more negative values in the 1990s. Gulkana Glacier, in the central Alaska Range, has a predominantly negative net mass balance (Fig. 3a) and lost $11 \pm 5$ m in ice equivalent thickness averaged over the whole glacier between 1954 and 1993.
Further south, in the Kenai Mountains, Wolverine Glacier has a very variable annual mass balance, which is statistically indistinguishable from zero (Fig. 3a). Recent airborne laser altimeter measurements of seven additional Alaskan glaciers indicate a complex pattern since 1957. Five of these glaciers decreased in volume and two had near-zero volume change (Sapiano, 1996).

A more detailed inspection of the mass balance time series suggests some pattern within the records for individual glaciers. For example, in southern Scandinavia, one glacier (Storbreen) has been measured continuously since 1948 and the mass balances of a number of other glaciers have been monitored since 1962, providing a west–east profile from the coast inland. The results show a different trend for the western, maritime glaciers than for the more continental glaciers 200 km inland. Glaciers such as Nigardsbreen in the west (Fig. 3c) have been increasing in volume, with a cumulative mass increase of 6.5 m water equivalent in the 26-yr period 1962–1988. By contrast, the more easterly Jotunheimen glaciers have a generally negative balance before 1988, with almost 12 m of water equivalent lost on Storbreen in the 40-yr period 1948–1988. Since then, however, Storbreen and other Jotunheimen glaciers have experienced a series of positive balance years, resulting in an increase of 3 m of water equivalent from 1988 to 1993 (Fig. 3c).

Further north in Scandinavia, Storglaciären lost approxi-
Iceland since about 1970, excluding surges associated with internal ice dynamics, also suggests a positive mass balance for the main ice caps since the 1960s (Björnsson, 1979; Sigurdsson and Jonsson, 1995).

We can summarize the behavior of lower Arctic glaciers as follows. These glaciers clearly have a greater absolute interannual variability than those in the High Arctic (Figs. 2 and 3). Despite this short-term variability, most ice masses throughout the lower Arctic have experienced either a negative or a near-zero mass balance over the period of observations, which is a maximum of almost 50 yr. However, gla-

FIG. 2. Net mass balance measurements for High Arctic glaciers over the past 45 years (Jania and Hagen, 1996). The measurement sites are shown in Figure 1a. (a) Canadian High Arctic, (b) Svalbard, and (c) Russian High Arctic.

approximately 35 m in thickness between 1910 and 1972 (Holmlund, 1988). Between 1972 and 1987, the mass inputs and outputs were approximately balanced and, since about 1988, the mass balance has been strongly positive (Fig. 3b). The Icelandic ice masses of Hofsjökull and Tungnaajökull, on the west side of Vatnajökull, have also experienced high interannual variability, with a predominance of positive balance years, since observations began in the mid–late 1980s (Fig. 3b). Evidence from several other Icelandic glaciers, for example Dyngjújökull and Brúarjökull, also shows a positive net mass balance during the early 1990s (H. Björnsson, unpublished data). The advance of several outlet glaciers in

FIG. 3. Net mass balance measurements for glaciers at lower latitudes within the Arctic over the past 45 years (Jania and Hagen, 1996). The measurement sites are shown in Figure 1a. (a) Alaska, (b) Iceland and Sweden, and (c) Norway.
### TABLE 1
Areas of Circum-Arctic Glaciers and Ice Caps North of 60° N, Excluding Greenland and the Ice Masses in Alaska and the Yukon South of the Alaska Range

