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The Cryosphere Discussions

Record mass loss from Greenland's best-observed local glacier

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Abstract

Warming in the Arctic during the past several decades has caused glaciers to thin and retreat, resulting in increased freshwater runoff to the ocean. Local glaciers peripheral to the ice sheet are also retreating, but few mass-balance observations are available to quantify that retreat and determine the extent to which these glaciers are out of equilibrium with present-day climate. Here, we document record mass loss in 2009/2010 for the Mittivakkat Glacier (henceforth MG), the only local glacier in Greenland for which there exist long-term observations of both the surface mass balance and glacier front fluctuations. We attribute this mass loss to record high mean summer (June–August) and higher-than-average winter (September–May) temperatures and to lower-than-average winter precipitation. Also, we use the 15-year mass-balance record to estimate present-day and equilibrium accumulation-area ratios for the MG. We show that the glacier is significantly out of balance and will likely lose approximately 70% of its current area and 80% of its volume even in the absence of further climate changes. Temperature records from coastal stations in Southeast Greenland suggest that recent MG mass losses are not merely a local phenomenon, but are indicative of glacier changes in the broader region. Mass-balance observations for the MG therefore provide unique documentation of the general retreat of Southeast Greenland's local glaciers under ongoing climate warming.

1 Introduction

Greenland has warmed significantly during the past two decades. Summer air temperatures in Greenland's coastal areas increased by an estimated 1.7 °C, on average, from 1991 to 2006 (Comiso 2006). Mass loss from the Greenland Ice Sheet (GrIS) and from smaller glaciers and ice caps is making a significant and growing contribution to global sea-level rise (Dowdeswell, 2006; Meier et al., 2007; van den Broeke, 2009; Dyugerow et al. 2009; Mernild et al., 2010). Recent mass-balance estimates for Greenland have

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focused on the main ice sheet (Hanna et al., 2008; Ettema et al., 2009). In 2010, Greenland experienced record-setting surface melt extent and glacier area loss due to a relatively warm, dry winter followed by an exceptionally warm summer. Mean recorded temperatures were 0.6 to 2.4 °C above the 1971–2000 baseline, with the largest anomalies in the west, where melt rates were the highest since systematic observations began in 1990 (Box et al., 2010). Greenland last experienced comparable conditions in 2007, when high summer temperatures led to increased melting (Mote, 2007; Tedesco, 2007; Steffen et al., 2008), surface mass loss, and freshwater runoff (Mernild and Hasholt, 2009). As the climate has warmed, Greenland's outlet glaciers have accelerated and thinned, and the surface mass balance (the difference between annual accumulation and ablation) has become more negative. During the past several years the GrIS is estimated to have lost mass at a rate of more than 200 Gt yr^{-1} (Allison et al., 2009).

Comparable estimates are not available for glaciers and ice caps (GIC) peripheral to the main ice sheet. Although GIC have a relatively small total mass (an estimated 4.4 cm sea-level equivalent for Greenland and 60 cm globally (Radić and Hock, 2010)), they are sensitive to surface-mass-balance changes and can equilibrate to climate changes on time scales of a few decades. The rate of global mean sea-level rise resulting from GIC retreat has been estimated to be ~1 mm yr^{-1}, comparable to that from the Greenland and Antarctic ice sheets combined (Meier et al., 2007; Velicogna, 2009). This study provides information about the only local glacier in Greenland (WGMS, 2009) – the Mittivakkat Glacier in SE Greenland – for which there exist long-term observations of both the surface mass balance (since 1995) and glacier front fluctuations (since 1931). We estimate accumulation-area ratios for the MG to quantify the extent to which the glacier is out of balance with present-day climate, and we suggest that recent MG mass losses are not merely a local phenomenon but are indicative of regional changes.

