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Associations between Accelerated Glacier Mass Wastage and Increased Summer Temperature in Coastal Regions

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Abstract

Low-elevation glaciers in coastal regions of Alaska, the Canadian Arctic, individual ice caps around the Greenland ice sheet, and the Patagonia Ice Fields have an aggregate glacier area of about 332×10^3 km^2 and account for approximately 42% of all the glacier area outside the Greenland and Antarctic ice sheets. They have shown volume loss, especially since the end of the 1980s, increasing from about 45% in the 1960s to nearly 67% in 2003 of the total wastage from all glaciers on Earth outside those two largest ice sheets. Thus, a disproportionally large contribution of coastal glacier ablation to sea level rise is evident. We examine cumulative standardized departures (1961–2000 reference period) of glacier mass balances and air temperature data in these four coastal regions. Analyses indicate a strong association between increases in glacier volume losses and summer air temperature at regional and global scales. Increases in glacier volume losses in the coastal regions also coincide with an accelerated rate of ice discharge from outlet glaciers draining the Greenland and West Antarctic ice sheets. These processes imply further increases in sea level rise.

Introduction

Acceleration of wastage of mountain and subpolar glaciers has been reported for many regions of the globe (Arendt et al., 2002; Kaser and Osmaston, 2002; Rignot et al., 2003; Meier et al., 2003). Glaciers in coastal regions have experienced exceptionally large volume losses, and glacier retreat during the late 1980s and early 1990s has been observed in Alaska, the Patagonia Ice Fields (PIF), coastal sections of large islands in the Canadian Archipelago, and glaciers around the Greenland Ice Sheet (Rignot et al., 2003; Thomas et al., 2003; Bradley and Serreze, 1987; Braun et al., 2001). We have found that amplification of glacier wastage appears to be related primarily to climate warming (Fig. 1). The purpose of this paper is to provide new quantitative evidence on the association between increases in summer temperatures and increases in volume losses of glaciers in several coastal regions.

Data and Methods

In this paper we analyze new and recently updated observations of glacier mass balance for a number of glaciers across the globe for the period 1960 through 2003 (Dyurgerov, 2002, updated in 2005). The data are from a number of sources (IASH (ICSI)–UNESCO, 1973, 1977, 1985; IAHS (ICSI)–UNEP–UNESCO, 1988, 1993, 1998, 2005; Cogley, 2002; Dyurgerov, 2002; Dyurgerov and Meier, 2005). We focus on glaciers in coastal regions located in four regions: Alaska (glacier area is $\sim 90 \times 10^3$ km^2), coastal sections of large Islands in the Canadian Archipelago (glacier area is $\sim 151.8 \times 10^3$ km^2), glaciers around the Greenland Ice Sheet (glacier area is $\sim 70 \times 10^3$ km^2), and the Patagonia Ice Fields (glacier area is $\sim 19.9 \times 10^3$ km^2). Different, but commonly accepted methods have been used to measure, calculate, and estimate accuracy in glacier mass balance changes in these regions (Mayo et al., 1972; Østrem and Brugman, 1991; Arendt et al., 2002; Dyurgerov, 2002).

To compute a time series of global annual mass balance (b30) we used mass balance time series for all glaciers with record lengths of 30 yr and longer (Fig. 1). For Alaska (Fig. 2B), we used observations from three benchmark glaciers (i.e., Gulkana, Wolverine, and Lemon Creek). The average annual mass balance time series for these three glaciers matches well the time series derived using repeated laser altimetry methods (Arendt et al., 2002; Meier and Dyurgerov, 2002). Data for the Canadian Archipelago were obtained from a number of sources (Cogley, 2002; Dyurgerov, 2002; data from R. Koerner, private communication).

We used all available observational mass balance data for Greenland [IAHS (ICSI)–UNESCO, 1985; IAHS (ICSI)–UNEP–UNESCO, 1988; Hasholt, 1988; Knudsen and Hasholt, 2003]; however, there are limited and sporadically measured data for these sites. These limited observations have been compiled during the last three decades [IAHS (ICSI)–UNEP–UNESCO, 1988; Hasholt, 1988; Dyurgerov, 2002; Knudsen and Hasholt, 2003] and indicate significant correlation with mass balances in western Svalbard and the Canadian Archipelago (correlation coefficient of 0.72, significant at a 0.95 confidence level). Because of these significant correlations, observations for western Svalbard and the Canadian Archipelago were used to reconstruct mass balances for the Greenland glaciers back to 1961 (Fig. 2C).

Because glacier mass balance data for the Patagonia Ice Fields (Fig. 2D) are extremely scarce, we used measurements of glacier thickness from surveys made in 1995 and 2000 by the Shuttle Radar Topography Mission (SRTM) (Rignot et al., 2003). These measurements have been compared with digital-elevation-model–derived topographic maps developed in 1975, and surface changes for 63 glaciers have been determined (Rignot et al., 2003).

Monthly temperature reanalysis data set from the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml) was used to compute global and regional time series of annual and summer (June through August for the Northern Hemisphere, and December through February for the Southern Hemisphere) temperatures.

