Climate, glacier mass balance and runoff (1993–2005) for the Mittivakkat Glacier catchment, Ammassalik Island, SE Greenland, and in a long term perspective (1898–1993)

S. H. Mernild, D. L. Kane, B. U. Hansen, B. H. Jakobsen, B. Hasholt and N. T. Knudsen

ABSTRACT

Climate, glacier mass balance and runoff are investigated in the Low-Arctic Mittivakkat Glacier catchment on Ammassalik Island, Southeast Greenland. High-resolution meteorological data from the catchment covering 1993–2005 and standard synoptic meteorological data from the nearby town of Tasiilaq (Ammassalik) from 1898–2005 are used. Within the catchment, gradients and variations are observed in meteorological conditions between the coastal and the glacier areas. During the period 1993–2005 about 15% lower annual solar radiation was observed in the coastal area. Further, decreasing mean annual air temperatures (MAAT) occur in the coastal area, indicating an approximately 20-d shorter thawing period. The higher lying glacier area, in contrast, experiences an increasing MAAT, an approximately 40-d longer thawing period and a 60-d longer snow-free period. The Mittivakkat Glacier net mass balance has been almost continuously negative, corresponding to an average loss of glacier volume of 0.4% yr^{-1}. The total catchment runoff is averaging 1973 ± 281 mm w.eq. yr^{-1}, and around 30% of the runoff is explained by glacier net loss. Over the 106 years (1898–2004) MAAT has, on average, increased significantly in the catchment by 1.3°C. However, time periods of considerable variability occur. All seasons show increasing air temperatures, with the highest increase during winter season. The period 1995–2004 was the warmest 10-yr period within the last 60 yr, and 1936–1946 the warmest within the last 106 years. The calculated glacier net mass balance indicates an average glacier loss of 550 ± 530 mm w.eq. yr^{-1}, and 89 out of 105 mass balance years show a negative net mass balance. For the 106-yr period average runoff was estimated to be 1957 ± 254 mm w.eq. yr^{-1}.

Key words | Ammassalik Island, Arctic, climate, glacier mass balance, Mittivakkat Glacier, 106 years perspective (1898–2004), runoff

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INTRODUCTION

Global mean surface air temperatures have increased approximately 0.6°C over the last century (Lemke *et al.* 2007). In this period, the six warmest years have all occurred since 1998, and the 15 warmest years since 1988 (Hansen *et al.* 2007), with the largest air temperature changes in winter (Box 2002; Sturm *et al.* 2005). Climate change is a worldwide observed phenomenon; however, observations indicate that most pronounced changes occur in Arctic regions. The climate has warmed substantially since the end of the Little Ice Age to present, most significantly over the last 30 years (Serreze *et al.* 2000). The warming has been accompanied by a general increase in precipitation in the Arctic of approximately 1% decade^{-1} (ACIA 2005).

doi: 10.2166/nh.2008.101

The dynamic climate of Greenland is characterized by extremes: very cold winter temperatures, an annual cycle and a strong South–North Greenland trend of solar radiation input, a dominance of snow and glacier cover, and relatively low rates of precipitation (except for the south eastern part of Greenland), all of which results from its elevation, topography and geographic position. There are essentially two seasons, one frozen and one thawed, with an abrupt transition between them. During the winter or frozen season, which lasts 6–10 months of the year, unfrozen surface water is rare and a negative annual radiation balance is established. It is this negative radiation balance that creates the gradients that drive the Greenland and the Arctic climate (Hinzman *et al.* 2005).

A warming climate will initiate and evolve a cascade of impacts that affect, for example, glaciological and hydrological processes, and at present the Arctic is experiencing such a system-wide response to an altered climatic state. New extreme and seasonal surface climatic conditions occur and a range of processes influenced by the threshold and phase change at the freezing point are being altered. It appears that first-order impacts on the terrestrial regions of the Arctic, expected with a warming climate, will result from a longer thawing period combined with possible increases in precipitation (e.g. Anisimov & Fitzharris 2001; Hinzman *et al.* 2005; Mernild *et al.* 2007*a*,*b*). The combined effect generally results in longer snow-free seasons and produces secondary impacts that could cause, for example, greater melt of glacier ice and snow, and a deeper active layer. At present, the Arctic hydrological cycle is shifting, and the effect of a warmer climate on the hydrological processes in the Arctic has already become apparent. Basins with a substantial glacier component consistently display an increasing trend in runoff, presumably due to increases in glacier melt. River basins without significant glaciers tend to show a decreasing runoff (Kane & Yang 2004).

The aim of this study is to describe the climate and observed climatic variations and trends in the Mittivakkat Glacier catchment in Low Arctic East Greenland from 1993 to 2005, and its control on freshwater runoff from the catchment and glacier mass balance. Based on the period of detailed observations (1993–2005) and supported by synoptic meteorological data from the nearby town of Tasiilaq (Ammassalik) from 1898 to 2004, variations and trends in catchment air temperature, Mittivakkat Glacier net mass balance and catchment freshwater runoff were modeled, to get a long term perspective.

STUDY AREA

The Mittivakkat Glacier catchment (18.4 km^2) (65°42′N latitude; 37°48′W longitude) (Figure 1) is located on the western part of Ammassalik Island, Southeast Greenland, approximately 15 km northwest of Tasiilaq and 50 km east of the eastern margin of the Greenland Ice Sheet (GrIS). The island is separated from the mainland by the 10–15 km wide north–south-going Sermilik Fiord. The area is considered to be Low Arctic according to Born & Böcher (2001), and representing a very humid part of Greenland. The catchment is characterized by sporadic permafrost and by a strong alpine relief and ranges in elevation from 0 to 973 m a.s.l., with the highest altitudes in the eastern part of the catchment. The Mittivakkat Glacier catchment is drained by the glacier outlet from the most southwestern part of the Mittivakkat Glacier (31 km^2) through a proglacial valley (Figure 1). The ice-free land within the catchment (22%; 4.0 km^2) is dominated by bare bedrock in the upper parts, and loose talus and debris-flow deposits in the lower parts of the slopes. The proglacial valley contains both glacial deposits and fluvial sediments (e.g. Hasholt & Mernild 2004). The catchment is covered by parts of the Mittivakkat Glacier complex (78%; 14.4 km^2), a temperate glacier with an average thickness of approximately 115 m, and ranging from approximately 160–930 m a.s.l. in elevation (Knudsen & Hasholt 1999). Since 1933 the glacier terminus has retreated about 1.3 km, with a decrease in glacier surface elevation up to 100 m in the ablation area below 300 m a.s.l.

DEGREE DAY INDICES AND PARAMETER DEFINITIONS

The accumulated number of Thawing Degree Days (TDD) is the sum of positive mean daily air temperatures (Mernild *et al.* 2005) (TDD is also referred as PDD (Positive Degree Days)). TDD is related to the release of water from both the