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2 Methods and results

As a result of harsh climate conditions and logistical difficulties, few reliable long-term observations of mass loss and retreat are available for Greenland's remote local glaciers. The MG in Southeast Greenland (17.6 km^2; 65° 41 N, 37° 48 W) is an exception. This glacier and the surrounding landscape have been photographed at regular intervals since 1931, supplemented more recently by topographic surveys. As illustrated by Figs. 1 and 2, the glacier terminus has retreated by about 1300 m since 1931. In 1995 the observing program was expanded with the initiation of continuous and annual surface-mass-balance measurements and an automated glacier climate program. These measurements are supplemented by meteorological data from the coastal town of Tasiilaq, 15 km to the southeast.

The annual surface mass balance of the MG has been recorded since 1995/1996. In 10 out of 15 years, both winter mass balance (accumulation measured at the end of May) and summer mass balance (ablation measured at the end of August) were observed. Net mass balance data from 1995/1996–2009/2010 are illustrated in Fig. 3a. The stake method – also known as the "direct glaciological method" (Østrem and Brugman, 1991) – was used to determine annual variations and possible trends in snow and ice extent and ice volume. Snow accumulation and snow/ice ablation were measured using cross-glacier stake lines at separations of approximately 500 m. The stakes in each line were 200–250 m apart, and measurements were obtained at a total of 30–40 stakes. End-of-winter snow density was measured vertically at 25 cm depth intervals in pits at 250, 500, and 750 m a.s.l. The observed mass balance is considered to be accurate to within ∼15% for the entire glacier. Larger errors may occur locally, particularly in crevassed areas.

Meteorological conditions at the MG have been recorded since 1995 at an automated weather station operated by the Department of Geography and Geology, University of Copenhagen, located on a small nunatak at 515 m a.s.l., close to the equilibrium line (the average altitude where the net surface mass balance is zero). Long-term

(1900–2010) climatic data representative of the region are available from a synoptic meteorological station at 44 m a.s.l., operated by the Danish Meteorological Institute and located 15 km to the southeast of the MG in the outskirts of Tasiilaq, a small coastal town.

Data collected during the past year show that the MG experienced an average surface mass loss of 2.16 m water equivalent (w.eq.), or about 2% of the total glacier volume, from September 2009 through August 2010. This was the greatest annual mass loss since the expansion of the observing program in 1995, 0.34 m above the previous record set in 2005 and significantly above the 15-year average of $0.87 \pm 0.65\,\mathrm{m\,yr^{-1}}$ (Fig. 3a). At the glacier terminus the observed area-averaged melt rate ranged from 4.5 to 5.2 m, twice the 15-year average of approximately 2.5 m.

Local meteorological data indicate that higher-than-average temperatures in both winter and summer, along with somewhat lower-than-average winter precipitation, were primarily responsible for this record mass loss. During the 2010 summer ablation season (June through August) the mean MG air temperature, recorded on a nunatak (an ice-free prominence) at 515 m a.s.l., was 7.5 °C, and the mean temperature at Tasiilaq was 7.8 °C (Fig. 3b). These values are 1.8 °C and 1.4 °C, respectively, above the 1995–2010 average. During the 2009/2010 winter accumulation season (September through May), mean temperatures at the MG and Tasiilaq were −3.4 °C and −2.0 °C, respectively, or 1.3 °C and 0.5 °C above average. Uncorrected winter precipitation at Tasiilaq was ∼440 mm w.eq., or ∼260 mm w.eq. (∼40%) below the 15-year average (Fig. 3b). High summer temperatures favored increased surface ablation (evaporation, sublimation, and melt), and high winter temperatures contributed to an early start of the melt season due to the lower “cold content” of the snowpack (Bøggild et al., 2005). Low winter snowfall led to earlier exposure of glacier ice and of the previous year’s summer snow surface; these surfaces have a lower albedo than fresh snow (Douville et al., 1995), promoting greater solar absorption and increased melting. Similar weather conditions were observed in 2009/2010 throughout Greenland, more pronounced in the west and less so in the northeast (Box et al., 2010).