<table>
<thead>
<tr>
<th>Region of the Arctic</th>
<th>Ice-covered area (km²)</th>
<th>Averaged glacier mass balance (m yr⁻¹)</th>
<th>Calculated sea-level rise (mm yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Svalbard, Arctic Norway</td>
<td>36,600</td>
<td>-0.55</td>
<td>0.056</td>
</tr>
<tr>
<td>Franz Josef Land, Russia</td>
<td>13,700</td>
<td>-0.03</td>
<td>0.001</td>
</tr>
<tr>
<td>Novaya Zemlya, Russia</td>
<td>23,600</td>
<td>-0.14</td>
<td>0.009</td>
</tr>
<tr>
<td>Severnaya Zemlya, Russia</td>
<td>18,300</td>
<td>-0.03</td>
<td>0.002</td>
</tr>
<tr>
<td>Ellesmere Island, Canada</td>
<td>80,500</td>
<td>-0.08</td>
<td>0.018</td>
</tr>
<tr>
<td>Axel Heiberg Island, Canada</td>
<td>11,700</td>
<td>-0.08</td>
<td>0.003</td>
</tr>
<tr>
<td>Devon Island, Canada</td>
<td>16,200</td>
<td>-0.08</td>
<td>0.004</td>
</tr>
<tr>
<td>Baffin and other Canadian Arctic</td>
<td>43,400</td>
<td>-0.23</td>
<td>0.028</td>
</tr>
<tr>
<td>Iceland</td>
<td>11,200</td>
<td>-0.16</td>
<td>0.005</td>
</tr>
<tr>
<td>Norway and Sweden</td>
<td>2900</td>
<td>+0.03</td>
<td>-0.0002</td>
</tr>
<tr>
<td>Brooks and Alaska Ranges, Alaska</td>
<td>14,600</td>
<td>-0.21</td>
<td>0.008</td>
</tr>
<tr>
<td>Total for the Arctic</td>
<td>272,700</td>
<td></td>
<td>0.13</td>
</tr>
</tbody>
</table>

*The period over which mass balance measurements are available varies (Figs. 2 and 3), and mass loss by iceberg calving is not included in any calculations of net mass balance, because the glaciers measured for mass balance all terminate on land. However, iceberg calving provides an additional increment to net mass loss, and in this sense the values for net mass balance used in this table are likely to be more negative in areas where significant mass loss through iceberg calving takes place.*

Glaciers in maritime western Norway, for example both Nigardsbreen in the south (Fig. 3c) and Engabreen in the north (Haakensen, 1995) (not illustrated in Figure 3), have had a clearly positive mean mass balance since 1962. A recent shift toward more positive annual balances has also been observed over the whole of Scandinavia since 1988. In Iceland, glaciers have also experienced a positive balance in most years, although the datasets are of limited length. Thus, the Iceland and Scandinavia sector of the eastern Polar North Atlantic is the main region from which there are signs of glacier mass balance either being or becoming positive. On the other hand, mass balances have become increasingly negative in northern Alaska as a result of warmer summers (Rabus *et al.*, 1995). Throughout the remainder of the Arctic, where the vast bulk of ice masses are located (Table 1), mass balances show no significant trend through time, being either consistently negative, or, in a few cases, statistically indistinguishable from zero.

**Trends in the Glacier Mass Balance Time Series**

Linear regression analysis of the mass balance time series for the 18 glaciers shown in Figures 2 and 3 yielded 14, or 77%, with positive slope coefficients. Given that over 80% of the glaciers have a negative mean annual balance, this implies a tendency toward a less negative state. However, when the correlation coefficients for the fit of least squares regression lines are examined, almost all are very low. *R* values are less than 0.3 in all but four cases, and two of these are for Icelandic glaciers with six or fewer data points. Storglaciären has the highest *R* value (0.47). We conclude that the vast majority of Arctic glaciers for which mass balance time series are available show no statistically significant trend in the data. This finding is in agreement with the work of Cogley *et al.* (1995). It further implies that the mass balance of most Arctic glaciers continues to be negative.

Cogley *et al.* (1995) suggest that there is some evidence (at the 68% level of significance) for a trend toward less negative mass balance in the records from a small number of Arctic glaciers: Meighen Ice Cap in Arctic Canada, Storglaciären in Scandinavia, and Storglaciären in the Russian High Arctic. Two Spitsbergen glaciers, not included in Figure 2, also show significant positive trends. It should be emphasized, however, that each of these glaciers nonetheless has a negative mean annual balance over the period of observation.