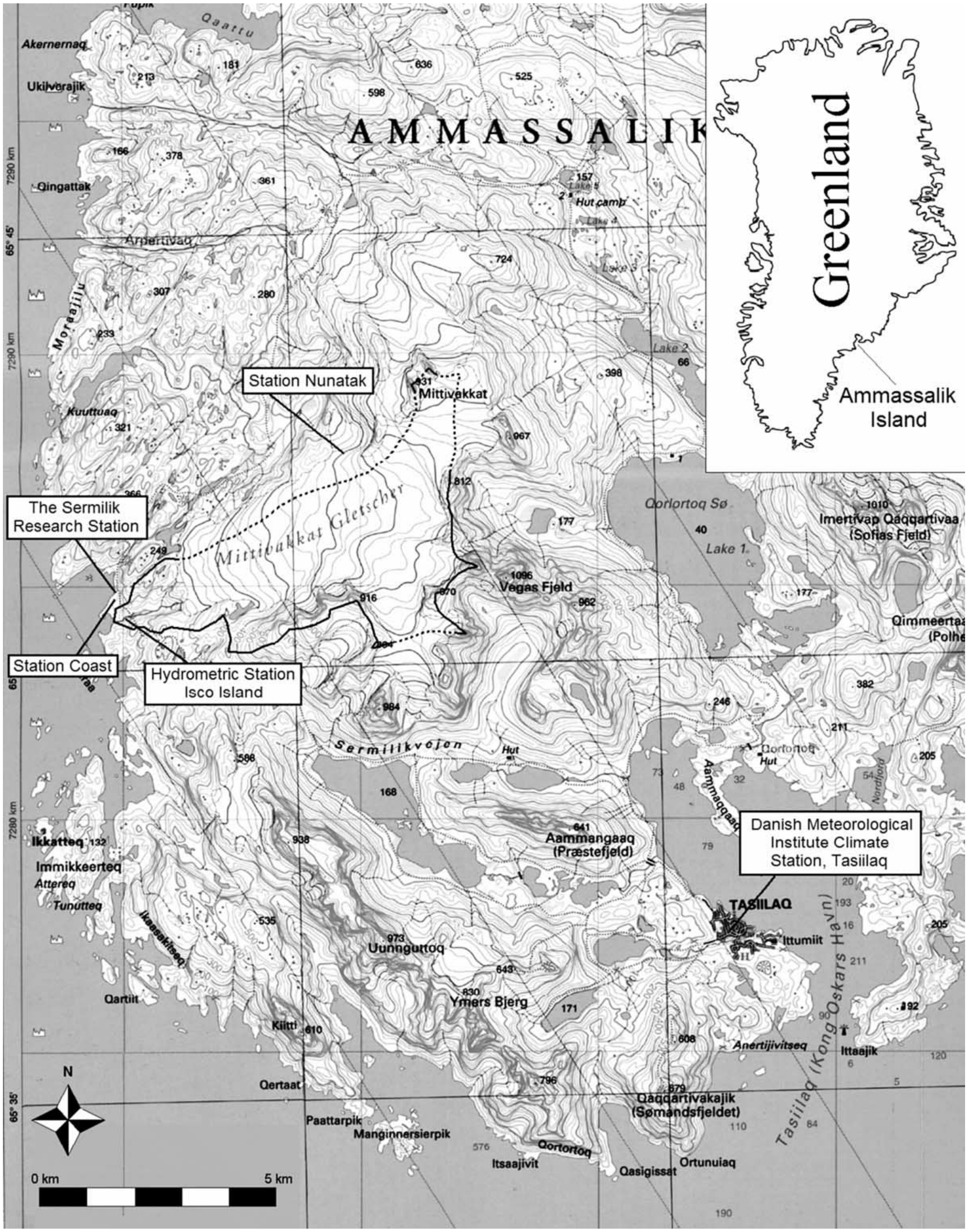

Figure 1 | Location map showing the Mittivakkat Glacier catchment (18.4 km^2), Ammassalik Island, including meteorological stations: Station Nunatak (515 m a.s.l.) and Station Coast (25 m a.s.l.), the Danish Meteorological Institute (DMI) climate station in Tasiilaq (Ammassalik) (named Station Tasiilaq), and the hydrometric station at Isco Island. The dashed line indicates the topographic watershed divide on the Mittivakkat Glacier and the solid line the topographic watershed divide on bedrock for the Mittivakkat Glacier catchment. The inset figure indicates the general location of the Mittivakkat Glacier catchment within Eastern Greenland (modified after Greenland Tourism).

perennial snow pack and the exposed glacier ice surfaces after the annual snow cover has ablated. An increase in TDD will cause increased surface melt and catchment runoff for the Mittivakkat Catchment.

The elements of the water balance for a drainage basin depend on drainage basin characteristics and water balance processes. The yearly water balance simulation period goes from September through August of the following year; this is mainly due to the annual cycle of the Mittivakkat Glacier net mass balance (Knudsen & Hasholt 2004; Mernild *et al.* 2006*c*). The Mittivakkat Glacier catchment water balance Equation (Equation (1)) is

$$P-(ET+SU)-R\pm\delta S=0\pm\eta \tag{1}$$

where P is the precipitation input from snow, rain and possible condensation, ET is evaporation, SU is sublimation, R is runoff and δS is change in mass balance resulting from changes in glacier storage and snow pack storage. Storage also includes changes in supraglacial storage (lakes, pond, channels, etc.), englacial storage (ponds, water table, ice lenses and superimposed ice) and subglacial storage (cavities and lakes); these storage components were not simulated. Here η is the water balance discrepancy (error). The error term should be 0 (or small) if the major components (P, ET, SU, R and δS) have been determined accurately. The total runoff is normally the most reliable component measured in the water balance if the stage–discharge relation is stable and valid. The runoff is an integrated response of the hydrological processes in the catchment and, unlike most other variables in the water balance equation, it is not affected by how representative the measuring station is (Killingtveit *et al.* 2003).

DATA AVAILABILITY AND METHODS

This study is based on: (1) meteorological and hydrological data from 1993–2005 measured and modeled within the Mittivakkat Glacier catchment and (2) standard synoptic meteorological data from 1898–2005 recorded at the Danish Meteorological Institute (DMI) climate station at Tasiilaq; named Station Tasiilaq (Figure 1).

In order to capture the glacier's climate, a meteorological station, Station Nunatak, has continuously every third hour since 1993 measured the meteorological conditions on the nunatak (65°42.3′N; 37°48.7′W, 515 m a.s.l.) situated on the northern side of the Mittivakkat Glacier, close to the equilibrium line altitude (ELA: where annual ablation equals annual accumulation). The station registers the following parameters: wind direction (4.0 m above terrain), wind speed and wind gust (2.0 and 4.0 m), air temperature (2.0 and 4.0 m), relative humidity (4.0 m), incoming and outgoing short-wave radiation and net radiation (4.0 m) (e.g. Hasholt & Mernild 2004; Hasholt *et al.* 2004). Liquid (rain) precipitation was measured by a tipping bucket 0.45 m above the ground, approximately the height of local roughness element (Mernild *et al.* 2006*c*). Snow water equivalent (SWE) was calculated from snow depth sounding observations (Campbell SR50 station) after Anderson (1976), and SWE values are assumed to be accurate within ±10–15%.

Later, in 1997 a second automated meteorological station, Station Coast, was established on a rock hill at the coast (65°40.8′N; 37°55.0′W, 25 m a.s.l.) in order to record the climate in the coastal region, and gradients and orographic effects between the two stations. Again, average values are measured in three hour intervals. The following sensors were mounted 2.0 m above the terrain: wind direction, wind speed, wind gust, air temperature, relative humidity, incoming and outgoing short-wave radiation, and net radiation. Liquid precipitation was measured by a tipping bucket 0.45 m above the ground. SWE was calculated by depth sounding observations during winter at the nearby hydrometric station Isco Island, where the summer river stage variations were measured. The hydrometric station Isco Island (65°40.6′N; 37°54.7′W, 6 m a.s.l.) is located close to the coast and approximately 200 m southwest from Station Coast.

After noise was removed manually from the snow depth data (Campbell SR50), the snow-depth sounding observations were partitioned into liquid (rain) precipitation and solid (snow) precipitation at different air temperatures (Førland & Hanssen-Bauer 2003). For air temperatures below −1.5°C, sounding observations represent solid precipitation in 100% of the events, and for temperatures above 3.5°C precipitation is liquid for 100% of the events. In between (−1.5°C to 3.5°C) the fraction of snow and rain (mixed precipitation) is calculated by linear interpolation

(Førland & Hanssen-Bauer 2003). Air temperature at the nunatak was used to determine whether precipitation in solid, mixed or liquid occurred. The air temperature at the nunatak (at the higher elevation) is more representative for the air temperature where snow flakes form. Measured increases in snow depth at relative humidity $<80\%$ and at wind speeds $>10\,\mathrm{m\,s^{-1}}$ were removed to distinguish between the situations of real snow accumulation based on precipitation events and blowing snow redistribution (Mernild *et al.* 2008*a*; 2007*a*,*b*). The snow-depth increases were adjusted using a temperature-dependent snow density (Brown *et al.* 2003) and an hourly snow pack settling rate for estimating the snow depth (Anderson 1976): snow settles as it accumulates and thus the snow depth on the ground is always less than the measured thickness of the initial snowfall. Further, Station Nunatak simulated end-of-winter SWE depth was compared and adjusted against the observed Mittivakkat Glacier winter mass balance, showing an average underestimated SWE depth of 29% (1999–2002) before adjustment due to the exposed station location and redistribution of snow by wind on the nunatak (Mernild *et al.* 2006*c*, 2008*b*). The sensor type, accuracy and range were described in Hasholt *et al.* (2004).