The general trend for the MG since 1995 has been toward higher temperatures, less snowfall, and a more negative glacier mass balance (Fig. 3a and b). Summer temperatures have increased significantly ($p < 0.01$, where p is the level of significance) at both meteorological stations by 1.7 °C at the MG and by 1.8 °C at Tasiilaq. Winter precipitation has declined by ~230 mm w.eq., although this change is within the variability of the 15-year record (Fig. 3b). In 13 of the last 15 years, the MG had a negative surface mass balance. The two years with a slightly positive balance, 1995/1996 (0.01 m w.eq.) and 2002/2003 (0.34 m w.eq.), were associated with unusually high winter precipitation (>1000 mm w.eq.) and mean summer temperatures of 4.2 and 6.1 °C (Station Nunatak) and 5.6 and 7.9 °C (Station Tasiilaq), respectively. Figure 3a shows the cumulative net mass balance for the MG since 1995/1996. The total mass loss is estimated at 13.0 ± 1.9 m w.eq., or 11% of the total ice volume determined in 1994 (Knudsen and Hasholt, 1999). Since 1995 the glacier terminus has retreated by about 200 m, as illustrated by the front observations (Fig. 1c).

The long-term record of surface temperature in Tasiilaq is reproduced in Fig. 4, together with meteorological observations from Southeast Greenland's coastal stations (ranging in elevation from 13 to 88 m a.s.l.), and from the Summit station at the top of the Greenland Ice Sheet (3208 m a.s.l). Mean-annual-air-temperature (MAAT) anomalies at Station Tasiilaq are significantly correlated with MAAT anomalies at other coastal stations (r^2 values of 0.61–0.91, $p < 0.01$, where r^2 is the explained variance) and at Summit ($r^2 = 0.42$, $p < 0.10$) (Fig. 4). These data suggest that recent MG mass losses, which have been driven largely by higher surface temperatures, are representative of the broader region, which includes many hundreds of local glaciers. Observations of eight other glaciers in the Mittivakkat region, including Sermilik Fjord and Ammassalik Island, show terminus retreats comparable to that of MG. These glaciers are similar to the MG in size and elevation range.

The accumulation-area ratio (AAR: the ratio of the accumulation area to the area of the entire glacier) has been estimated for the MG each year since 1995 (Fig. 3a), a period long enough to reduce interannual variability but significantly shorter than the time scale of adjustment to equilibrium. As shown in Table 1, the glacier is partitioned into 100 m bands, and the AAR for a given year is determined based on the equilibrium line altitude (ELA: the elevation where annual accumulation is exactly balanced by ablation) and the glacier area above and below the ELA. The average AAR is 0.15, with an uncertainty of ~0.05, and can be determined as follows. A linear regression between the AAR and the surface mass balance ($r^2 = 0.89$, $p < 0.01$) gives the relation AAR = m b + AAR$_0$, where b is the net mass balance (m yr^{-1}), m = 0.49 m yr^{-1} is the slope, and AAR$_0$ = 0.61 is the AAR when b = 0. Zero values of AAR are excluded from the regression, since AAR and mass balance are not linearly related when ablation occurs everywhere on the glacier. Based on this regression, the average AAR is defined as the predicted AAR during a year when the mass balance is equal to its 15-year mean value of −0.87 m yr^{-1}. The resulting average AAR of 0.15 is slightly lower than the 15-year arithmetic mean AAR of 0.22, which includes several years of strongly negative mass balance and zero AAR.

In several years (1998, 2001, 2005, 2007, and 2010), net ablation was recorded at all elevations between the summit (930 m a.s.l.) and the terminus (180 m a.s.l). Glaciers and ice caps in equilibrium with local climate typically have an AAR of 0.5–0.6, with a global average of 0.579 ± 0.009 (Dyurgerov et al., 2009). Expected changes in glacier area and volume can be derived from α_r=AAR/AAR$_0$, the ratio of the current AAR to its equilibrium value. (Specifically, $p_s = \alpha_r - 1$ and $p_v = \alpha_r^{\gamma} - 1$, where p_s is the expected fractional area change, p_v is the fractional volume change, and $\gamma = 1.36$ is an empirical constant (Bahr et al., 2009)). As stated above, the MG has an AAR$_0$ of approximately 0.61, close to the global average. The resulting α_r=0.25 ± 0.06 implies that the MG will lose about 75 ± 11% of its present area and 85 ± 12% of its volume (a volume loss of ~1.5 ± 0.2 km^3) if current climate conditions persist.