All time series (except data for the Patagonia Ice Fields) were standardized for ease of comparison using data for 1961–2000 as the reference period for the computation of departures. The standardization was performed by subtracting the long-term (i.e., 1961–2000) mean of

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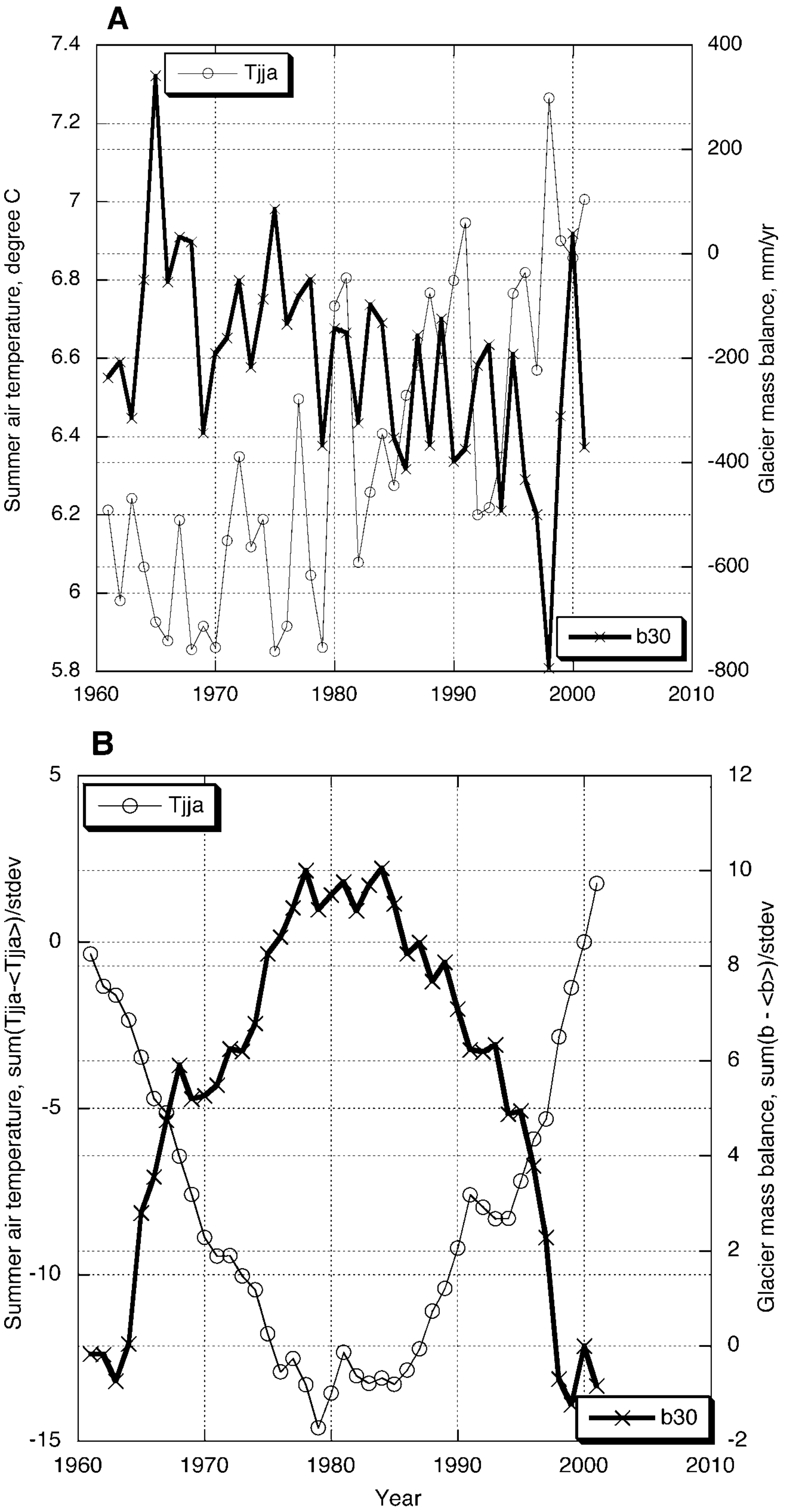

FIGURE 1. (A) Changes in globally averaged summer (June, July, August) air temperature (Tjja) and annual glacier mass balance averaged for all time series with at least 30 yr of data (b30). (B) Cumulative standardized departures of globally averaged Tjja and cumulative standardized departures of annual glacier mass balance b30. The reference period for the standardized departures is 1961–2000.

a time series from each value and then dividing by the respective long-term standard deviation. Subsequently, the time series of standardized departures were integrated to produce time series of cumulative standardized departures. Data for the Patagonia Ice Fields were not standardized because only three estimates of annual glacier mass balance were available. These data were included in the analysis because they provide some indication of glacier mass changes for glaciers in the Southern Hemisphere.

Global and regional time series of cumulative standardized departures of annual glacier mass balance and summer air temperature were compared to identify associations between these time series and to identify coincident shifts in the time series.

