Climate, glacier mass balance, and runoff 1993–2005, and in a long term perspective (106 year), Mittivakkat Glacier catchment, Ammassalik Island, SE Greenland

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ABSTRACT
Climate, glacier mass balance, and subsequently river discharge are investigated based on high-resolution time series (1993–2005) from the Low-Arctic Mittivakkat Glacier catchment at the Ammassalik Island (65°N), Southeast Greenland. Meteorological data from the Mittivakkat Glacier catchment (18.4 km^2) together with standard synoptic meteorological data are extrapolated from 1898 to 1993 to estimate variations and trends in air temperature, glacier net mass balance, and catchment runoff. Characteristic variations in meteorological conditions within the catchment, between the coastal (Station Coast) and the glacier area (Station Nunatak) during the investigation period occur: ~15% lower annual solar radiation, four weeks longer snow-free period, and ~50% higher maximum snow depth in the coastal area. Further, decreasing mean annual air temperatures (MAAT) occur in the coastal area (-0.13ºC y^{-1}) during the high-resolution investigation period, indicating an approximately 20-day shorter thawing period, while the higher glacier area undergoes an increasing MAAT (0.09ºC y^{-1}), an approximately 40-day longer thawing period, a 60-day longer snow-free period, and an (linear trend) increasing release of melt water from the exposed glacier surface. The Mittivakkat Glacier net mass balance has been almost continuously negative averaging -0.59±0.51 m w.eq. y^{-1} during the recent continuous observations, corresponding to 0.4% y^{-1} loss of volume. Further, the glacier mass balance observations indicate an increasing negative trend. The total annual runoff from the catchment for the period 1993–2004 ranges between 24.4 and 42.0×10^6 m^3 (1,326–2,282 mm w.eq. y^{-1}), averaging 36.3×10^6 m^3 (1,973±281 mm w.eq. y^{-1}). Changes in air temperature within the last 106 years (1898–2004) show an average increase of 1.3ºC for the catchment: An increase highest for the in winter season of 3.1ºC. The period 1995–2004 was the warmest 10 year period within the approximately last 60 years. The glacier net mass balance from 1898–2004 indicate an average glacier recession of -0.55±0.53 m w.eq. y^{-1}, and a cumulative estimated balance of -56.7 m w.eq.; 89 out of 105 balance years had a negative estimated net mass balance. Average annual runoff (1898–2004) was estimated to 1,957±254 mm w.eq. y^{-1}, with a range between 2,522 and 1,326 mm w.eq. y^{-1}, respectively.

KEYWORDS
Arctic; Ammassalik Island; climate; Greenland; Mittivakkat Glacier; river discharge; glacier mass balance; 106 years perspectives (1898–2004)

1. INTRODUCTION
Over the last 100 years mean global surface air temperature has increased by 0.3 to 0.6°C (e.g., Maxwell, 1997; Kane, 1997). In this period, nine of the ten warmest years measured globally occurred between 1990 and 2001 (WHO, 2001), and it has been suggested that the 1990s were the warmest decade during the past

1,000 years (Crowley, 2000), with the largest air temperature changes in winter time (Box, 2002; Sturm *et al.*, 2005). The Arctic climate is also changing. From the mid-1800s to mid-1900s, the Arctic warmed to the highest temperatures in 400 years (Overpeck *et al.*, 1997). The climate has warmed substantially since the end of the Little Ice Age to present, significantly in the last 30 years (Serreze *et al.*, 2000). The warming has been accompanied by an increase in precipitation in the Arctic of approximately 1% decade^{-1} (ACIA, 2005).

Warming climate will initiate and evolve a cascade of impacts that affect e.g., glaciological and hydrological processes (Hinzman *et al.*, 2005). The Arctic is undergoing a system-wide response to an altered climatic state. New extreme and seasonal surface climatic conditions are being experienced, a range of processes influenced by the threshold and phase change of freezing point are being altered. It appears that first-order impacts to the terrestrial regions of the Arctic expected with a warming climate result from a longer thawing period combined with increased precipitation (e.g., Anisimov and Fitzharris, 2001; Hinzman *et al.*, 2005; Mernild *et al.*, 2007a). The longer snow-free season and greater winter insulation produces secondary impacts that could cause e.g., greater melt of glacier ice and snow, and deeper thaw of the active layer.