Nevertheless, with a few exceptions (e.g., Devon Island Ice Cap), glaciers where mass balance measurements have been made tend to be small, and to occur at relatively low altitudes. As a consequence, they may not be fully representative of larger ice masses within the same region. Several Svalbard glaciers also have relatively low surface gradients, whereas Kongsvegen, a larger, higher-elevation ice mass (100 km²), had a net balance of +0.06 m yr⁻¹, averaged over the past 9 yr (Hagen, 1996). This contrasts with consistently negative values recorded at a number of smaller, lower-gradient Spitsbergen glaciers, e.g., −0.3 m yr⁻¹ for Austre Brøggerbreen (5 km²) averaged over the same interval (Fig. 2b; Hagen and Liestøl, 1990).

**METEOROLOGICAL RECORDS OF RECENT ARCTIC CLIMATE CHANGE**

Climate forcing is a major external control on glacier mass balance. It is therefore important to consider how meteoro-
FIG. 4. Meteorological records of fluctuations in mean annual and mean July temperature at Arctic stations (located in Fig. 1b). (a) Fairbanks, Alaska (64°54′N, 147°54′W). (b) Resolute, Cornwallis Island, Canada (74°43′N, 95°59′W). (c) Alert, Ellesmere Island, Canada (82°30′N, 62°20′W). (d) Upernavik,
logical variables have changed and to compare time series for them with the mass balance records presented in Figures 2 and 3. However, temperature and precipitation records from the High Arctic prior to the Second World War are available from only a few stations (Dowdeswell, 1995). Furthermore, long-established meteorological stations are usually close to Arctic settlements and often at a considerable distance from the glaciers for which mass balance observations are available. Given the strong meso- and microclimatic gradients associated with the mountainous topography in which many of the observed glaciers are located, these meteorological data provide only an indication of the climate at a given glacier.

Time series of temperature (Fig. 4) and precipitation (Fig. 5) data are available for 10 stations forming an arc around the Arctic from the Canadian sector, through Greenland and Iceland, and into Eurasia (Fig. 1b). Both the mean annual and the July mean temperature are shown. The only records from the High Arctic islands extending back earlier than the 1920s are those from Upernavik in West Greenland and Isfjord Radio (now relocated to Svalbard Airport) in Spitsbergen. Meteorological records beginning in the mid-nineteenth century are also available from Scandinavia and Iceland, and examples from Bodø, a west coast station in Norway, and Stykkisholmur in Iceland are illustrated.

The most marked trends in temperature and precipitation are found in the longest records (Figs. 4 and 5). The relatively large shifts to warmer conditions and increased precipitation are inferred to indicate the end of the Little Ice Age in these areas of the Arctic. Temperature measurements from 1875 at Upernavik (73\textdegree N) in West Greenland show a warming of 2\textdegree C in mean annual temperature between the last quarter of the nineteenth century and the mid-twentieth century, with a particularly rapid rise of about 3.5\textdegree C if the 10 years around 1920 are taken alone (Fig. 4). The mean annual temperature in Svalbard (78\textdegree N) also rose by 4\textdegree –5\textdegree C between 1912 and 1920. At Bodø there is also an upward shift of 2\textdegree –3\textdegree C in temperature, which is particularly marked in summer. However, mean July temperatures at the Greenland and Svalbard stations show much less change over the same periods (ca. 20\textdegree–40\textdegree% of the mean annual change; Fig. 4). This is significant for glacier mass balance, because summer temperatures are closely linked to glacier surface ablation, whereas a relative warming between about October and May does not lead to enhanced melting.