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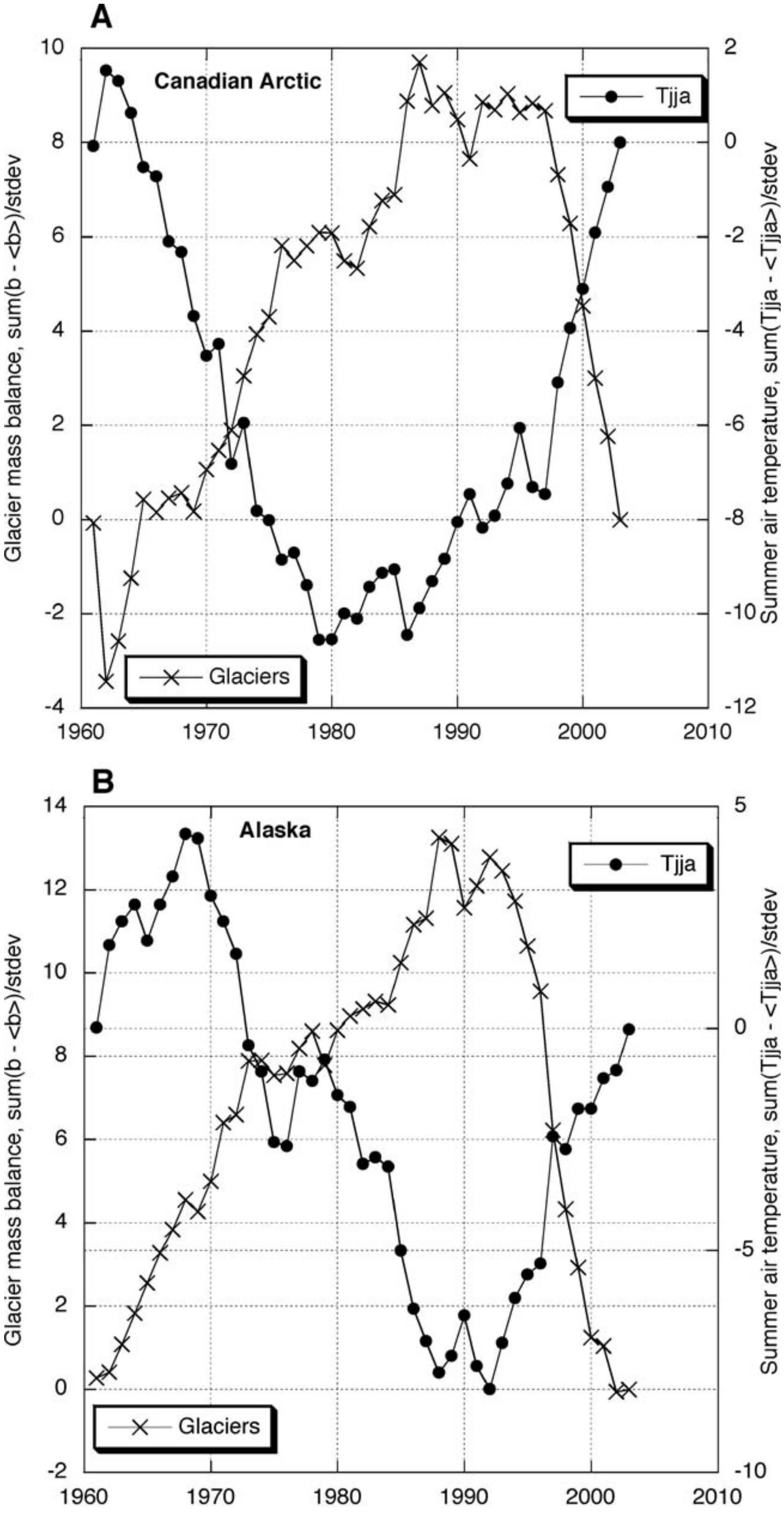

FIGURE 2. Changes in glacier mass balance averaged for all existing time series for (A) the Canadian Archipelago, (B) Alaska, (C) individual glaciers in Greenland, and (D) Northern and Southern Patagonian Ice Fields. Summer (June, July, August) air temperatures (Tjja) were computed for three of these regions using data from the following latitude/longitude boxes: Canadian Archipelago (75°N–80°N, 80°W–110°W), Alaska coast (57°N–62°N, 140°W–150°W), Greenland (60°N–70°N, 40°W–55°W). Data for (A), (B), and (C) are expressed as cumulative standardized departures (see Fig. 1). The reference period for the computation of the standardized departures is 1961–2003. For Patagonia Ice Fields (D), glacier data are given in meters of thickness change.

Acceleration in Glacier Wastage in Coastal Regions

Comparison of annual glacier mass balance with summer temperature for the Canadian Archipelago indicates a close association between these time series. In addition, an increase in the wastage of Canadian Archipelago glaciers during the late 1980s appears to coincide with an increase in summer temperature (Fig. 2A). Increases in summer temperature and melting have resulted in upward movements of the equilibrium line altitude (ELA) and runoff line altitude. Ice caps in the Canadian Archipelago are especially sensitive to changes in the ELA due to their geometry (Bradley and Serreze, 1987; Braun et al., 2001; Burges and Sharp, 2004). Similarly, time series of annual glacier mass balance for Alaska indicate an increase in mass wastage during the late 1980s that also appears related to an increase in summer air temperature (Fig. 2B).

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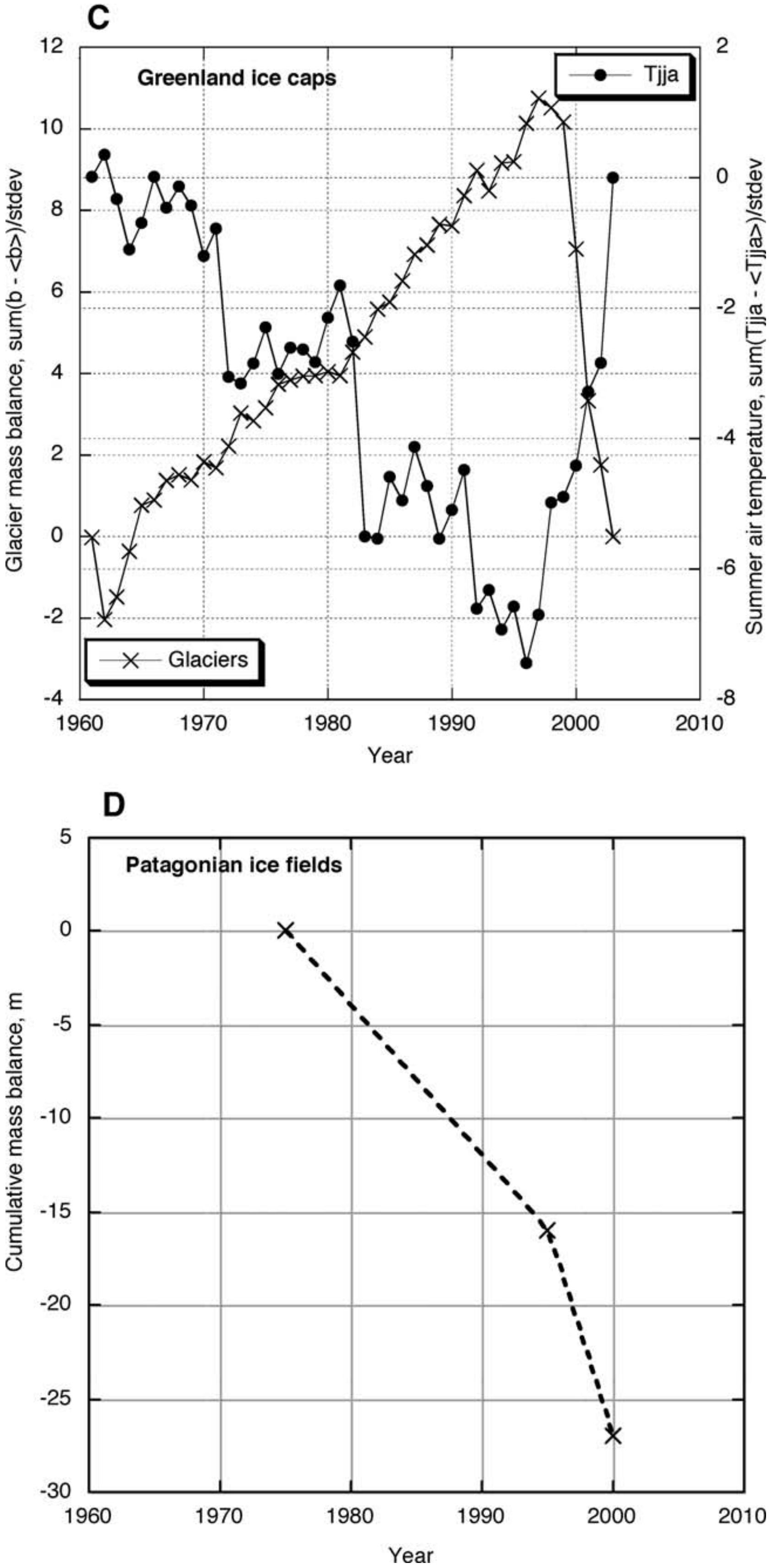