3 Discussion and conclusions

Local glacier observations in Greenland are rare, and MG is the only glacier in Greenland for which long-term observations of both the surface mass balance and glacier front fluctuations exist. Since 1995, the general trend for the MG has been toward higher temperatures, less snowfall, and a more negative glacier mass balance, with record mass loss in 2009/2010. In 13 of the last 15 years, the MG had a negative surface mass balance: The two years with a slightly positive balance were associated with unusually high winter precipitation. The MG is significant out of balance; an analysis of accumulation area ratios suggests that the glacier will likely lose approximately 70% of its current area and 80% of its volume even in the absence of further climate changes.

A similar analysis of glacier AARs has been used to obtain lower bounds for global sea-level rise associated with the shrinking of GIC that are out of equilibrium with present-day climate (Bahr et al., 2009). From 1997 through 2006 the average AAR for a global sample of 86 glaciers and ice caps was 0.44, suggesting that GIC will lose at least 27% of their volume (the equivalent of an 18 cm rise in global average sea level) in order to reestablish equilibrium under present-day conditions. None of these 86 glaciers is located in Greenland. Given that the average AAR for the MG is well below the global average and is likely to be typical of many of Greenland's peripheral glaciers, observations of the mass balance of MG are relevant to more informed estimates of future glacial retreat and sea-level rise.

During the past century, mean temperatures at Tasiilaq have been characterized by early-twentieth-century warming (ETCW) from 1900 until the 1930s and late-twentieth-century warming (LTCW) from 1970 to the present, interrupted by several decades of mid-century cooling (Fig. 4). Similar trends have been observed throughout the Arctic (Bahr et al., 2009). Both the ETCW and the cooling during the 1960s and 1970s appear to be connected to internal variability in the North Atlantic Ocean (Brönnimann 2009), whereas it is generally accepted that the LTCW is a regional amplification of global warming driven mainly by increased fossil fuel burning (IPCC, 2007; Chylek et al., 2010). To the extent that the recent warming is anthropogenic in origin, temperatures in the Mittivakkat region are likely to continue to increase, leading to larger area and volume losses than are projected based on the current average AAR, and possibly to the complete melting of the MG and other local glaciers of Southeast Greenland.

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Table 1. Area and accumulation-area ratios. The left column lists MG elevation bands at 100 m intervals; the middle column gives the glacier area located within each band; and the right column gives the estimated AAR when the equilibrium line altitude falls within the given band.

MG elevation bands (m a.s.l.)	Area (km^2)	AAR
> 930	–	0.00
800–930	0.77	0.04
700–799	2.65	0.19
600–699	3.99	0.42
500–599	2.70	0.56
400–499	3.16	0.75
300–399	2.35	0.89
200–299	1.44	0.97
< 200	0.54	1.00
Total	17.6	–

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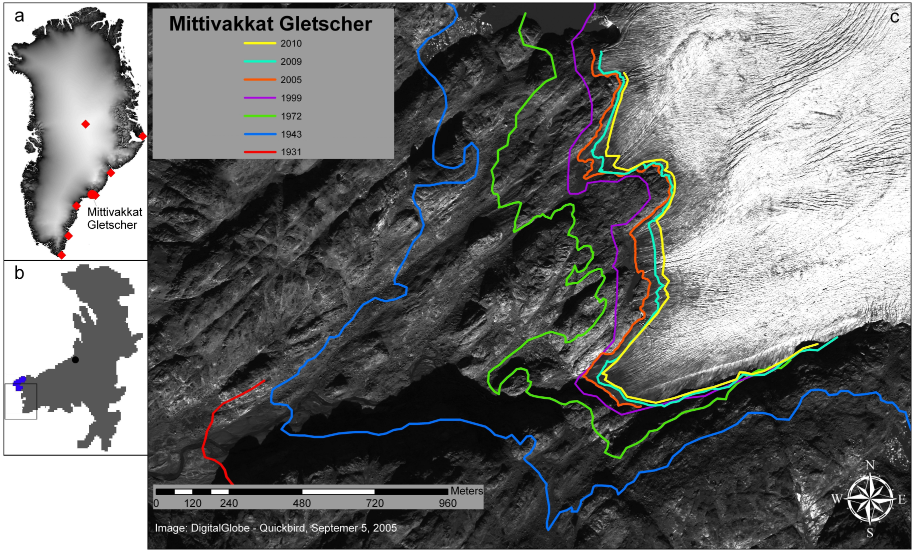