The dynamic nature of Greenland is framed by extremes: very cold winter temperatures, highly skewed annual cycle and North–South Greenland trend of solar radiation input, dominance of snow and glacier cover, and relatively low rates of precipitation (expect for the South eastern part of Greenland), all of which results from its elevation, topographic, and geographic position. There are essentially two seasons, one frozen and one thawed, with abrupt transition between them. During the winter or frozen season, which last 6–10 months of the year, unfrozen surface water is rare, and a negative annual radiation balance is established (more solar radiation is lost to space as enters). It is this negative radiation balance that creates the gradient that drive the Greenland and the Arctic climate (Hinzman *et al.*, 2005).

The Arctic hydrological cycle is shifting. The effect of a warmer climate on the hydrological processes in the Arctic are already becoming apparent. Basins with a substantial glacier component consistently display increasing trend in runoff, presumably due to increases in glacier melt. River basins lacking large glaciers tend to show decreasing runoff, probably because evapotranspiration rates have increased faster than increasing precipitation. Information on climate and river discharge in East Greenland was absent before the International Geophysical Year (IGY) 1957–58 (also known as the Third International Polar Year (IPY)). As a contribution, the first simultaneously related measurements of meteorology and terrestrial freshwater runoff was carried out in the Mittivakkat Glacier catchment, Ammassalik Island. In 1972, the Sermilik Research Station, in the Mittivakkat Glacier catchment, was established. Since then, an extensive monitoring program to study the climate-landscape processes and interactions has been on-going. Present, the Mittivakkat Glacier catchment is one of two catchments on the entire east Greenland (along the approximately 3,000 km coast), where permanent automatic meteorological and hydrometric monitoring stations occur. This, due to the rough terrain, harsh climatic conditions, and the remote locations. In the Mittivakkat Glacier catchment studies of simultaneous effects of climate in the form of recorded glacier mass balance changes and measured runoff are carried out so changes in climate can be directly linked to short and long term effects.

The goal of this study is to describe the climate (variations and trends in meteorological conditions) and its effect on the freshwater runoff in the Mittivakkat Glacier catchment with focus on the glacier mass balance during the period (1993–2005) of measurements. Further, we estimate the variations and trends in air temperature, Mittivakkat Glacier net mass balance, and catchment freshwater runoff over a 106 year period from 1898 to 2004, based on nearby standard synoptic meteorological data from the town Tasiilaq (Ammassalik).

2. STUDY AREA

The Mittivakkat Glacier catchment (18.4 km^2) (65°42'N latitude; 37°48W longitude) (Figure 1) is located on the western part of the Ammassalik Island, Southeast Greenland, approximately 15 km northwest of the town of Tasiilaq and 50 km east of the eastern margin of the Greenland Ice Sheet and is separated from the mainland by the 10–15 km wide north-south Sermilik Fiord. The area is considered to be Low Arctic. 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 land cover 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. Proglacial valley bottoms contain both moranic deposits and fluvial sediments (e.g., Hasholt and Mernild, 2004). The catchment (78%; 14.4 km^2) is covered by parts of the Mittivakkat Glacier complex (a temperate glacier with an average thickness of 115 m), ranging from approximately 160 to 930 m a.s.l. in elevation (Knudsen and Hasholt, 1999). The catchment watershed divide is located partly on the Mittivakkat Glacier: it is a non-stable topographic watershed divide, due to glacier dynamic