Measured daily air temperatures and calculated TDD values from the climate stations in the Mittivakkat Glacier catchment have been compared with daily data from Station Tasiilaq (Table 1) in order to generate time series at the Mittivakkat Glacier catchment covering the last 106 years. This allowed us to calculate monthly values for the two stations in the Mittivakkat Glacier catchment for the period 1898–1993. The data were converted into cumulative winter TDD (September–May), summer TDD (June–August) and annual TDD values (September–August). When data from the Mittivakkat Glacier catchment are compared to other data series it is clear that the combined meteorological observations and predictions at the catchment are in line with other long term records. Further, the summer TDD (June–August) was related to the Mittivakkat Glacier summer mass balance for the period 1995/96 to 2002/03, and station Tasiilaq uncorrected winter precipitation (September–May) was compared to the Mittivakkat Glacier winter mass balance (1995/96 to 2002/03) in order to predict the net glacier mass balance for the period 1898/99 through 1994/95 (Table 2). For 1995/96 to 2002/03 linear regression indicate a R^2 value (the explained variance) of 0.71 ($p < 0.01$) between observed and calculated Mittivakkat net glacier mass balance (Table 2). The mass balance measurement on the glacier at 1986/87 showed a net balance of -0.12 m w.eq. yr^{-1} (Hasholt 1988): The estimated value for 1986/87 is -0.15 m w.eq. yr^{-1}.

Table 1 | Statistical information about air temperatures between the stations in the Mittivakkat catchment (Station Nunatak and Station Coast) and Station Tasiilaq, where *n* is the number of observations, *p* is the level of significance and rmse is root mean square error

	Air temperature Station Tasiilaq and Station Nunatak	Air temperature Station Tasiilaq and Station Coast
Time	1997–2004	1997–2004
Method	Linear regression	Linear regression
Time step	Daily	Daily
n	2,921	2,921
R^2	0.86	0.88
p	0.01	0.01
Rmse	3.2	2.3

In the Mittivakkat Glacier catchment, melting glacier snow and ice are responsible for up to 90–95% of the yearly catchment runoff (Mernild 2006*a*), due to the high percentage of glacier cover of 78%. Therefore, the observed net glacier mass balance was related to the annual observed catchment runoff (September–August) (1995/96 to 2003/04) by linear regression ($R^2 = 0.76$) in order to calculate the annual runoff (September–August) from 1898–2004.

Winter and summer glacier mass-balance observations were carried out in late May and early June, and in late August, respectively, to estimate changes in glacier storage and snow pack storage. During the field campaigns, snow depth, density and ablation from snow and glacier ice were measured using cross-glacier stake lines spaced approximately 500 m apart. The distance between the stakes on each line was 200–250 m apart (Knudsen & Hasholt 2004). The assumed accuracy of the observed winter and summer mass balances are each within ±15%; however, larger errors might occur, especially in parts of the glacier with many crevasses (Knudsen & Hasholt 2004).

SnowModel is a spatially distributed snow-pack evolution modeling system (Liston & Elder 2006*a*). The model simulates accumulation and loss from snow

Table 2 | Statistical information between Station Tasiilaq uncorrected winter precipitation (September–May) and observed Mittivakkat winter balance, Station Tasiilaq thawing degree day (TDD) and observed Mittivakkat summer balance, and observed and calculated Mittivakkat Glacier net mass balance

	Station Tasiilaq uncorrected winter precipitation (September–May) and the Mittivakkat Glacier winter mass balance	**Station Tasiilaq cumulative summer TDD (June–August) and the Mittivakkat Glacier summer mass balance**	**Observed and calculated Mitivakkat Glacier net mass balance**
Time	1995/96–2002/03	1995/96–2002/03	1995/96–2002/03
Method	Linear regression	Linear regression	Linear regression
n	8	8	8
R^2	0.68	0.55	0.71
p	0.01	0.01	0.01

precipitation, blowing-snow redistribution, evaporation, sublimation, snow-density evolution, snow-pack ripening, snow and glacier ice melt, and snow and glacier ice runoff for the Mittivakkat Glacier catchment for the period 1998–2004. The model is specifically designed to be applicable over the wide range of snow landscapes and climates (Liston & Elder 2006*b*; Mernild *et al.* 2006*c*; Liston *et al.* 2007).

SnowModel includes a micrometeorological model (MicroMet). MicroMet is a quasi-physically-based meteorological distribution model (Liston & Elder 2006*a*) designed to produce high-resolution meteorological forcing distributions of meteorological data into a wide variety of terrestrial landscapes. SnowModel simulations have previously been compared and validated against observations in the United States: Colorado (Greene *et al.* 1999), Wyoming (Hiemstra *et al.* 2002, 2006), Idaho (Prasad *et al.* 2001) and Arctic Alaska (Liston *et al.* 1999, 2002, 2007; Liston & Sturm 1998, 2002); Norway, Svalbard and central Norway (Bruland *et al.* 2004), Greenland (Hasholt *et al.* 2003; Mernild *et al.* 2006*b*,*c*; 2007*b*; 2008) and near-coastal Antarctica (Liston *et al.* 1999, 2000). In the Greenland studies, SnowModel produced maximum discrepancies of 8% in SWE depth (Mernild *et al.* 2006*b*,*c*).

Intra- and inter-annual catchment runoff was simulated through the use of the NAM model (Nedbørs Afstrømnings Model means Rain and Runoff Model in English) (a lumped conceptual rainfall–runoff model) (DHI 2003*a*,*b*; Mernild & Hasholt 2006). The model describes in a quantitative form the behavior of the land phase hydrological cycle by a set of linked mathematical statements, simulating hydrological processes such as overland-flow, inter-flow and base-flow components. This as a function of the moisture content in four different interrelated reservoirs representing snow storage, surface storage, root zone storage and groundwater storage. Simulated discharge and runoff values for the Mittivakkat Glacier catchment were compared against observed values, showing a maximum daily difference up to 3.4 $m^3 s^{-1}$, and up to 11% difference between observed and simulated cumulative discharge. The model also predicted river break-up defined as days with subsequent continuous discharge. Simulated date for river break-up occurred 1–3 d before observed river break-up (Mernild & Hasholt 2006). Observed discharge at the Isco Island hydrometric station (Figure 1) was calculated from stage–discharge relationships estimated each year (R^2 values from 0.91–0.99) using regression analysis. The discharge cross section has been stable for approximately 30 yr, yielding an assumed 10–15% accuracy when measured values are compared with values calculated from a stage discharge relationship (e.g. Mernild & Hasholt 2006).

RESULTS AND DISCUSSION

Overall climatic conditions

The climate in the Ammassalik area is affected by the GrIS and the East Greenland Polar Sea Current which has a surface temperature close to 0°C throughout the year and which transports drift ice most of the year. Winters are moderately cold with only short periods of above-freezing temperatures. In coastal areas, summers are very cool with moist and foggy conditions, whereas slightly warmer and sunny conditions are found inland and in the inner parts of the fjords, away from the ocean. Winds and precipitation in the area are strongly affected by lows. Most lows affecting Greenland arrive from directions between south and west, steered by an upper level cyclone, the 'polar vortex', in winter centered over the Canadian Cold Pole, and in summer less pronounced and situated over the Arctic Ocean (Hansen *et al.* 2008).

Meteorological conditions 1993–2005

Solar radiation, albedo and snow cover

The midnight sun (summer solstice) line passes through Tasiilaq, while the polar night (winter solstice) line is located about 200 km further north. The surrounding topography, slope/aspect of the terrain and cloud cover has a great influence on the amount of incident incoming solar radiation. In high latitude Arctic regions the geographical latitude is the main factors determining the weather and climate. At Station Nunatak the surface is gently sloping from N, NE, and E towards SW and W; diurnal variations in outgoing solar radiation are measured compared to a horizontal surface. Morning values are lower and afternoon values are higher than average. At Station Coast, the solar measurements are influenced by the mountains to the E and NE of the station. In periods with dense cloud cover direct solar radiation is reduced, leaving only diffuse radiation (about 20–30% of potential radiation) to reach the surface. The mean annual solar radiation is respectively 113 W m^{-2} and 95 W m^{-2} for Station Nunatak (1993–2005) and Station Coast (1997–2005) (Figure 2). This indicates approximately 15% lower annual solar radiation in the coastal area due to the high frequency of dense clouds or thin sea fog, occurring when relatively warm, moist air flows in over a cold surface. Further to the north, at the Zackenberg catchment (74°N) the mean annual solar radiation is 106 W m^{-2} (1995–2003) (Mernild *et al.* 2007*a*,*b*), approximately 6% lower compared to Station Nunatak. Variations in albedo at Station Nunatak and Station Coast are also seen in Figure 2, where low values around 15–20% indicate snow-free periods at the stations; a period that occurred approximately 4 weeks earlier in the coastal area compared to the nunatak. However, the maximum average yearly snow depth in the coastal area is 2.2 m, and up to ~0.8 m (~50%) higher (1998–2004) than at the nunatak, based on variations in coastal micro-climate between Station Coast and the hydrometric station Isco Island. The maximum annual snow depth at Station Nunatak varies between 0.95 m (2002/03) and 1.72 m (2000/01), while at Station Coast between 1.73 m (2002/03) and 2.52 m (1999/00). During the 6-yr period (1998–2004), a continuous winter snow cover each year at Station Nunatak is established between the end of September/beginning of November, and it lasts until the end of June/beginning of July (Figure 3). Linear regression shows that the number of days with snow cover at Station Nunatak has decreased by 62 d; this partitions into 43 d in autumn ($R^2 = 0.57$; $p < 0.05$) and by 19 d in spring ($R^2 = 0.92$; $p < 0.01$). In total the snow cover changed from 286 snow cover days in 1998/99 to 224 snow cover days in 2003/04. Prudence should be drawn when only six years of data are used; however, the observations clearly indicate a longer snow-free season (Figure 3). During the same period, a longer snow-free period is also observed in the Zackenberg catchment. The length of the snow-cover period has decreased 50 d (10 d in spring and 40 d in autumn) from 304 d in 1997/98 to 253 d in 2002/03 (Mernild *et al.* 2007*a*,*b*). At both sites, and probably for East Greenland in general, the decreasing length of the snow-cover period is presumably caused by increasing air temperatures and enhanced thawing rates.