Precipitation also appears to have increased since the early twentieth century (Fig. 5), although it should be noted that solid precipitation is difficult to measure accurately and is often highly variable both spatially and with altitude (e.g., Woo et al., 1983; Cogley et al., 1995). A precipitation increase is most evident in the records from Icelandic stations and those on the Norwegian mainland, where the increase is on the order of 200 mm yr\textsuperscript{–1}. Indications of a similar upward shift can also be seen in the more abbreviated record from Svalbard and in the incomplete time series from Upernavik in West Greenland (Fig. 5). For these High Arctic locations, the absolute increase in precipitation is about 100 mm yr\textsuperscript{–1}.

The remaining High Arctic stations in Figures 4 and 5, with meteorological records of less than 50 yr, show a high degree of interannual variability, but also some more consistent changes on the scale of decades. For example, the interval from 1940 to the mid-1950s was relatively warm at Fedorova in the northern Taymyr Peninsula, Russia. A period of relative cooling in summer temperature, in particular from about 1964 to 1977, was recorded at Resolute, Canada (Bradley and England 1978), followed by warmer temperatures. The period from about 1920 to 1950 was especially warm in West Greenland and was followed by a cooling of approximately 1.5\textdegree C in mean annual temperature since then.

It is difficult to pick out significant trends in climate from the shorter records of most other High Arctic stations, and the minor excursions in temperature that have taken place in these areas are considerably less pronounced than the more significant changes that mark the end of the Little Ice Age in the longer datasets from Upernavik and Svalbard.

Regression analysis of trends in each of the temperature and precipitation time series in Figures 4 and 5 demonstrates that considerable spatial, as well as temporal, variability exists across the Arctic. For both mean annual and July temperatures, half the stations show a warming trend and half show a cooling trend. Trends in precipitation are almost as varied, with 6 of 10 stations exhibiting positive slopes on linear regression. Mean annual temperatures from Svalbard provide the strongest trend, with a regression slope of +0.06\textdegree C yr\textsuperscript{–1} and an R value of 0.51. The same station also provides the strongest precipitation trend of 3.2 mm yr\textsuperscript{–1} (R = 0.50). This station is, of course, one of the longer time series and arguably encompasses the end of the Little Ice Age in Svalbard.

The Canadian Arctic island stations of Resolute and Alert (Fig. 1b) show negative trends in both mean annual and July temperatures. The shorter time series, where data begin in the late 1940s, do not show statistically significant trends in meteorological parameters.

Independent analysis of Canadian Arctic meteorological datasets by Walsh and Chapman (1990) demonstrated that none of the large set of stations they examined showed statistically significant trends. Chapman and Walsh (1993) have also analyzed temperature data for Arctic stations below 75\textdegree N, first presented by Jones et al. (1986). These data are

West Greenland (72\textdegree47'N, 56\textdegree10'W). (c) Danmarkshavn, East Greenland (76\textdegree46'N, 18\textdegree40'W). (f) Stykkisholmur, Iceland (65\textdegree05'N, 22\textdegree44'W). (g) Bodø, Norway (67\textdegree16'N, 14\textdegree22'W). (h) Isfjord Radio, Svalbard (78\textdegree04'N, 13\textdegree38'W). (i) Krenkel Station, Hayes Island, Franz Josef Land, Russia (80\textdegree37'N, 58\textdegree03'W). (j) Fedorova, northern Taymyr Peninsula, Russia (77\textdegree43'N, 104\textdegree17'W).
FIG. 5. Meteorological records of fluctuations in annual precipitation at Arctic stations (located in Fig. 1b). (a) Fairbanks, Alaska (64°54'N, 147°54'W), (b) Resolute, Cornwallis Island, Canada (74°43'N, 95°59'W), (c) Alert, Ellesmere Island, Canada (82°30'N, 62°20'W), (d) Upernavik, West Greenland (72°47'N, 56°10'W), (e) Danmarkshavn, East Greenland (76°46'N, 18°40'W), (f) Stykkisholmur, Iceland (65°05'N, 22°44'W), (g) Bodo, Norway (67°16'N, 14°22'E), (h) Isfjord Radio, Svalbard (78°04'N, 13°38'E), (i) Krenkel Station, Hayes Island, Franz Josef Land, Russia (80°37'N, 58°03'E), (j) Fedorova, northern Taymyr Peninsula, Russia (77°43'N, 104°17'E).
gridded into 5° by 5° latitude–longitude cells to form a circum-Arctic dataset, with the following general trends; a marked warming from the early 1900s until the early 1940s, a slight cooling from then until the late 1960s, and a warming from the late 1960s to the termination of the time series in 1990 (Chapman and Walsh, 1993). In addition, they note that warming is most marked in winter and spring (December to May) and is limited in summer. The warming is also reported to be strongest over Alaska, northwest Canada, and northern Eurasia.