Fig. 1. (a) Location of the Mittivakkat Gletscher (red circle) and coastal meteorological stations (red diamonds) in Southeast Greenland; **(b)** glacier outline with a black square indicating the photographic area and a black circle showing the location of the meteorological station at the nunatak on the glacier; and **(c)** the location of the glacier margin delineated as thick lines for 1931, 1943, 1972, 1999, 2005, 2009, and 2010. The 1931, 1943, and 1972 margins were estimated from aerial photos, and the more recent margins were obtained from topographic surveys: Kern Theodolite and GPS-measurements (background photo: DigitalGlobe, Quickbird, 2005).

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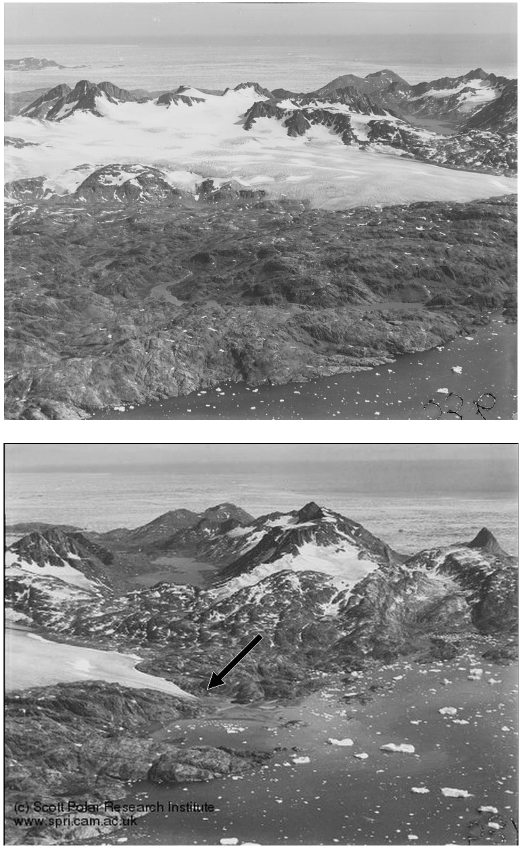

Fig. 2. (above, in black and white) Photographs of the Mittivakkat Gletscher in 1931, when the glacier margin, shown by the arrow, was within 200 m of the coastline. The photos are taken toward SSE, and in the foreground is Sermilik Fjord, and in background Irminger Sea (source: Licensed with permission of the Scott Polar Research Institute, University of Cambridge). (below, in color) Photograph of the MG in 2006, when the glacier margin was approximately 1500 m from the coast. The photo is taken toward ESE (source: Department of Geography and Geology, University of Copenhagen).

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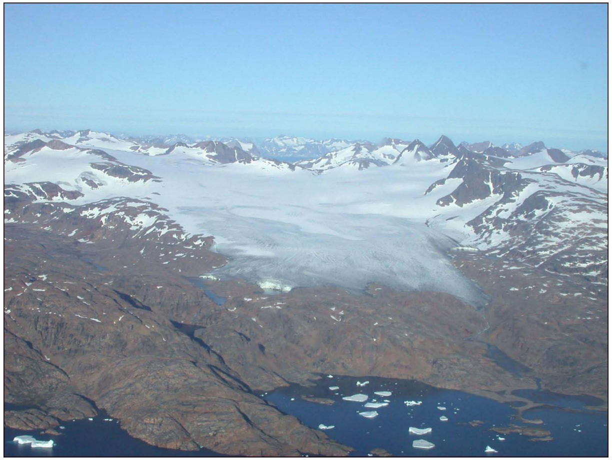

Fig. 2. Continued.