Air temperature and degree day

The Mittivakkat Glacier catchment mean annual air temperature (MAAT) is −1.7°C (1998–2004), −2.4°C (2.0 m) at Station Nunatak (1994–2004) and −1.1°C (2.0 m) at Station Coast (1998–2004). Linear regression shows a significant increasing MAAT of 0.06°C yr^{-1} in the upper glacier area and decreasing values in the coastal area of −0.13°C yr^{-1} for the period 1998 to 2004 (Figure 4(a), Table 3). The difference in MAAT between the stations has decreased from −1.6°C in 1998 to 0°C in 2003 (Figure 4(a)). This probably emphasizes a shift in regional climate regimes towards more maritime conditions. At the Zackenberg catchment observed air temperatures further indicate an annual warming of approximately 0.1°C yr^{-1}

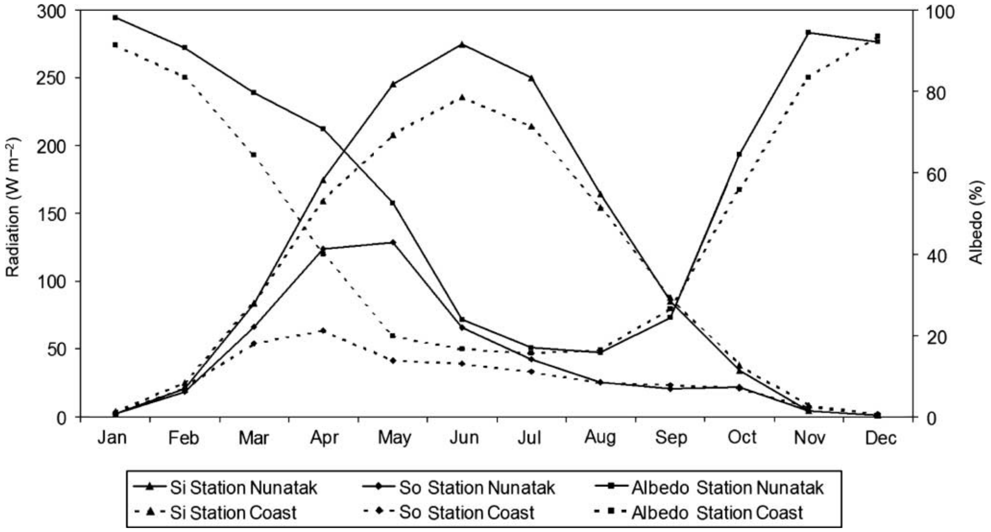

Figure 2 | Mean monthly incoming (Si) and outgoing solar radiation (So) and albedo at Station Nunatak (1993–2005) and at Station Coast (1997–2005).

(1996–2003) and a warming in all seasons except in the spring (March–May) (Mernild *et al.* 2007*a*,*b*). Mean minimum air temperature occur in February for both Station Nunatak and Station Coast, in contrast to the average warmest month which is July at the nunatak and August at the coast (Table 3). A difference in warmest months between the stations, both in value and time, is probably due to, for example, differences in albedo, heat capacity of the Sermilik Fjord, near Station Coast and the high frequency of dense clouds or thin sea fog in the coastal area. At Station Coast, positive mean monthly air temperatures occur from May to September and at Station Nunatak from June to September (Figures 4(b, c), Table 3).

Mean monthly air temperature lapse rates for the Mittivakkat Glacier catchment are shown based on data from the two meteorological stations (Figure 4(d)). The mean annual air temperature lapse rate was approximately −0.3°C per 100 m (1997–2004), with an average range between the most negative and the most positive mean monthly lapse rate of around 1.0°C 100 m^{-1}. February had the lowest average lapse rate of −0.6°C per 100 m, while July had the highest of 0.4°C per 100 m (Figure 4(d)).

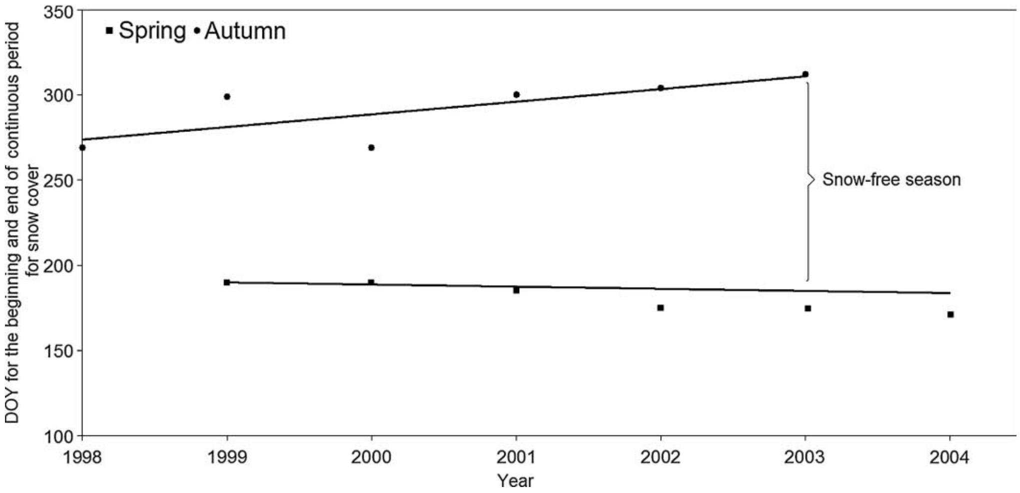

Figure 3 | Day of year (DOY) for the beginning and the end of the continuous period for snow cover (1998–2004) at Station Nunatak. The area between the two trend lines indicates the snow-free season.