In conclusion, the records for both temperatures and precipitation are very noisy in terms of interannual and interdecadal variability for the period since the end of the Little Ice Age and even since the establishment of a relatively comprehensive network of High Arctic meteorological stations after World War Two.

**DISCUSSION**

**Glacier Mass Balance and Links with Meteorological Parameters**

Both the time series of glacier mass balance and the temperature and precipitation are quite variable from year to year across the Arctic. We have shown (Figs. 2 and 3) that a number of the records indicate that the net balance in many Arctic areas has been significantly negative over periods of up to ca. 40 yr. The few meteorological time series that extend back to and beyond the early twentieth century show that the end of the Little Ice Age was associated with warming and increased precipitation. The many negative Arctic mass balance records since that time imply that the effects of increased temperatures (Fig. 4) have dominated the rise in precipitation at these stations (Fig. 5).

A more detailed analysis of the links between Arctic glacier mass-balance and meteorological parameters can be made based on winter accumulation measured in spring and on summer melting measured in late summer or early autumn. We plot these winter and summer balances, together with the net mass balance, for several glaciers in Figure 6. The amplitude of each mass balance measurement varies between sites. However, in each case, the winter balance, affected mainly by solid precipitation, is relatively consistent from year to year, although varying more in maritime settings, and is significantly less variable than the summer mass losses (Fig. 6). The net mass balance mimics the summer balance closely, implying that variations in summer melting are most significant in influencing the net mass balance and its variability. This, in turn, implies that changes in summer conditions, rather than shifts in winter precipitation values, provide a first-order control on net mass balance over most of the High Arctic. By contrast, winter precipitation in maritime Scandinavia has increased since about 1990 (Figs. 3 and 6).

The information from glacier mass balance time series suggests no indication of a systematic increase in negative mass balance conditions which might, a priori, be expected from anthropogenically induced global warming. However, any such signal might be hidden within the noise of summer variability in mass balance records (Figs. 2, 3, and 6). By contrast, the trend toward less negative mass balance on some glaciers is consistent with the response that might be expected following the step-like warming in the early twentieth century that is linked to the end of the cold Little Ice Age.

**FIG. 6.** Examples of winter and summer mass balance data for three Arctic glaciers (Jania and Hagen, 1996). (a) Svalbard (Austre Brøggerbreen), (b) Scandinavia (Storglaciären, Sweden), and (c) Arctic Canada (Meighen Ice Cap). See Figure 1a for glacier locations. Note that net annual mass balance is influenced predominantly by variations in summer melting rather than the more consistent values for winter accumulation.
Age (Grove, 1988). Thus, Arctic glaciers may have adjusted their geometry, at least in part, to the warmer recent climate.

**Glacier Response Time to Climate Change**

The link between climate change and the response of glacier mass balance and geometry to that change is not instantaneous. A time lag is present because mass balance is perturbed throughout glacier length, but is transferred down-glacier at finite velocities over a range of distances (Johannesson et al., 1989; Dowdeswell, 1995). The effect on a glacier margin of a climatic shift is spread out over time, and the terminus position is then a weighted mean of past climate changes over the time interval \( T_m \) beyond which there is no memory of former climate (Johannesson et al., 1989). \( T_m \) is the time constant in an exponential, asymptotic approach to a new steady state after a given shift in climate. Johannesson et al. (1989) propose that