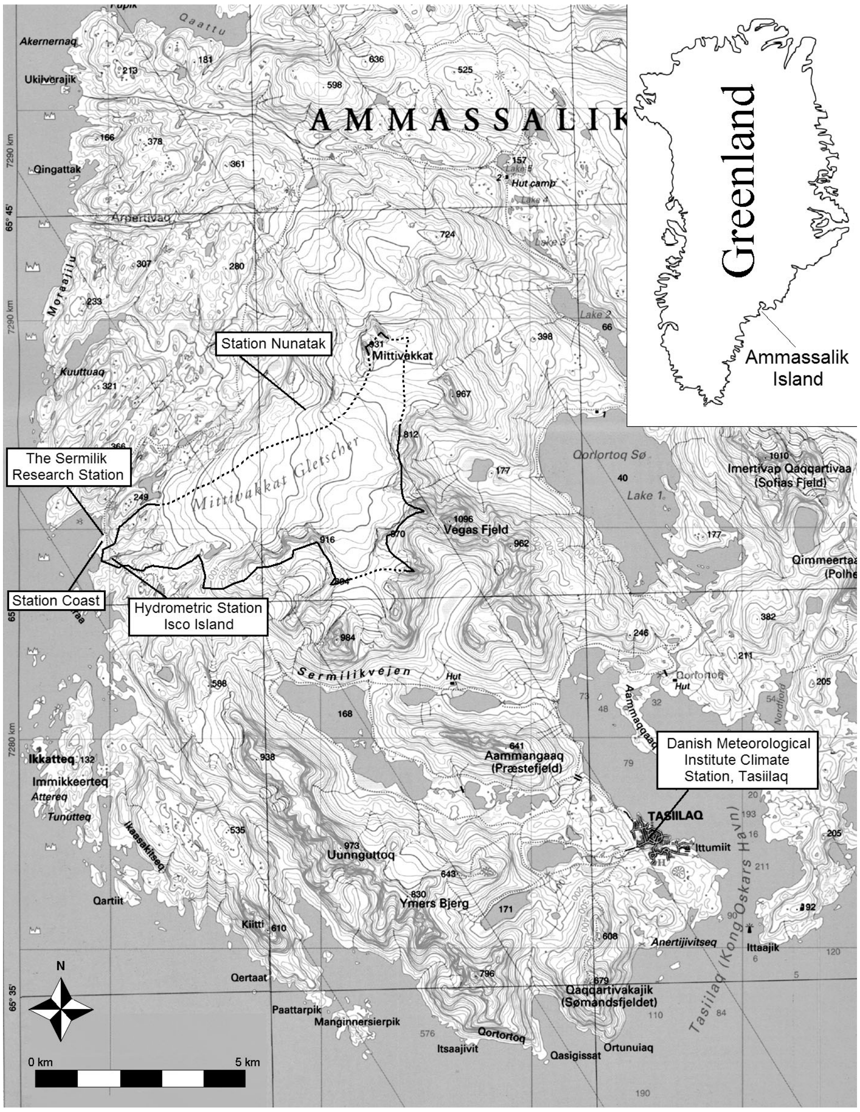

Figure 1: Location map showing the Mittivakkat Glacier catchment (18.4 km^2), Ammassalik Island, including meteorological stations: Station Nunatak (515 m a.s.l.) and Station Coast (25 m a.s.l.), the Danish Meteorological Institute (DMI) climate station in Tasiilaq (Ammassalik), and the hydrometric station at Isco Island. The dashed line indicates the non-stable topographic watershed divide on the Mittivakkat Glacier and the solid-drawn 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).

and basal sliding (Figure 1). Therefore, a change in catchment size can occur (Mernild *et al.*, 2006c). Avalanches are rare near the glacier. Since 1933 the glacier terminus has retreated about 1.2 km (approximately 16 m y^{-1}), with a decrease in glacier surface elevation up to 100 m (below the 300 m a.s.l. elevation) (e.g., Mernild and Hasholt, 2006).

3. INDICES AND PARAMETRES

The following indices: The accumulated number of Thawing Degree Days (TDD) is the sum of values of positive mean daily air temperatures. TDD is related to release of water from both the snowpack and the exposed glacier ice surfaces after the annual snowcover has ablated. An increase in TDD will cause increased surface melt and catchment runoff.