FIGURE 2. (Continued)

This result is supported by changes in mass balance and glacier volume in Alaska derived from laser altimetry surveys (Arendt et al., 2002). These surveys indicate unprecedented acceleration of glacier wastage for glaciers in Alaska since the late 1980s (Fig. 2B).

The reconstructed mass balances for Greenland also show a shift toward increased mass wastage. However, the acceleration in mass wastage for Greenland appears to have occurred later than the shift observed for the Canadian Archipelago and Alaska, i.e., around 1997,

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TABLE 1

Glacier mass balance (*b*), summer air temperature (*Ts*), and annual precipitation of earlier and recent periods in glacier regions in the Canadian Archipelago (CA), Alaska (AK), Greenland individual ice caps (GR), and Patagonia Ice Fields (PIF).

Coastal regions, periods	b (mm yr^{-1})	Ts (°C)	Annual precipitation (mm yr^{-1}), period 1961–2003*
CA, 1961–1986	−49	−0.11	230
CA, 1987–2001	−166	0.51	
AK, 1961–1993	−398	8.87	1080
AK, 1994–2001	−1452	9.57	
GR, 1961–1997	−116	0.52	1010
GR, 1998–2001	−384	1.07	
PIF, 1961–1995	−620		1170
PIF, 1996–2001	−2179		

* Values are from meteorological observations in these regions. Snow accumulation at the glacier surface likely is substantially larger, but such data are not available.

coincident with increases in summer air temperature during that time. An acceleration of glacier volume losses in Greenland is consistent with rapid surface thinning of ice observed in the southwestern and southeastern parts of the Greenland Ice Sheet; this thinning has propagated to elevations as high as 1500 and 2000 m a.s.l. (Thomas et al., 2003; Zwally et al., 2002; Krabill et al., 2004).

Other evidence of increased glacier mass wastage is the increased loss of mass from outlet and tidewater glaciers in the Northern and Southern Patagonia Ice Fields. Figure 2D suggests that glacier mass balance has declined rapidly in the Patagonia Ice Fields during the past few decades. It has been estimated that Patagonia Ice Fields have experienced a volume loss of 41.9 ± 4.4 km^3 yr^{-1} during 1975–2000 (Rignot et al., 2003). In addition, the average rate of thinning of this ice has more than doubled during the 1995–2000 period (Rignot et al., 2003). There is growing evidence that glacier retreat and volume loss in the Patagonia Ice Fields also has accelerated (Fig. 2D), but the cause of the acceleration remains unknown because of a scarcity of meteorological records on or near the Patagonia Ice Fields. There may be several causes of the apparent accelerated glacier wastage, such as increase in thinning rate in ablation areas, resulting from longitudinal stretching, ice calving into lakes, and other dynamic processes related to increased melt water on the surface and on the glacier bed (Rivera and Casassa, 2004). Warming during the winter and summer seasons during about the past 40 yr has been approximately 0.5°C at the 850 hecto-Pascal atmospheric pressure level. This warming has resulted in about a 5% decrease in the percentage of precipitation that occurs as snow and also has increased the annual melt rate in ablation areas by about 50 cm yr^{-1} (Rasmussen et al., 2003; Carasco and Quintana, 2003). In addition, other researchers have reported a slight increase in winter precipitation and increases in both winter and summer temperatures during recent years for the southern part of South America and the Antarctic Peninsula (Carasco and Quintana, 2003). The winter warming was found to be larger than the summer warming in these regions. Examination of temperature data from the NCEP/NCAR reanalysis data set indicates increased winter temperatures near the Patagonia Ice Fields after the late 1980s, but there is no increase evident in summer temperatures. Because of few observations of temperature near the Patagonia Ice Fields and the low resolution of the reanalysis data, these conclusions are only suggestive.

An important and common feature of near-coastal glaciers is that they are at low elevations, and their frontal parts, grounded or floating, are near sea level where increases in air temperature may have an enhanced effect on the melting of snow and ice. Previously it has been shown that the magnitude of summer melting is non-linearly related with increases in summer air temperature. A cubic parabola is a reliable approximation for the relation between glacier-summer melt and June–August air temperature (Krenke and Khodakov, 1966). Thus, low-elevation glaciers are highly sensitive to increases in air temperature (Meier, 1984; Oerlemans, 2001). In addition, the ratio of rain to snow increases with increases in air temperature, and increases in this ratio may have strong effects on melting because of reductions in average surface albedo and increases in absorbed solar radiation. Although glaciers in near-coastal regions generally occur in places where precipitation is high, these glaciers have been found to be mostly sensitive to changes in air temperature (Naito et al., 2001).