\[
T_m = h/l - b_c,
\]

where \( h \) approximates maximum glacier thickness and \( b_c \) is the mass balance at the terminus, which is a negative value. This yields timescales for adjustment to changing mass balance on the order of \( 10^2 \) yr for many Arctic valley and outlet glaciers and provides an approximation of the lag time between climatic variations and glacier response. The larger ice caps in the High Arctic, where ice may be \( > 500 \) m thick and mass loss at the margins is relatively small, probably have much longer time constants. However, Eq. (1) was developed for temperate glaciers without the dynamic complexities introduced, for example, by a spatially complex thermal structure or surge activity in some Arctic regions (e.g., Dowdeswell et al., 1991; Hagen et al., 1993).

**Arctic Glaciers and a Simple Calculation of Their Contribution to Sea-Level Change**

The implication of the Arctic mass balance data is that most glaciers have either a consistently negative net mass balance or, in a few cases, a balance very close to zero. If extrapolated to all Arctic ice masses (total area about 275,000 km², Table 1), excluding the Greenland Ice Sheet, this would produce an increase in global sea level, which is at present rising \( 1 - 2 \) mm yr\(^{-1} \) (Warrick et al., 1993). Meier (1984) has calculated that the contribution of all glaciers and ice caps to global sea-level rise, excluding Antarctica and Greenland, is about \( 0.4 \pm 0.2 \) mm yr\(^{-1} \) (Meier, 1984, 1993). Cogley et al. (1995) have used mass balance data from the Canadian Arctic islands, with a spatially averaged net mass balance of \( -0.08 \) m yr\(^{-1} \), to calculate a sea-level rise of \( 0.024 \) mm yr\(^{-1} \) contributed by the 110,000 km² of ice in this region. This is similar to Meier’s (1984) calculation of \( 0.019 \) mm yr\(^{-1} \) for the same region, based on measured and inferred ice volume changes and hydrometeorological modeling.

Thus, although the Canadian High Arctic has about 20% of the global ice cover outside the large ice sheets, by these estimates it contributes only about 5% of the water decanted to the oceans due to the melting of these glaciers and ice caps (Cogley et al., 1995). In reality, this is a minimum estimate, since mass loss through iceberg calving from grounded tidewater glaciers is neglected.

Utilizing the approach of Cogley et al. (1995), with its simple assumption that measured mass balance for a small subset of glaciers is representative of all ice masses in the region, we can derive estimates of the current contribution of Arctic glaciers to global sea-level change (Table 1). Based on this assumption, Arctic glaciers at present contribute about \( 0.13 \) mm yr\(^{-1} \) to global sea level. This is more than 30% of the worldwide contribution from small glaciers and ice caps (Meier, 1984). The regional breakdown presented in Table 1 suggests that the most significant Arctic glacier contributions are from Norwegian Svalbard and Baffin Island, and from neighboring ice masses in the Canadian Arctic (ca. \( +0.06 \) and \( 0.03 \) mm yr\(^{-1} \), respectively).

The sea-level rise from the melting of Svalbard ice masses may be overestimated, however, because the net mass balance for the large, high-altitude Kongsvegen system is approximately zero and this may be more representative of the more extensive ice caps of eastern Svalbard than the smaller valley glaciers where the bulk of mass balance measurements have been made (Hagen and Liestøl, 1990). Even so, most large non-surging Svalbard glaciers continue to retreat from their Little Ice Age limits, implying that their mass balance has been negative in the recent past (e.g., Dowdeswell, 1986). In addition, iceberg production from the 1030 km of tidewater glacier ice cliffs around the archipelago is neglected as a source of mass loss (Dowdeswell, 1989).

In some more climatically sensitive areas, such as Iceland, net mass balance has varied in sign over the past 10 yr or so. For example, the net balance for the Vatnajökull ice cap (8200 km²) is \( +0.5 \) m yr\(^{-1} \) since 1991, indicating that the calculated sea-level increment for Iceland in Table 1 has shifted in sign since the end of the last decade. Its value remains small, however.