The elements of the water balance for a drainage basin depend on drainage basin characteristics and processes. 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 and Hasholt, 2004; Mernild *et al.,* 2006a). The Mittivakkat Glacier catchment water balance equation (Eq. 1) is:

$$P - ET - R \pm \Delta S = 0 \pm \eta \qquad (1)$$

where P is the precipitation input from snow, rain, and condensation; ET is the evapotranspiration and sublimation; R is total runoff from surface, subsurface, rain, snow, glacier, and nearby catchment contributions; ΔS is change in surface storage (surface depressions, lakes, channels, etc.), subsurface storage, glacier storage and snowpack storage; and η is the balance discrepancy (Error). 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 opposite to most other parameters in the water balance, it is not affected by the representativity of the measuring station (Killingtveit *et al.*, 2003).

4. DATA AVAILABILITY AND METHODS

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

A meteorological station, Station Nunatak, has since 1993 continuously every third hour monitored the meteorological conditions on a nunuatak (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) in order to capture the glacier climate, with sensors registering 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), relatively humidity (4.0 m), incoming and outgoing short-wave radiation and net radiation (4 m) (e.g., Hasholt *et al.*, 2004; Hasholt and Mernild, 2004). Liquid (rain) precipitation was measured 0.45 m above the ground, approximately the height of local roughness (Mernild *et al.*, 2006a). Solid (snow) precipitation was calculated from snow depth sounding observations (Campbell SR50-station) that assumed to have an accuracy of within ± 10–15%.

Later, in 1997 a meteorological station, Station Coast, was established on a rock hill (65°40.8’N; 37°55.0’W, 25 m a.s.l.) in order to record information about the climate in the coastal region, and trends and orographic effects by comparison with the former. Since 1997 the station has continuously every third hour monitored the meteorological conditions in the coastal area. The following sensors were mounted 2 m above terrain: wind direction, wind speed, wind gust, air temperature, relatively humidity, incoming and outgoing short-wave radiation and net radiation. Liquid precipitation was measured 0.45 m above the ground. Solid precipitation was calculated by sounding observations at the hydrometric station Isco Island during winter, and during summer runoff variations were observed. The hydrometric station Isco Island is located close to the coast and approximately 200 m southwest from Station Coast.

After noise was removed from the snow depth data (Campbell SR50), the snow-depth sounding observations were fractionated into liquid (rain) precipitation and solid (snow) precipitation at different air temperatures based on observations from different locations on Svalbard. For air temperatures below -1.5ºC, sounding observations represents solid precipitation in 100% of the events and for temperatures above 3.5ºC precipitation is liquid for 100% of the events, in between (-1.5ºC to 3.5ºC) the fraction of snow and rain is calculated by linear interpolation (Førland and Hanssen-Bauer, 2003). Snow-depth increases at relative humidity <80% and at wind speed >10 m s^{-1} were removed to distinguish between the proportions of real snow accumulation based on precipitation events and blowing snow redistribution. The remaining snow-depth increases were adjusted using a temperature-dependent snow density (Brown *et al.*, 2003), and an hourly snowpack settling rate (Anderson, 1976) for estimating the water equivalent precipitation (mm. w.eq.): snow settles as it accumulates and thus the snow depth on the ground is always less than the initial amount of snowfall. This settling process represents a 10–15% increase in snow precipitation a year (Mernild *et al.*, 2007c). Further, Station Nunatak simulated end-of-winter snow water equivalent (SWE) depth was compared and adjusted against observed Mittivakkat Glacier winter mass balance, showing an average underestimated SWE (snow water equivalent) depth of 29% (1999–2002) (Mernild *et al.*, 2006a) before adjustment due to the exposed station location on the nunatak. During summer the sounder observations in the coastal region was used for river stage variations. All data were logged every third hour. The sensor type, accuracy, and range were described in Hasholt *et al*. (2004). Annual values, for both stations, have been reported in scientific notes since 2002 (Hasholt *et al*., 2004) and until 2004 (Mernild *et al*., 2006b).