The amplification of melting rates for near-coastal regions has affected glaciers in coastal sections of southwestern and northwestern Scandinavia, as well. This is somewhat unusual in that these glaciers have accumulated mass since the start of observations in the early 1960s and during recent decades, when global temperatures have increased and glacier wastage has accelerated for most other glaciers worldwide (Meier et al., 2003). However, glaciers in the coastal areas of Scandinavia have started to lose mass and retreat during the past few years, possibly responding to observed changes in temperature. The recent observations of glacier mass changes for this region suggest that changes in Scandinavian glaciers are now consistent with the changes in mass balances observed for other coastal and continental regions around the world during recent decades (Meier et al., 2003; Kjøllmoen, 2003a, 2003b, 2004).

Oceanic Forcing

Another major forcing of mass changes for near-coastal glaciers is water temperature. Increases in global sea-surface temperature (0–3000 m depth) during 1955–2003 have been reported recently (Levitus et al., 2005). At the base of glaciers where floating ice is in contact with oceanic water, glacier melting may have exceeded the rate of surface melting by several orders of magnitude. Bottom melting along the 50 km floating length of the Petermann outlet glacier in Greenland (81°N) has been estimated to be on average 7 m yr^{-1}, reaching in some places as much as 50 m yr^{-1} (Steffen et al., 2004). Similarly, melting along the coastal sections of the Greenland ice sheet has been estimated to be approximately 10 m yr^{-1} (Thomas, 2004), and up to 5.5 m yr^{-1} for the West Antarctic ice sheet (Shepherd et al., 2004). Observations of mass loss for coastal regions of Greenland and West Antarctica suggest that the changes in mass and the driving processes are similar to the processes occurring in regions outside the ice sheets. Jakobshavn outlet glacier, which drains about 7% of the entire Greenland Ice Sheet, indicates an acceleration of flow rates and mass wastage since about the early 1990s (Thomas et al., 2003; Joughin et al., 2005). In addition, rapid disintegration of ice shelves and tidewater glaciers in West Antarctica and in the High Arctic has been observed (Scambos et al., 2000; Mueller et al., 2003). Ward Hunt Ice Shelf, which was the largest ice shelf in the Arctic, has rapidly disintegrated during recent summers, most likely due to increases in surface melting and the warming of sea water (Mueller et al., 2003).

Glacier Sensitivity to Temperature

A comparison of changes in glacier mass balance with changes in summer temperature (Table 1) shows the sensitivity db/dTs of glacier mass balances to changes in summer air temperature (here b is the annual mass balance and Ts is the summer air temperature averaged for three summer months). For the period 1961–2001, our observed globally averaged db/dTs was –380 mm °C yr^{-1}, which is reasonably close to the –350, –370, –390, and –410 mm °C yr^{-1} calculated by different authors and methods (see Raper and Braithwaite, 2006).

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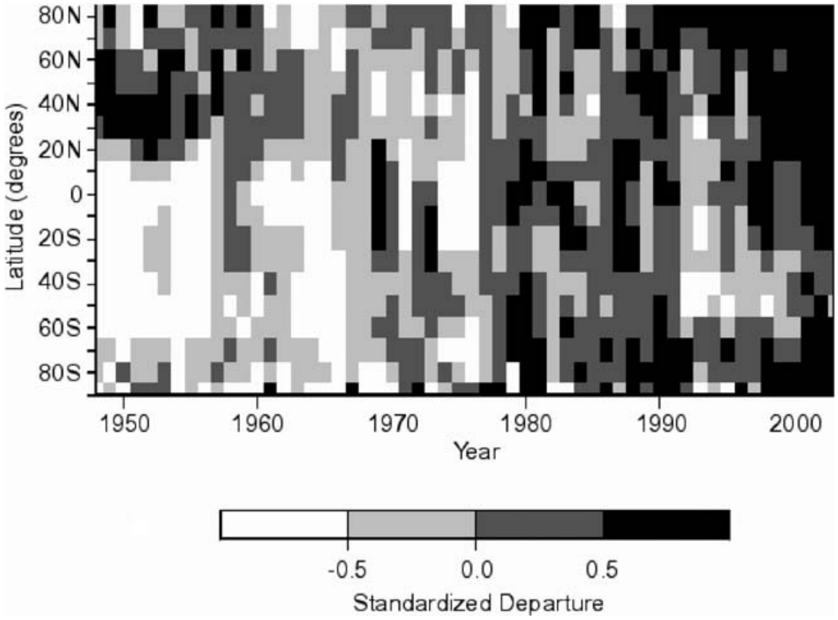

FIGURE 3. Zonally averaged standardized departures of annual air temperature for 10° latitudinal bands, 1948–2003. The reference period for the standardized departures is 1961–2000.

These global-scale similarities imply that serious progress has been made in glacier mass balance observations and modeling.