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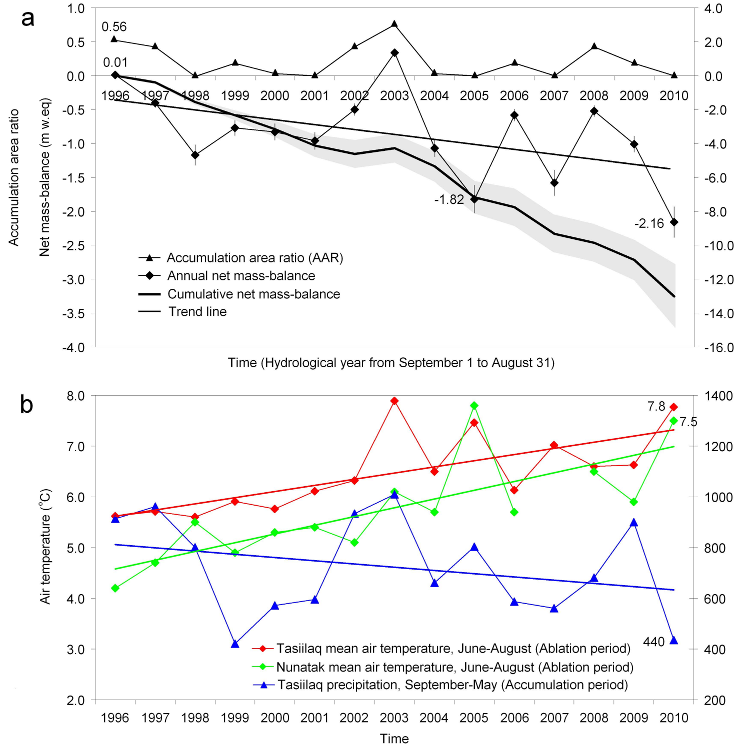

Fig. 3. (a) Observed annual mass balance (with 15% error bars), cumulative net mass balance (with a gray zone indicating the 15% error), and accumulation-area ratio for the Mittivakkat Gletscher, 1995–2010. **(b)** Time series (1995–2010) of observed winter precipitation and mean summer air temperature (June–August, ablation period) from Tasiilaq (44 m a.s.l.) and Station Nunatak (515 m a.s.l.). The straight lines are linear fits to the data; the temperature trends are statistically significant.

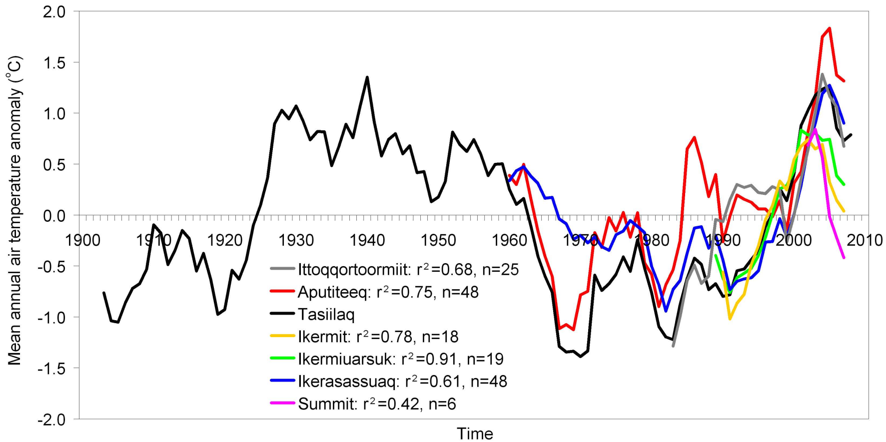

Fig. 4. Long-term time series of observed mean-annual-air-temperature anomaly from Tasiilaq and other meteorological stations in Southeast Greenland. The r^2 values indicate the correlation between the Tasiilaq anomaly and anomalies from other stations shown in Fig. 1a (Ittoqqortoormiit is farthest north, and Ikerasassuaq is farthest south).