**The Greenland Ice Sheet: A Gap in Our Knowledge**

A major gap in our knowledge of circum-Arctic glacier mass balance is the Greenland Ice Sheet. At present it is not known whether the Greenland Ice Sheet is growing larger or smaller (Reeh, 1985). Indeed, Warrick and Oerlemans (1990) conclude that available data are inadequate to detect an imbalance in mass turnover of up to 30%. Both the size of the ice sheet and the difficulties of measuring mass loss by iceberg production pose considerable problems. Short time series of stake measurements and energy balance studies have been made at several locations in the ablation zone and around the equilibrium line in West Greenland (Braithwaite and Olesen, 1993; Bøggild et al., 1994; van der Wal
and Russell, 1994). These West Greenland records, several of which are from small independent ice caps, have maximum mass balance time series of about 10 yr (Weidick, 1995). Ohmura and Reeh (1991) have summarized existing estimates of snow accumulation over the whole ice sheet.

Localized studies in the southern part of the ice sheet, applying volume-conservation principles to measurements of snow accumulation, velocity, and strain rate, suggest low rates of ice thickening. Further north, at about 70°N latitude, repeat levelling along the EGIG line showed thickening of about 0.1 m yr\(^{-1}\) in the accumulation zone between 1959 and 1968 with thinning of 0.24 m yr\(^{-1}\) below 1200 m altitude (Seckel, 1977). Using repeat satellite radar altimeter data, Zwally et al. (1989) concluded that the higher-elevation parts of the ice sheet south of 72°N had thickened by 0.2 to 0.3 m yr\(^{-1}\) between 1978 and 1986. These results were questioned by Douglas et al. (1989), based on uncertainties in the accuracy of the satellite orbits. In an attempt to resolve these questions, and to extend coverage to the entire ice sheet, satellite radar altimeter data from ERS-1 and ERS-2, together with NASA airborne laser altimetry data, are presently being obtained and analyzed. Definitive results regarding the mass balance of the Greenland Ice Sheet await a longer time series of measurements using both satellite and airborne methods.

**CONCLUSION**

- Most Arctic glaciers have experienced predominantly negative mass balance over the past few decades, although within a context of high interannual variability (Figs. 2 and 3). More than 80% of the mass balance time series from throughout the Arctic (Fig. 1) display a negative mean net mass balance. Only in maritime Scandinavia and Iceland are there recent indications of positive mass balances, associated with increased winter precipitation.

- There are few regional trends in glacier mass balance over the vast bulk of the Arctic during the past ca. 45 yr of field observations. Thus, there is no compelling indication of increasingly negative balance conditions which might, a priori, be expected from anthropogenically induced global warming. The detailed picture is complex; however, increasingly negative mass balances in northern Alaska have been accompanied by increasingly positive mass balances in maritime Scandinavia and Iceland.

- Arctic glaciers may have responded to a step-like warming in the early twentieth century associated with the end of the Little Ice Age (Fig. 4). Ice-core records from the Canadian High Arctic islands indicate that the generally negative glacier mass balances observed over the past 50 yr have probably been typical of Arctic glaciers since the end of the Little Ice Age, ca. 100 yr ago.

- The ice caps and glaciers of the Arctic adjust more quickly than the Greenland Ice Sheet to climatic perturbations such as the end of the Little Ice Age.

- Arctic glaciers and ice caps now contribute ca. 0.13 mm yr\(^{-1}\), or >30%, of the contribution to sea-level rise from glaciers and ice caps outside Antarctica and Greenland. This is about 5% of the observed global sea-level rise of about 2 mm yr\(^{-1}\). However, this calculation excludes the additional mass loss from iceberg production at tidewater glacier margins.

- It is still not known whether the Greenland Ice Sheet is in balance with the present climate. Conclusions on the growth or decay of this great ice sheet await a longer time series of measurements from satellite radar altimetry and airborne laser altimetry.

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