The air temperature and TDD from the measured climate stations at the Mittivakkat Glacier catchment have been compared with data from the DMI station in Tasiilaq, in order to generate a time series at the Mittivakkat Glacier catchment covering the last 106 years. Linear regressions of air temperatures between the stations were used on daily basis (Station Coast and Tasiilaq DMI (1997 to 2004): $R^2 = 0.88$; $p<0.01$ (where p is the level of significance), and Station Nunatak and Tasiilaq DMI (1993 to 2004): $R^2 = 0.86$; $p<0.01$)). This allowed us to calculate monthly values for the two stations in the Mittivakkat Glacier catchment for the period 1897–1993. Then we converted this data into cumulative winter TDD (September to May), summer TDD (June to August), and annual TDD values (September to 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 records. Further, the summer TDD was related by linear regression to the Mittivakkat Glacier summer mass balance (1995/96 to 2002/03, n = 8) ($R^2 = 0.65$; $p<0.01$), and station DMI winter precipitation (September to May) to the Mittivakkat Glacier winter mass balance (1995/96 to 2002/03) ($R^2 = 0.75$; $p<0.01$), in order to predict the net glacier mass balance for the period 1898/99 to 1994/95. The mass balance measurement on the glacier during 1986/87 showed a net balance of -0.12 m w.eq. y^{-1} (Hasholt, 1988): The estimated value for 1986/87 is -0.15 m w.eq. y^{-1}.

In the Mittivakkat Glacier catchment, the glacier is responsible for up to 90% of the yearly catchment runoff (Mernild, 2006), therefore, the observed net mass balance was related (linear regression) to the annual catchment runoff (September to August) (1995/96 to 2003/04) by linear regression ($R^2 = 0.76$; $p<0.01$) in order to calculate the annual runoff (September to August) from 1898–2004.

Winter and summer mass-balance observations were carried out in late May and early June, and in late August, respectively. During these 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 in each line were 200–250 m apart (Knudsen and Hasholt, 2004). The assumed accuracy of the observed winter and summer mass balances are each within ±15%; however large errors might occur especially in glacier areas with many crevasses (Knudsen and Hasholt, 2004).

SnowModel is a spatially distributed snowpack evolution modeling system simulating accumulation and loss from snow precipitation, blowing-snow redistribution, sublimation, snow-density evolution, and snowpack ripening and snow and ice melt, and specifically designed to be applicable over the wide range of snow landscapes and climates (Liston and Elder, 2006b). SnowModel includes a micrometeorological model (MicroMet). MicroMet is a quasi-physically-based meteorological distribution model (Liston and Elder, 2006a) designed to produce high-resolution meteorological forcing distributions of meteorological data into the terrestrial landscape. SnowModel simulations have previously been compared against observations in alpine,

Arctic, and Antarctic landscapes (e.g., Greene *et al*., 1999; Liston *et al*., 2000; Hiemstra *et al*., 2002; Liston and Sturm, 2002; Hasholt *et al.* 2003; Bruland *et al.* 2004; Mernild *et al.*, 2006a, 2006c, 2007b). In Eastern Greenland, SnowModel was used and produced maximum discrepancies of 8% in SWE and snow depth, and within ±100 m a.s.l. in spatial snow cover extent (Mernild *et al.*, 2006a, 2006c).
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, 2003a, 2003b; Mernild and Hasholt, 2006). The model describe in a simple quantitative form the behavior of the land phase hydrological cycle by a set linked mathematical statements by simulating hydrological processes 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 runoff values for the Mittivakkat Glacier catchment were compared against observed runoff values, with a discrepancy up to 11% in cumulative discharge volume (Mernild and Hasholt, 2006). Observed discharge at the Isco Island hydrometric station was calculated from stage-discharge relationships estimated each year (R^2-values from 0.91 to 0.99) using regression analysis (Figure 1). The discharge cross section has been stable for approximately 30 years, yielding an assumed 10–15% accuracy when a single discharge measurement is made (e.g., Hasholt and Mernild 2004).