We have recently shown that the sensitivity of glaciers to temperature in the Northern Hemisphere has both increased and become dramatically less variable since 1987 (Dyurgerov, 2006). We suggest that these changes in sensitivity and its variability may have resulted from changes in zonal *Ts* distribution patterns (Fig. 3). Before the late 1980s temperature anomalies across the Earth were both positive and negative (Fig. 3). Since the late 1980s zonally averaged annual air temperature anomalies have been positive for almost all latitudinal zones (Figs. 1 and 3). These changes are global phenomena, likely related to global climate change but not yet fully explained. Glaciological observations show that these changes affected glaciers more at low elevation and near the ocean. The acceleration of volume losses for glaciers in near-coastal regions is likely indicative of larger changes at the margins of the Greenland and Antarctic Ice Sheets. Recent observations, during the 1991 through 2000 period, indicate large volume losses of the Greenland Ice Sheet that have averaged approximately 78 km^3 yr^{-1}. These volume losses correspond to a 0.21 mm rise in sea level (Box et al., 2004). In addition, glacier thinning rates in some coastal regions of West Antarctica (e.g., Amundsen Sea) for recent years are double those observed during the 1990s (Thomas et al., 2004). Vaughan (2006) suggests that mass loss from the Antarctic Peninsula as a direct response to global warming has been significant (i.e., 0.008–0.055 mm yr^{-1}) and could triple over the next 50 yr.

Increase in Glacier Wastage in Coastal Regions and Sea Level

Several recent studies have provided new estimates of sea-level rise (SLR) that are not consistent with previously published values (e.g., Church and Gregory, 2001). Cabanes et al. (2001) suggest that previously reported rates of SLR have been 2–3 times too high because many of the gauges that measure SLR are located in coastal areas where ocean temperatures are relatively warm. Cabanes et al. suggest that the true value for the thermosteric component is about 0.5–1.0 mm yr^{-1} (for 2001). Lombard et al. (2004) report an even smaller value of 0.3 mm yr^{-1} for the steric component and report a much larger residual value of SLR (observed minus thermosteric) of 1.4 ± 0.6 mm yr^{-1} (Lombard et al., 2004). Antonov et al. (2002) report a similar value of 1.4 mm yr^{-1}, which was derived based on estimates of the amount of freshwater needed to increase sea level. Antonov et al. suggest that the ice-melt on land, mostly from glaciers, is the source of this freshwater. After a reanalysis of tide-gauge data, Miller and Douglas (2004) stated that evidence suggests that changes in ocean temperature and salinity only account for a fraction of SLR and that the change in mass (the eustatic component) played a dominant role in 20th century global SLR. The findings of Miller and Douglas are consistent with the non-thermosteric value of SLR of 1.4 mm yr^{-1} by Antonov et al. (2002) and Lombard et al. (2004).

The increased wastage observed for glaciers in near-coastal regions has resulted in an increased contribution of near-coastal glaciers to globally averaged glacier volume loss (Fig. 4). The acceleration of wastage observed for near-coastal glaciers also is likely in progress at the largest ice sheets, which suggests that larger than previously estimated eustatic contributions to SLR may be occurring.

Conclusion

We compiled new mass balance observations for glaciers in coastal regions, filled gaps in some time series, and extended time series for Alaska, the Canadian Archipelago, and individual ice caps around the Greenland Ice Sheet back to 1961. We also synthesized new and previously published glacier mass balance observations. Analysis of these records indicates an increase in ice wastage for near-coastal glaciers since the late 1980s or early 1990s. This volume loss has increased from about 45% in the 1960s to 67% in 2003 of the total mass wastage from all glaciers on Earth outside the two largest ice sheets. Thus, a disproportionally large contribution of coastal glaciers to sea level is evident. These increases in volume losses are strongly associated with increases in surface summer air temperature. In addition, near-coastal glaciers indicate an increased sensitivity to air temperature. The increase in temperature sensitivity appears to have occurred during 1987–2001 for glaciers in the Canadian Archipelago, around 1994–2001 for glaciers in Alaska, during 1998–2001 for Greenland ice caps, and near 1996–2001 for the Patagonia Ice Fields. The large negative mass balances for glaciers in coastal regions are in agreement with reports of an acceleration in surface and basal melting, iceberg calving in Greenland, and observed disintegration of ice shelves in West Antarctica.

A concern raised by these results is that the acceleration in wastage of mountain glaciers and subpolar ice caps in coastal areas

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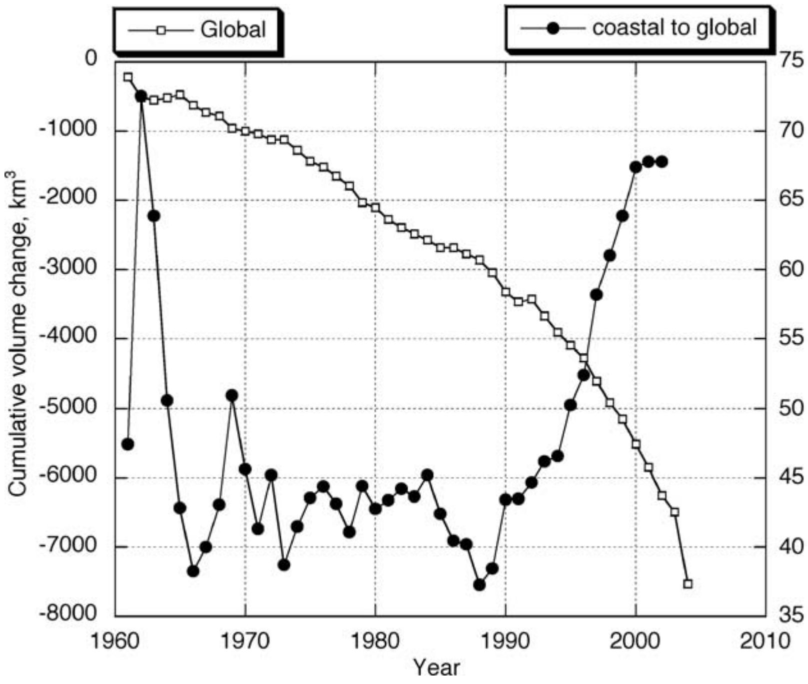

FIGURE 4. Cumulative volume change (in km^3) of the global total of changes in mountain glaciers and subpolar ice caps (these glaciers together have an aggregate area of 785 × 10^3 km^2) (Dyurgerov and Meier, 2005). Contributions of glaciers in coastal regions to this global volume change of mountain glaciers and subpolar ice caps are expressed as a % of global volume change (right y-axis).

may be an early warning of larger changes in two ice sheets; Greenland and West Antarctic. In addition, recent observations suggest that changes of these large ice sheets may have already started.