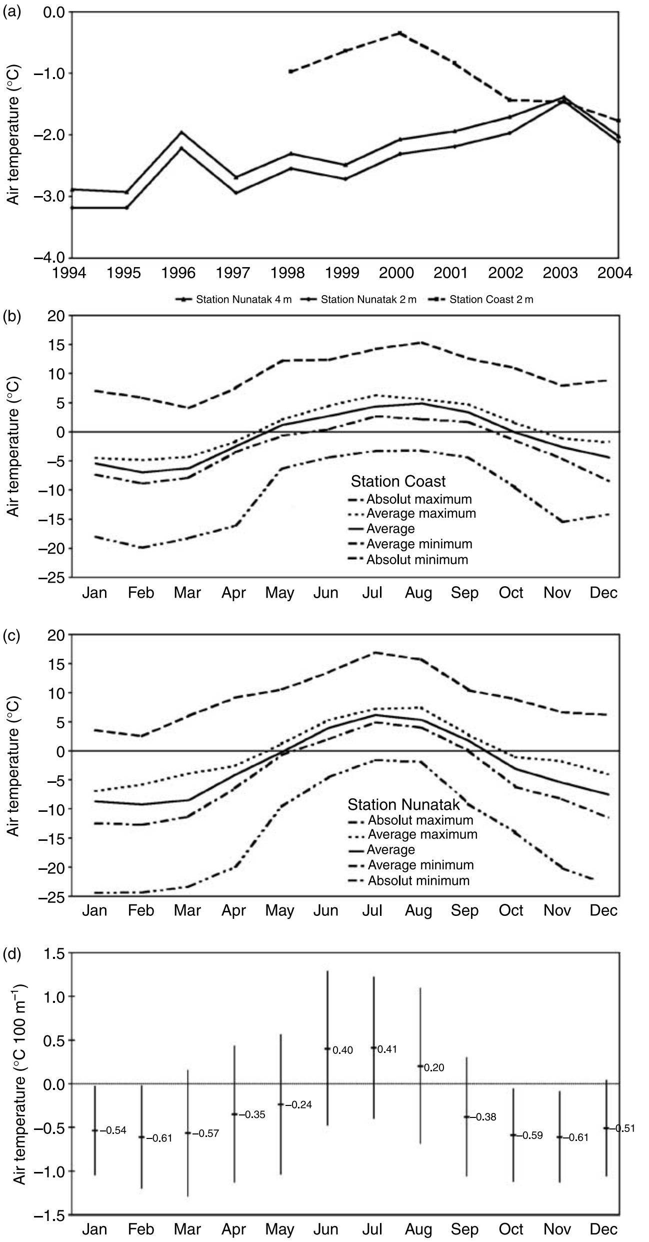

Figure 4 | (a) Mean annual air temperature (MAAT) at Station Coast (2.0 m) (1998–2004) and at Station Nunatak (2.0 and 4.0 m) (1994–2004); (b) Station Coast maximum, mean and minimum monthly mean air temperatures (2.0 m) for the time period (1998–2004); (c) Station Nunatak maximum, mean and minimum monthly mean air temperatures (2.0 m) for the time period (1998–2004); and (d) monthly lapse rates based on air temperature (2.0 m) from Station Coast and Station Nunatak (1998–2004).

The positive average air temperature lapse rates from June to August are highly controlled by the wind regime. During summer, sea breezes governed by local temperature differences in the heating of sea and land prevail, causing an influence of relatively cold and foggy air, primarily in the coastal landscapes. The same yearly trend is present for periods without the occurrence of dense clouds or thin fog at the coast (Mernild *et al.* 2005). The trend in monthly lapse rates is almost similar to other Arctic coastal areas, e.g. the Zackenberg catchment (Mernild *et al.* 2007*a*,*b*).

The lower part of the Mittivakkat Glacier catchment, the proglacial valley and the coastal area are highly dominated by air temperature inversion, shown by frequent situations where temperatures increase rather than decrease with altitude, affecting the air temperature lapse rates in the catchment. In summer time (June–August), air temperature inversions are estimated to be present in approximately 60% of the observations due to coastal wind regime. Based on radio-sonde observations in July 2006 air temperature inversions occur at 300 m a.s.l. around 50% of the time. In winter the occurrence of temperature inversion is decreasing, probably because sea and land surfaces are much the same, since they are both covered more or less continuously in ice and snow, and local temperature differences in the heating of sea and land therefore does not occur. Additionally, high wind speeds during winter will counteract the development of air temperature inversion in the catchment. In the Zackenberg catchment air temperature inversions formations are just the opposite, present around 50–80% of the time during the winter months whereas in summer and autumn 10–50% of the time show evidence of temperature inversion (Mernild *et al.* 2007*a*,*b*; Hansen *et al.* 2008). A similar air temperature inversion trend is described by Serreze *et al.* (1992) and a common feature for the Eurasian Arctic environment.

At Station Nunatak data indicate a longer thawing period (Figure 5). In autumn the thawing season was significant extended by 31 d and in the spring by 10 d, resulting in a net increased thawing increasing period of 41 days (1993–2004) (Table 3). At Station Coast the opposite occurred. The net thawing period was abbreviated by 18 d (1998–2004): in autumn by 12 d and in spring by 6 d. In the Zackenberg catchment the trend lines (1996–2003) indicate lengthening of the thawing season in autumn by 16 d and shortening in spring by 2 d, indicating a net lengthening of the thawing season of 14 d (Mernild *et al.* 2007*a*,*b*). Inland, away from the near-coastal areas, the thawing trend is equal for the two studied catchments in East Greenland,

Table 3 | Air temperature, degree day, wind conditions, relative humidity and precipitation at Station Nunatak, Station Coast and for the Mittivakkat Glacier catchment. Measurements are recorded at 2.0 m above the surface unless another is mentioned. Linear regressions were used to describe trends

	Station Nunatak (515 m a.s.l.) representing glacier conditions	Station Coast (25 m a.s.l.) representing coastal conditions	Mittivakkat Glacier catchment
MAAT	−2.4°C (1994–2004) −2.2°C (4.0 m) (1994–2004)	−1.1°C (1998–2004)	−1.7°C (1998–2004)
Trend in MAAT	0.06°C yr^{-1} (1998–2004) ($R^2 = 0.69$; $p < 0.01$)	−0.13°C yr^{-1} (1998–2004)	–
Mean minimum monthly temperature	−9.2°C (February)	−7.1°C (February)	–
Mean maximum monthly temperature	6.2°C (July)	4.9°C (August)	–
Positive mean monthly temperature	June–September	May–September	–
Trend in thawing period	Increased 41 d (1993–2004), 31 d in autumn ($R^2 = 0.46$; $p < 0.01$) 10 d in spring	Decreased 18 d (1998–2004), 12 d in autumn 6 d in spring	–
TDD	47% increase (1993–2004) ($R^2 = 0.65$; $p < 0.01$), from 442 to 649	16% decrease (1998–2004), from 604 to 509	–
Mean annual wind speed	3.8 m s^{-1} (1994–2004) 4.0 m s^{-1} (4.0 m) (1994–2004)	4.0 m s^{-1} (1998–2004)	–
Trend in mean annual wind speed	0.04 $\text{m s}^{-1}\text{yr}^{-1}$ (1994–2004)	0.41 $\text{m s}^{-1}\text{yr}^{-1}$(1998–2004) ($R^2 = 0.91$; $p < 0.01$)	–
Relative humidity	83% (4.0 m) (1998–2004)	82% (1998–2004)	82% (1998–2004)
Precipitation	1,767 mm w.eq. (1999–2004) Snow: 1,487 mm w.eq. Mix: 116 mm w.eq. Rain: 164 mm w.eq	1,313 mm w.eq. (1999–2004) Snow: 667 mm w.eq. Mix: 379 mm w.eq. Rain: 258 mm w.eq	1,472 mm w.eq. (1999–2004)

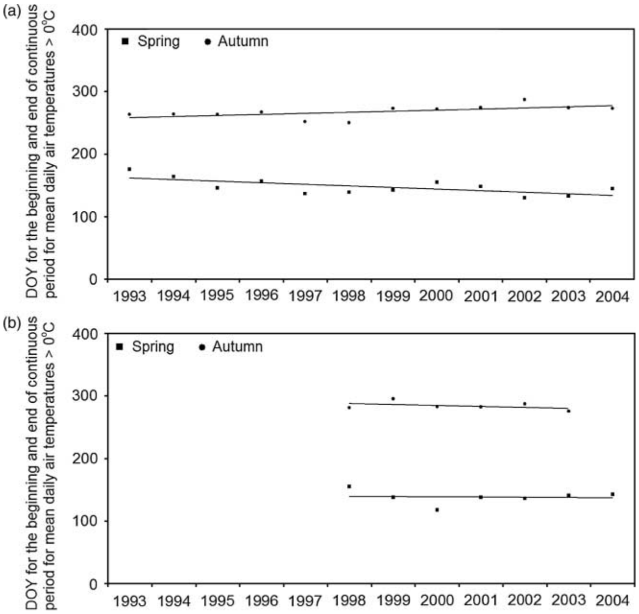

Figure 5 | Day of year (DOY) for the beginning and the end of the continuous period for mean daily air temperatures above 0°C for: (a) Station Nunatak (1993–2004) and (b) Station Coast (1998–2004). The trend lines (linear regression) indicate a longer thawing season at Station Nunatak and a shorter thawing season at Station Coast.

and presumably a general phenomenon for East Greenland, showing an increasing thawing period during the last decade. Furthermore, at Station Nunatak linear regression shows an increasing yearly TDD of 47% from 442 to 649 for the period 1993–2004, while at Station Coast the TDD decreased 16% from 604 in 1998 through 509 in 2004 (Table 3).