5. RESULTS AND DISCUSSION

5.1 Overall climatic conditions

The climate in the Ammassalik area is affected by the East Greenland Polar Sea Current which has both surface temperatures close to 0ºC and drift ice most of the year. Winters are therefore cold with only short periods of above freezing temperatures. Summers are cold with fog at the outer coast, but relatively warm and sunny in the inner parts of the fjords. Winds and precipitation in the area are strongly affected by cyclonic activities around Iceland and along the Greenland east coast: the tracks of low pressure systems typically go from southwest to northeast.

5.2 Meteorological conditions 1993–2005

5.2.1 Solar radiation, albedo, and snow cover

The midnight sun line passes through Tasiilaq, while the polar night line is located about 200 km further north. Surrounding topography, slope/aspect of the terrain, and cloud cover has a great influence on the amount of incident incoming solar radiation. At Station Nunatak the surface is gently sloping from N, NE, and E towards SW and W; significant diurnal variations in 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 mountain to the N and E 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), indicating approximately 15% lower annual solar radiation in the coastal area due to the high frequency of dense clouds or thin sea fog (Figure 2). Variations in albedo is 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, up to ~0.8 m (~50%) higher (1998–2004) than the nunatak. The maximum annual snow depth at Station Nunatak varies between 0.95 m (2002/03) and 1.72 m (2000/01), and at Station Coast between 1.73 m (2002/03) and 2.52 m (1999/00) (Figure 3). During the 6-year 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 4). The number of days with snow cover have decreased by 62 days ($p<0.01$), 43 days in autumn and 19 days in spring: this is from 286 snow cover days (1998/99) to 224 days (2003/04) at Station Nunatak (Figure 4), indicating a longer snow-free season. A reduction probably caused by increased yearly thawing rates (see chapter 5.2.2) and reduced snow precipitation (see chapter 5.2.4).