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References Cited

Antonov, J. L., Levitus, S., and Boyer, T. P., 2002: Steric sea-level variations, 1957–1994: importance of salinity. *Journal of Geophysical Research*, 107: doi: 10. 1029/200/JC000964.

Arendt, A. A., Echelmeyer, K. A., Harrison, W. D., Lingle, C. S., and Valentine, V. B., 2002: Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science,* 297: 382–386.

Box, J. E., Bromvich, D. H., and Bai, L. S., 2004: Greenland ice sheet surface mass balance 1991–2000: application of Polar MM5 mesoscale model and in situ data. *Journal of Geophysical Research,* 109: Q16105, doi: 10.1029/2003JD004451.

Bradley, R. S., and Serreze, M. C., 1987: Mass balance of two High Arctic plateau ice caps. *Journal of Glaciology,* 33(113): 123–128.

Braun, C., Hardy, D. R., and Bradley, R. S., 2001: Recent recession of a small plateau ice cap, Ellesmere Island, Canada. *Journal of Glaciology*, 47(156): p. 154.

Burges, D. O., and Sharp, M. J., 2004: Recent changes in areal extent of the Devon ice cap, Nunavut, Canada. *Arctic, Antarctic, and Alpine Research,* 36(2): 261–271.

Cabanes, C., Cazenave, A., and Le Provost, C., 2001: Sea-level rise during the past 40 years determined from satellites and in situ observations. *Science,* 294: 840–842.

Carasco, J., and Quintana, J., 2003: Long-term temperature and precipitation variability in Chile: a review. Symposium on mass balance of Andean glaciers and 1st mass balance workshop on Andean glaciers, March 12–14, 2003, Centro de Estudios Cientificos (CECS), Valdivia, Chile, Abstracts, p. 45.

Church, J. A., and Gregory, J., 2001: Chapter 11. Changes in sea level. *In* Houghton, J. T., et al. (eds.), *Climate Change. The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press, 641–693.

Cogley, G., 2002: Glacier mass balance web site (http://www.trentu.ca/geography/glaciology.html).

Dyurgerov, M. B., 2002: *Glacier Mass Balance and Regime: Data of Measurements and Analysis.* Boulder: University of Colorado, Institute of Arctic and Alpine Research, Occasional Paper no. 55 (available online at http://instaar.colorado.edu/other/occ_papers.html) Updated in 2005 (Supplement).

Dyurgerov, M. B., 2006: Northern Hemisphere glaciers responding to climate warming by increasing their sensitivity and their contribution to sea level rise. *In* Knight, Peter (ed.), *Glacier Science and Environmental Change.* Oxford: Blackwell Publ. Ltd. (in press).

Dyurgerov, M. B., and Meier, M. F., 2005: *Glaciers and the Changing Earth System: A 2004 Snapshot.* Boulder: University of Colorado, Institute of Arctic and Alpine Research, Occasional Paper no. 58 (available online at http://instaar.colorado.edu/other/occ_papers.html).

Hasholt, B., 1988: Mass balance studies of the Mitdluagkat Glacier, Eastern Greenland. *Geografisk Tidsskrift,* 88: 82–85.

IAHS (ICSI)–UNESCO, 1973: Fluctuations of glaciers 1965–1970. Zürich: Compiled for the Permanent Service on the Fluctuations of Glaciers of the IUGG–FAGS/ICSU (compiled by P. Kasser), 2: 357 pp.

IAHS (ICSI)–UNESCO, 1977: Fluctuations of Glaciers 1970–1975. Zürich: Compiled for the Permanent Service on the Fluctuations of Glaciers of the IUGG–FAGS/ICSU (compiled by F. Müller), 3: 269 pp.

IAHS (ICSI)–UNESCO, 1985: Fluctuations of Glaciers 1975–1980. Zürich: Compiled for the Permanent Service on the Fluctuations of Glaciers of the IUGG–FAGS/ICSU (compiled by W. Haeberli), 4: 265 pp.

IAHS (ICSI)–UNEP–UNESCO, 1988: Fluctuations of Glaciers (FOG) 1980–1985, Vol. V. Zürich: World Glacier Monitoring Service (compiled by Haeberli, W., and Müller, P.), 5: 290 pp.

IAHS (ICSI)–UNEP–UNESCO, 1993: Fluctuations of Glaciers 1985–1990. Zürich: World Glacier Monitoring Service (compiled by Haeberli, W., and Hoelzle, M.), 6: 322 pp.

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IAHS (ICSI)–UNEP–UNESCO, 1998: Fluctuations of Glaciers 1990–1995, Vol. VII. Zürich: World Glacier Monitoring Service (compiled by Haeberli, W., Hoelzle, M., Suter, S., and Frauenfelder, R.), 7: 296 pp.

IAHS (ICSI)–UNEP–UNESCO, 2005: Fluctuations of Glaciers 1995–2000, Vol. VIII. Zürich: World Glacier Monitoring Service (compiled by Haeberli, W., Zemp, M., Frauenfelder, R., Hoelzle, M., and Kääb, A.), 8: 288 pp.

Joughin, I., Abdalati, W., and Fahnstock, M., 2005: Large fluctuations in speed on Greenland's Jakobshavn Isbrae Glacier. *Nature,* 432: 608–610; doi: 10.1038/nature03130.

Kaser, G., and Osmaston, H., 2002: *Tropical glaciers*. Cambridge: Cambridge University Press.

Kjøllmoen, B. (ed.), 2003a: *Glaciological investigations in Norway in 2001*. The Norwegian Water Resources and Energy Directorate (NVE), Report 1: 103 pp.