Wind direction, wind speed and relatively humidity

Local geographical factors such as distance from the Arctic Ocean and the GrIS, orography and topography (altitude and relief) significantly influence wind direction and speed (e.g. Przybylak 2003; Mernild *et al.* 2006*a*; Hansen *et al.* 2008). Wind directions at both stations are highly dependent on the orographic conditions. At Station Nunatak cold katabatic fall winds, especially from N to E, dominate 50% of the time in all months. The presence of the frequent katabatic winds also results in the almost total lack of calm periods. During winter (exemplified by January) and summer (exemplified by July) the main wind directions are from N to E at Station Nunatak. At Station Coast, winds from W to N dominate around 50% of the time. At Station Coast the wind direction is significantly influenced by the surrounding topography and during winter time, to some extent, by winds from the GrIS canalized through the Sermilik Fjord and also by the valley northeast of the station which channels cold katabatic winds. Approximately 50% of the time during the winter, winds are coming from the north. Due to this tunneling effect, the gust at Station Coast can be even greater than at Station Nunatak. In the summer the wind system at Station Coast is characterized by sea breezes, mainly coming from S and SW. These winds are governed by local temperature differences between the heating of sea and land.

The mean annual wind speed is 3.8 m s^{-1} (2.0 m) at Station Nunatak (1994–2004), and 4.0 m s^{-1} (2.0 m) at Station Coast (1998–2004), covering increasing wind speed values during the period (Table 3). The wind speed is highest in the winter time, with mean monthly speed around 6 m s^{-1} and gust values up to more than 30.0 m s^{-1}. Furthermore, the highest wind speeds occur from the dominating wind directions. Strong winds (neqqajaaq, similar to a Føhn wind) occur during winter on the Mittivakkat Glacier, mainly coming from the NE and E, and often followed by a Piteraq. Wind velocities during a piteraq can gust to 85 m s^{-1}.

The mean annual relative humidity is 83% for the period 1994–2004 (data from 2001–2003 is not included due to temporal error in recordings) at Station Nunatak, and 82% at Station Coast from 1998–2004 (Table 3).

Precipitation

The amount of precipitation over any area depends on the moisture content of the air, the pattern of weather systems affecting the area and the topography, altitude and character of the underlying surface (Hansen *et al.* 2008). The total annual precipitation (TAP) at Station Nunatak is 1767 mm w.eq. yr^{-1} (1999–2004), 1313 mm w.eq. yr^{-1} at Station Coast and 1472 mm w.eq. yr^{-1} for the Mittivakkat Glacier catchment (Figures 6(a, b), Table 3). At Station Tasiilaq the uncorrected mean annual precipitation is 894 mm w.eq. yr^{-1} (1999–2004). The total annual adjusted SWE at Station Nunatak is 1545 mm w.eq. yr^{-1} (1999–2004), calculated after applying a wind speed and winter glacier mass balance correction due to the

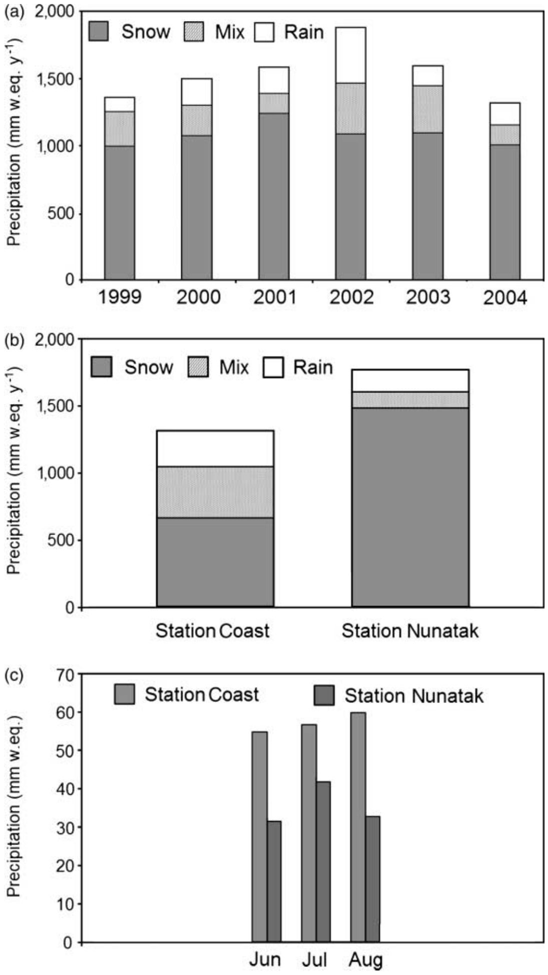

Figure 6 | (a) Average annual Mittivakkat glacier catchment snow, mix and rain precipitation (1999–2004) (derived from Snow and Micrometeorological Model (SnowModel/MicroMet) (Liston & Elder 2006*a*,*b*)); (b) average annual snow, mix and rain precipitation at Station Coast and Station Nunatak (1999–2004); and (c) monthly June, July and August average rain precipitation at Station Coast and Station Nunatak (1999–2004).

exposed location at the nunatak (Mernild *et al.* 2006*c*). At Station Coast SWE is 876 mm w.eq. yr^{-1}, indicating a positive orographic effect of 131 mm w.eq. per 100 m for SWE precipitation. The 131 mm w.eq. per 100 m SWE precipitation increase between the two meteorological stations is assumed to be closely related to the orographic influence of Ammassalik Island. This is almost identical with gradients found in previous studies on Ammassalik Island studies by Hasholt *et al.* (2003) and used in mountainous areas of Norway (Young *et al.* 2006). The opposite, a negative orographic effect, occurs for liquid precipitation during summer months, indicating an average orographic factor of -7 mm w.eq. per 100 m (1997–2004) (Figure 6(c)). This is due to the higher frequency of clouds and or thin fog in the coastal area or perhaps because the anticipated liquid precipitation actually falls as snow at higher altitudes (Mernild *et al.* 2006*a*).

Glacier mass balance and runoff conditions 1993–2004

The Mittivakkat Glacier mass balance observations are shown in Table 4 for the period 1995/96 through 2003/04, illustrating a negative glacier net mass balance values for almost all years. Only two of thsee years (1995/96 and 2002/03) have a positive net mass balance of 10 mm w.eq. yr^{-1} and 350 mm w.eq. yr^{-1}, respectively. The average observed winter, summer and glacier net mass balance are, respectively, 1270 ± 170, -1800 ± 400 and -590 ± 510 mm w.eq. yr^{-1}, showing a negative net mass balance (Table 4). Further, linear regression shows an average increasing negative net mass balance of 13 mm w.eq. yr^{-1}. During the period of observation the Mittivakkat Glacier lost on average 590 mm w.eq. yr^{-1}, corresponding to 8.5×10^6 m^3 yr^{-1}, and resulting in a 0.4% yr^{-1} loss of volume based on a determined glacier volume of $2{,}024 \times 10^6$ m^3 yr^{-1} in 1994. This glacier volume was measured by radio-echo sounding (Knudsen & Hasholt 1999). The observed net mass balance from 1995/96 to 2003/04, based on 100-m altitudal interval observations, indicate that the ELA was located around 500–600 m a.s.l., except for 1997/98 and 2000/01 where it was above 800 m a.s.l. (Knudsen & Hasholt 2004; Mernild *et al.* 2006*c*).

In the Mittivakkat Glacier catchment the NAM simulated date of river break-up at the catchment outlet varied from year to year between 10 May (1998) and 10 June (2003) during the period 1994–2004 (Table 5). The simulated river discharge varies between 1330 mm w.eq. yr^{-1} for 1999 and 2280 mm w.eq. yr^{-1} for 2001. The mean annual simulated river discharge for the period 1994–2004 was 1970 ± 280 mm w.eq. yr^{-1} (corresponding to a runoff of 36.3×10^6 m^3 yr^{-1}) (Mernild & Hasholt 2006). On an annual basis, the glacier net mass balance loss of 590 mm w.eq. explains on average 30% of the total catchment runoff of 1970 mm w.eq. yr^{-1}. High runoff peaks occur throughout the runoff season, mainly after periods with

Table 4 | Observed winter, summer and net mass balance for the Mittivakkat Glacier (1995/96 to 2003/04) based on data in Knudsen & Hasholt (2004), Mernild *et al*. (2006*c*) . Winter mass balance observations are carried out in late May and early June and summer mass balance observations in late August. Average observed winter and summer mass balance are calculated for the period 1995/96 to 2002/03 and average observed net mass balance from 1995/96 to 2003/04

Year	Observed winter mass balance (mm w.eq. yr^{-1})	Observed summer mass balance (mm w.eq. yr^{-1})	Observed net mass balance (mm w.eq. yr^{-1})
1995/1996	1,510	− 1,500	10
1996/1997	1,410	− 1,810	− 400
1997/1998	1,140	−2,310	− 1,170
1998/1999	980	− 1,750	−770
1999/2000	1,230	−2,060	− 830
2000/2001	1,180	−2,140	−960
2001/2002	1,280	− 1,780	− 500
2002/2003	1,400	− 1,050	350
2003/2004	No data	No data	− 1,060
Average and standard deviation	1,270 ± 170	− 1,800 ± 400	− 590 ± 510

high air temperatures and subsequent surface melt (snow and glacier ice melt) and rain events. In 2004, two main runoff peaks were observed: a 10 July peak ($11.6\,m^3\,s^{-1}$) caused by a precipitation event and an 13 August ($11.0\,m^3\,s^{-1}$) due to enhanced melting (Mernild 2006*b*). The maximum hourly observed river discharge of $40.3\,m^3\,s^{-1}$ at the catchment outlet was observed on 4 September 2000 after 36 h with a mean air temperature of 8.7°C coupled with an average rainfall of 34 mm in the catchment as modeled by MicroMet.