Kjøllmoen, B. (ed.), 2003b: *Glaciological investigations in Norway in 2002*. The Norwegian Water Resources and Energy Directorate (NVE), Report 3: 103 pp.

Kjøllmoen, B. (ed.), 2004: *Glaciological investigations in Norway in 2003*. The Norwegian Water Resources and Energy Directorate (NVE), Report 4: 98 pp.

Knudsen, N. T., and Hasholt, B., 2003: Mass balance observations at Mittivakkat Gletscher, Southeast Greenland 1995–2002. Northern Research Basins 14th International Symposium and Workshop, Kangerlussuaq.Sdrømfjord, Greenland, August 25–29, 2003, 77–84.

Krabill, W., Hanna, E., Huybrechts, P., Abdalati, W., Cappelen, J., Csatho, B., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., and Yungel, J., 2004: Greenland ice sheet: increased coastal thinning. *Geophysical Research Letters,* 31: L24402, doi:10.1029/2004GL021533.

Krenke, A. N., and Khodakov, V. G., 1966: O svyasi povercknostnogo tayaniya lednikov s temperaturoy vozdukha [On the relationship between melt of glaciers and air temperature]. *Moscow: Materialy Glyatsiologicheskikh Issledovaniy* [Data of Glaciological Studies], 12: 153–163.

Levitus, S., Antonov, J., and Boyer, T., 2005: Warming of the world ocean, 1955–2003. *Geophysical Research Letters,* 32: L02604, doi:10.1029/2004GL021592.

Lombard, A., Casenave, A., Cabanes, C., and Nerem, R., 2004: Contribution of thermal expansion to present-day sea level rise revisited [abstract]. American Geophysical Union 2004 Fall Meeting, GC51D-1074.

Mayo, L. R., Meier, M. F., and Tangborn, W. V., 1972: A system to combine stratigraphic and annual mass-balance systems: a contribution to the International Hydrological Decade. *Journal of Glaciology,* 11(61): 3–14.

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

Meier, M. F., Dyurgerov, M. B., and McCabe, G. J., 2003: The health of glaciers . . . Recent changes in glacier regime. *Climatic Change,* 59(1-2): 123–135.

Miller, L., and Douglas, B. C., 2004: Mass and volume contributions to twentieth-century global sea level rise. *Nature,* 428: 406–409.

Mueller, D. R., Vincent, W. F., and Jeffries, M. O., 2003: Break-up of the largest Arctic ice shelf and associated loss of an epishelf lake. *Geophysical Research Letters,* 30(20): 2031, doi: 10.1029/2003GLLO17931.

Naito, N., Ageta, Y., Nakawo, M., Waddington, E. D., Raymond, C. F., and Conway, H., 2001: Response sensitivities of summer-accumulation type glaciers to climate changes indicated with a glacier fluctuation model. *Bulletin of Glaciological Research,* 18: 1–8.

Oerlemans, J., 2001: *Glaciers and climate change*. Lisse: A. A. Balkema Publishers, 148 pp.

Østrem, G., and Brugman, M., 1992: *Glacier mass-balance measurements. A manual for field and office work*. NHRI Science Report no. 4: 224 pp.

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

Rasmussen, A., Conway, H., and Raymond, C., 2003: Influence of upper air conditions on the Patagonia icefields. Symposium on mass balance of Andean glaciers and 1st mass balance workshop on Andean glaciers, March 12–14, 2003, Centro de Estudios Cientificos (CECS), Valdivia, Chile, Abstracts, p. 4.

Rignot, E., Rivera, A., and Casassa, G., 2003: Contribution of the Patagonia icefields of South America to sea level rise. *Science,* 302: 434–437.

Rivera, A., and Casassa, G., 2004: Ice elevation, areal, and frontal changes of glaciers from Natioanl Park Torres del Paine, Southern Patagonia Icefield. *Arctic, Antarctic, and Alpine Research,* 36(4): 379–389.

Scambos, T., Hulbe, C., Fahnestock, M., and Bohlander, J., 2000: The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. *Journal of Glaciology,* 46(154): 516–530.

Shepherd, A., Wingham, D., and Rignot, E., 2004: Warm ocean eroding West Antarctic Ice Sheet. *Geophysical Research Letters,* 31: L23402, doi:10.1029/2004GL021106.

Steffen, K., Cuillen, N., Huff, R., Stewart, C., and Rignot, E., 2004: Petermann Gletscher's floating tongue in northwestern Greenland: peculiar surface features, bottom melt channels, and mass balance assessment. Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO, U.S.A., Proceedings, 34th International Arctic Workshop, March 10–13, 2004, 158–160.

Thomas, R. H., 2004, Greenland: recent mass balance observations. *In* Bamber, J., and Payne, A. (eds.), *Mass balance of the Cryosphere. Observations and modeling of contemporary and future changes*. Cambridge: Cambridge University Press, 393–436.

Thomas, R. H., Abdalati, W., Frederick, E., Krabill, W. B., Manizade, S., and Steffen, K., 2003: Investigation of surface melting and dynamic thinning on Jakobshavn Isbrae, Greenland. *Journal of Glaciology,* 49(165): 231–239.

Thomas, R., Rignot, E., Casassa, G., Kanagaratnam, P., Acuna, C., Akins, T., Brecher, H., Frederick, E., Gogineni, P., Krabill, W., Manizade, S., Ramamoorthy, H., Rivera, A., Russell, R., Sonntag, J., Swift, R., Yungel, J., and Zwally, J., 2004: Antarctic glaciers flowing into the Amundsen Sea are thinning twice as fast near the coast as they did in the 1990s. *Science,* 306(5694): 255–258.

Vaughan, D. G., 2006: Recent trends in melting conditions on the Antarctic Peninsula and their implications for ice-sheet mass balance and sea level. *Arctic, Antarctic, and Alpine Research,* 38: 147–152.

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K., 2002: Surface melt-induced acceleration of Greenland ice-sheet flow. *Science,* 297(5579): 218–222.

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