The water balance 1995–2004

Throughout the year, different surface processes like snow accumulation, evaporation and sublimation, snow and ice melt, and changes in storage affect the catchment high-latitude water balance (Equation (1)). Table 6 presents the water balance components: P, ET + SU, R, and δS for the Mittivakkat Glacier and the Mittivakkat Glacier catchment. The glacier covers 78% of the Mittivakkat catchment area. Table 6 shows annual precipitation values ranging from

Table 5 | Yearly observed and simulated accumulated discharge from the Mittivakkat Glacier catchment, together with maximum observed discharge and simulated date for river break-up (Mernild & Hasholt 2006). The simulated runoff period goes from September–August, identical with the Mittivakkat Glacier mass balance year

	Period with observed discharge	Accumulated observed runoff (mm w.eq.)	Maximum observed discharge ($m^3\,s^{-1}$)	Annual accumulated simulated runoff (mm w.eq.)	Simulated date for river break-up (date for river break-up based on photos from the proglacial valley)
1993/1994	30 Jun–28 Aug	1,310	9.3	2,140	22 May
1994/1995	1 Jul–31 Aug	1,900	11.7	2,090	27 May
1995/1996	No data	No data	No data	1,860	28 May
1996/1997	No data	No data	No data	2,130	17 May
1997/1998	No data	No data	No data	1,910	10 May
1998/1999	22 Jun–31 Aug	940	11.7	1,640	23 May
1999/2000	8 Jun–17 Sept	2,010	6.9	2,150	11 May (13 May)
2000/2001	18 Jun–15 Sept	1,730	6.1	2,280	23 May (26 May)
2001/2002	10 Jun–5 Sept	1,870	7.9	1,990	27 May (28 May)
2002/2003	7 Jun–20 Aug	930	5.7	1,330	8 Jun (10 Jun)
2003/2004	14 Jun–27 Aug	1,910	10.0	2,190	25 May (26 May)
Average	–	–	8.7	1,970 ± 280	23 May

1270 ± 170 to 1510 ± 180 mm w.eq. yr^{-1} for the glacier and the catchment; the variation is due to the different time periods. Further, Table 6 shows average ablation (evaporation, sublimation and runoff) values from −1800 ± 400 to −2240 ± 420 mm w.eq yr^{-1}, with average runoff values around 1950 ± 320 to 1980 ± 400 mm w.eq yr^{-1}. The runoff contribution from the glacier is nearly equal to the total catchment runoff, showing that mostly all catchment runoff originates from the glacier. Catchment runoff is exceeding precipitation by approximately one-third, displaying an average annual glacier loss between −590 ± 510 to −710 ± 510 mm w.eq yr^{-1} for the catchment. The water balance illustrates that glaciers have a dominant influence on the water balance in glacierized areas, producing a surplus of melting and runoff exceeding the precipitation. For the entire Mittivakkat Glacier, the negative storage indicates a glacier recession for the period.

Air temperature, glacier balance and runoff in a 106 yr perspective

To illustrate the effect of climate change in the Mittivakkat Glacier catchment, both in a broader perspective, but also related to the present conditions (1993–2005), data from a long-term 106 yr period (1898–2004) were used. Figure 7(a) illustrates the calculated mean annual air temperature variation from 1898–2004 for the Mittivakkat Glacier catchment. During the 106 yr period warming, cooling and constant air temperatures occurred in different intervals (Table 7). General periods of warming were observed from 1918 (the end of the Little Ice Age) to 1935 of 0.12°C yr^{-1} and 1978 to 2004 of 0.07°C yr^{-1}, in accordance with observations from the Arctic in general by Serreze *et al.* (2000). Air temperature cooling at the Mittivakkat Glacier catchment occurred from 1956–1978 of −0.05°C yr^{-1}, and approximately constant temperature conditions from 1898–1918 of 0.02°C yr^{-1} and 1936–1955 of −0.02°C yr^{-1}. Due to the fluctuations in air temperature over relatively short periods of time in a climate perspective, an assessment of climate change must be seen in a broader perspective. The overall trend in air temperature over the last 106 yr shows an annual increase of 1.3°C for the Mittivakkat catchment, compared to the mean global surface air temperature

Table 6 | The Mittivakkat Glacier and the Mittivakkat Glacier catchment water balance components: precipitation (*P*), evaporation and sublimation (*ET* + *SU*), runoff (*R*) and change in storage (*δS*). The components are based on observations and simulations. Be aware of the different time periods. The Mittivakkat glacier extent covers approximately 78% (14.4 km^2) of the total catchment area

	Accumulation	**Ablation**			
	Precipitation (*P*) (mm w.eq. yr^{-1})	**Evaporation and sublimation (*ET* + *SU*) (mm w.eq. yr^{-1})**	**Runoff (*R*) (mm w.eq. yr^{-1})**	**Change in storage (*δS*) (mm w.eq. yr^{-1})**	**The water balance discrepancy (*η*) (mm w.eq. yr^{-1})**
Mittivakkat Glacier, observations (1995–2004) (Knudsen & Hasholt 2004; Mernild *et al.* 2006c)	1,270 ± 170	−1,800 ± 400		−590 ± 510*	0
Mittivakkat Glacier, SnowModel simulations and observations (1999–2004) (Mernild *et al.* 2006c)	1,490 ± 170	−260 ± 20	−1,980 ± 400	−620 ± 370*,†	130 ± 20
Mittivakkat Glacier catchment, NAM simulations and observations (1997–2004) (Mernild & Hasholt 2006)	1,510 ± 180	−270 ± 20‡	−1,950 ± 320§	−710 ± 510*,†,‖	0

*The runoff does not include englacial and subglacial melting or changes in internal storage, e.g. glacial bulk water release.

†Change in glacier storage is based on observations.

‡Evaporation and sublimation (*ET* + *SU*) is calculated as a residual term in the water balance.

§Runoff is based on NAM simulations.

‖The value only includes changes in glacier storage, not storage changes outside the glacier in the glacier-free landscape.

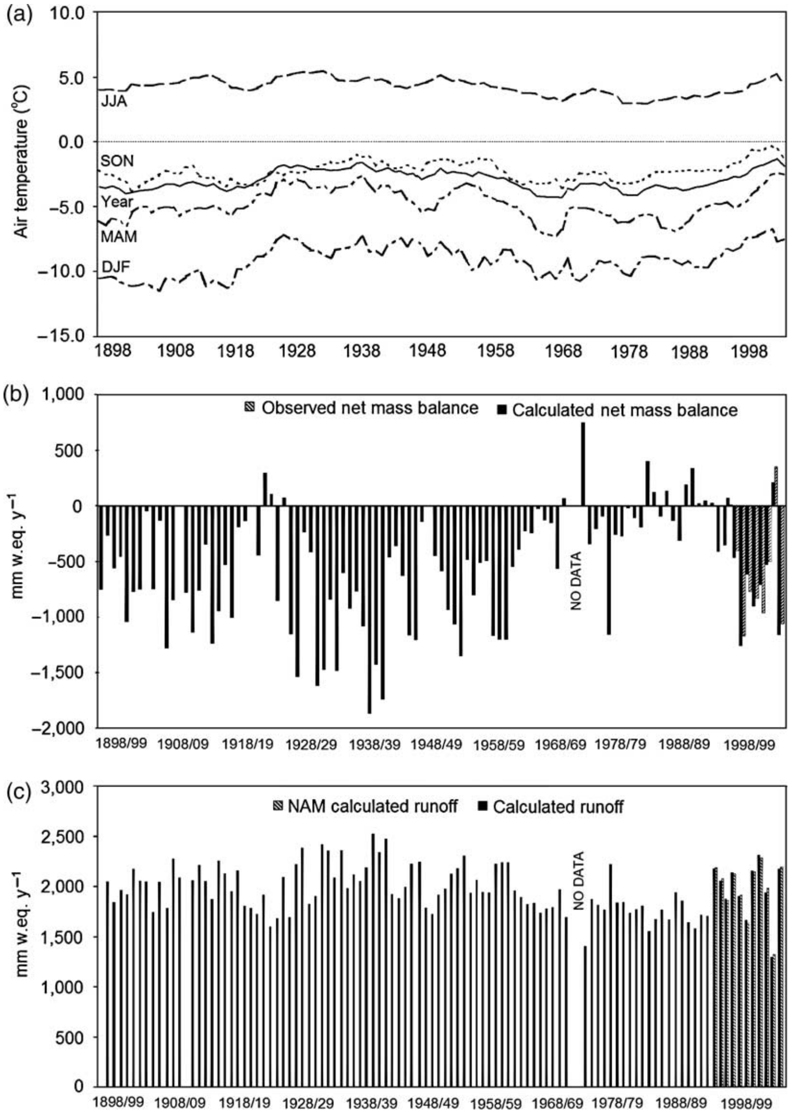

Figure 7 | (a) Five-year running mean annual and seasonal air temperature at the Mittivakkat Glacier catchment for the period 1898–2004. The abbreviations are DJM (December, January and February), MAM (March, April and May), JJA (June, July and August), SON (September, October and November) and Year (January to December). Data (from Station Tasiilaq) are missing in the period from September 1910 to August 1911 and from January 1971 to December 1972; (b) Yearly (September–August) observed (1995/96 to 2003/04) and calculated (1898/99 to 2003/04) glacier net mass balance (change in storage) for the Mittivakkat Glacier. For the period 1995/96 to 2003/04 linear regression indicate an R^2 value of 0.71 ($p < 0.01$) between observed and calculated net glacier mass balance. The assumed accuracy of the observed net mass balance is within ±15% (Knudsen & Hasholt 2004; Mernild *et al*. 2006*c*); and (c) yearly (September–August) runoff from the Mittivakkat Glacier catchment. Runoff values are based on NAM calculations (DHI 2003*a*,*b*; Mernild & Hasholt 2006), calibrated and validated against observed runoff values. For the period 1993/94 to 2003/04 linear regression indicate an R^2 value of 0.76 ($p < 0.01$) between observed and calculated runoff.

Table 7 | The overall air temperature change in the Mittivakkat Catchment from 1898 through 2004 in various time intervals

	1898–1918	1919–1935	1936–1955	1956–1977	1978–2004	1898–2004
Air temperature change	0.02°C yr^{-1}	0.12°C yr^{-1}	−0.02°C yr^{-1}	−0.05°C yr^{-1}	0.07°C yr^{-1}	1.3°C
Statistics	$R^2 = 0.06$; $p < 0.25$	$R^2 = 0.47$; $p < 0.01$	$R^2 = 0.03$; $p < 0.\ 25$	$R^2 = 0.47$; $p < 0.025$	$R^2 = 0.41$; $p < 0.01$	$R^2 = 0.03$; $p < 0.05$

increase of approximately 0.6°C over the past century (Lemke *et al.* 2007). All four seasons at the Mittivakkat Glacier catchment show warming over the period, especially during the winter season with 3.1°C, mainly due to warmer daytime temperatures. It can be concluded that the warmest average 10-yr period within the last 106 yr was the period from 1936–1946 (-1.8°C), while within the last 60 yr the warmest 10-yr period was the period from 1995–2004 (-2.0°C) for the Mittivakkat Glacier catchment (Figure 7(a)). Also on West Greenland the period 1936–1946 was the warmest period within the last 106 yr (Cappelen 2004). Globally, the 1990s was the warmest decade during the past 1000 yr.

At Station Tasiilaq the uncorrected mean annual precipitation is 863 mm w.eq. yr^{-1} (1898–2004), with a minimum of 422 mm w.eq. yr^{-1} (1950) and a maximum of 1485 mm w.eq. yr^{-1} (1908). Over the last 106 yr linear regression shows an average increasing precipitation of ~11 mm w.eq. $decade^{-1}$ ($R^2 = 0.02$; $p < 0.10$), or approximately 1% $decade^{-1}$. The increasing uncorrected precipitation of 1% $decade^{-1}$ is similar to the estimates for the Arctic area given by ACIA (2005).

A warming climate, as just described, initiates and produces a cascade of impacts that affect glaciological and hydrological processes. Figure 7(b) shows the estimated Mittivakkat Glacier net mass balance from 1898–2004, indicating an average glacier recession of -550 ± 530 mm w.eq. yr^{-1}. However, maximum and minimum values of 750 mm w.eq. yr^{-1} (1972/73) and -1870 mm w.eq. yr^{-1} (1939/40) occur, respectively. During the period from 1898–2004, 89 out of 105 mass balance years for the Mittivakkat Glacier show a negative estimated balance, with a cumulative estimated balance of approximately -57 m w.eq. The difference in surface elevation based on topographic maps from 1932/33 (Geodædisk Institut 1938) and 1972 (based on aerial photographs) showed that the glacier below 300 m a.s.l. had melted down as much as 100 m at the 1972 margin. Above 300 m a.s.l. the changes were smaller and at higher levels an increase was even observed locally (Knudsen & Hasholt 2004). Observations since 1933 indicates an almost continuous glacier margin recession totaling 1.3 km until 2004, representing an average retreat of about 18 m yr^{-1}.

In the Mittivakkat Glacier catchment, the glacier net mass balance and the freshwater runoff are closely related because 78% of the catchment is covered by the Mitivakkat Glacier. Average annual runoff was estimated to be 1960 ± 250 mm w.eq. yr^{-1}, with a range between 2520 mm w.eq. yr^{-1} and 1330 mm w.eq. yr^{-1}, respectively (Figure 7(c)). Around 30% of the average annual catchment runoff is explained by the glacier net mass balance loss of 550 mm w.eq. yr^{-1}.

CONCLUSIONS

From the above evaluation of twelve years of data (1993–2005) from meteorological stations within the Mittivakkat Glacier catchment on the western part of Ammassalik Island, Southeast Greenland, short-term significant trends in meteorological conditions within the catchment have been noted, including an increasing air temperature of 0.06°C yr^{-1} in the glacierized area and decreasing values of -0.13°C yr^{-1} in the coastal area. Changes in air temperature impact both the thawing period and the snow-free period in the lower part of the catchment and the glacier net mass balance in the upper ice-covered catchment. When data from the Mittivakkat Glacier catchment are compared to other data series, e.g., from the Zackenberg catchment, NE Greenland (74°N), it becomes clear that meteorological and snow-cover observations in the Mittivakkat catchment are in line with observations from Zackenberg, supporting the idea of widespread and similar changes along the east coast of Greenland. Further, observations from the Tasiilaq DMI station make it possible to estimate data (by linear regression) from the Mittivakkat Glacier catchment back in time to 1898. Over this 106-yr period the annual air temperature has increased 1.3°C, with the highest changes in the winter season. The period 1995–2004 was the warmest 10-yr period within the last approximately 60 yr and 1936–1946 was the warmest period within the last 106 yr for the Mittivakkat catchment. From 1933–2004 the glacier margin had retreated approximately 1.3 km, with an average net surface mass balance of -550 ± 530 mm w.eq. yr^{-1}. The glacier net loss contributes around 30% to the total annual catchment runoff of 1960 ± 250 mm w.eq. yr^{-1}.

ACKNOWLEDGEMENTS

The authors would like to thank Professor Jon Ove Hagen, Department of Geography, University of Oslo, Norway, and Professor Lars Bengtsson, Department of Water Resources Engineering, Lund University, Sweden, for their insightful reviews of this paper. Special thanks to Dr Glen E. Liston, Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University, for the use of SnowModel/MicroMet. This project is supported by grants from the University of Alaska Presidential IPY Postdoctoral Foundation, the University of Alaska Fairbanks Office of the Vice Chancellor for Research, the Department of Geography and Geology, University of Copenhagen, and the Copenhagen Global Change Initiative (COGCI), University of Copenhagen.

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First received 30 October 2007; accepted in revised form 25 March 2008