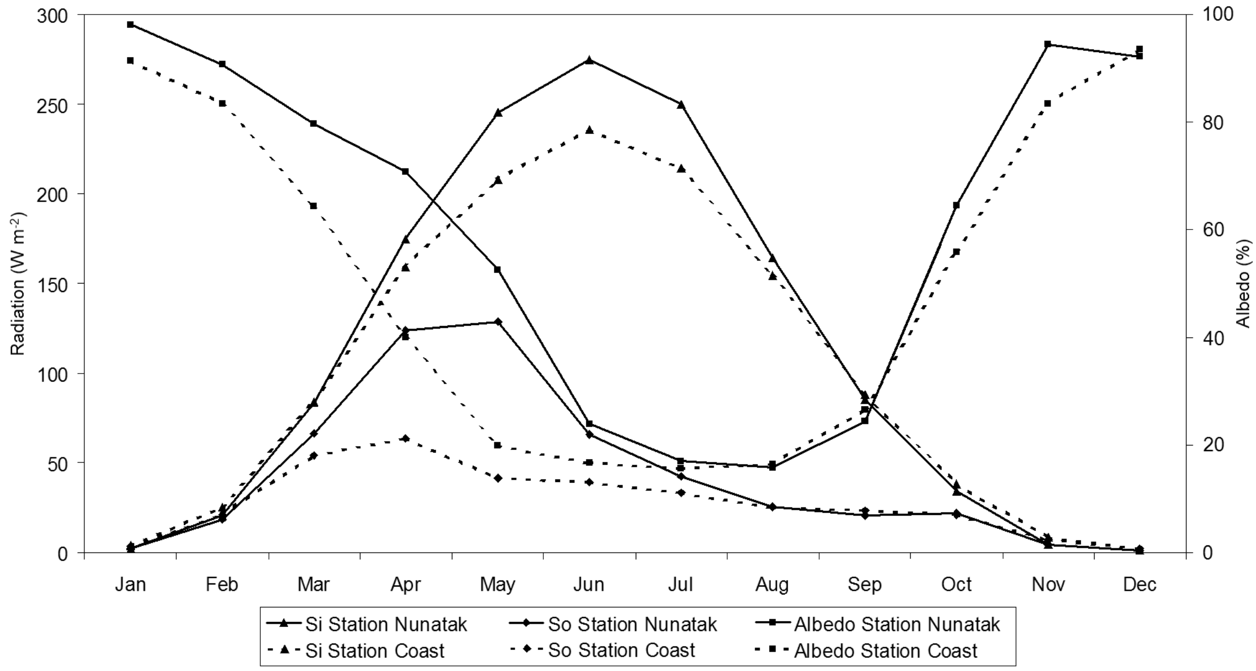

Figure 2: Mean monthly incoming (Si) and outgoing solar radiation (So) and albedo at Station Nunatak (1993–2005) and at Station Coast (1997–2005).

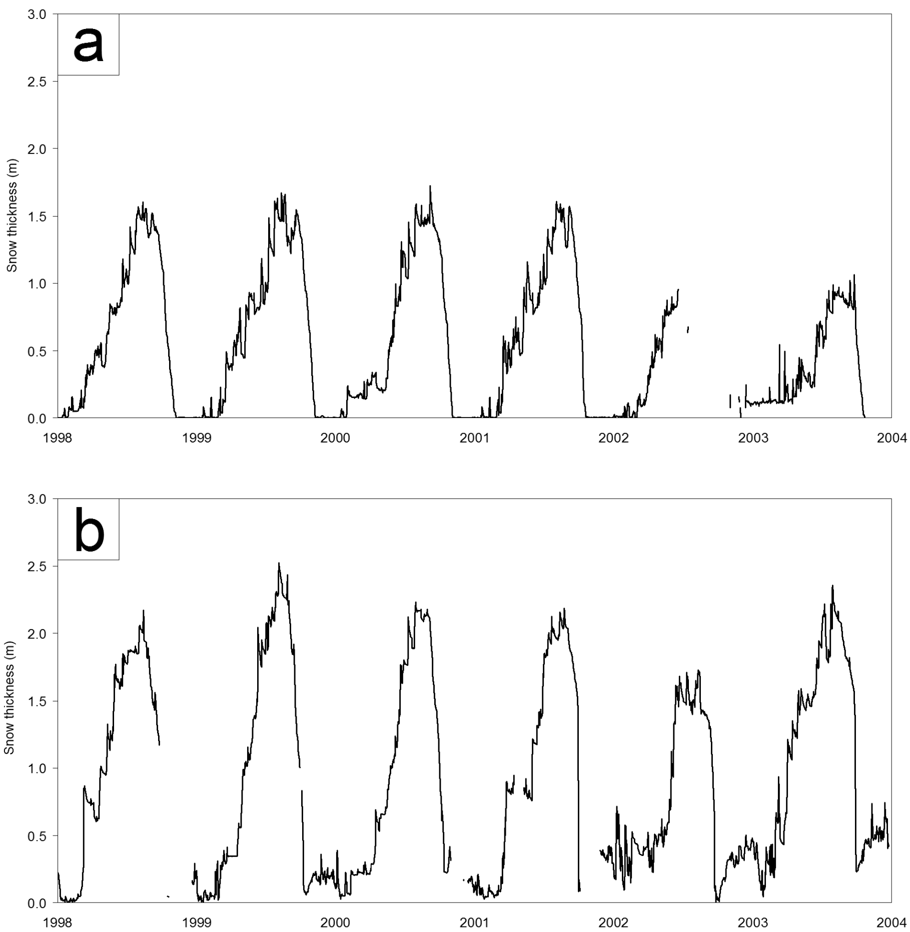

Figure 3: (a) Daily variation in snow depth at Station Nunatak (September 1998 to August 2004); and (b) at Station Coast (September 1998 to August 2004).

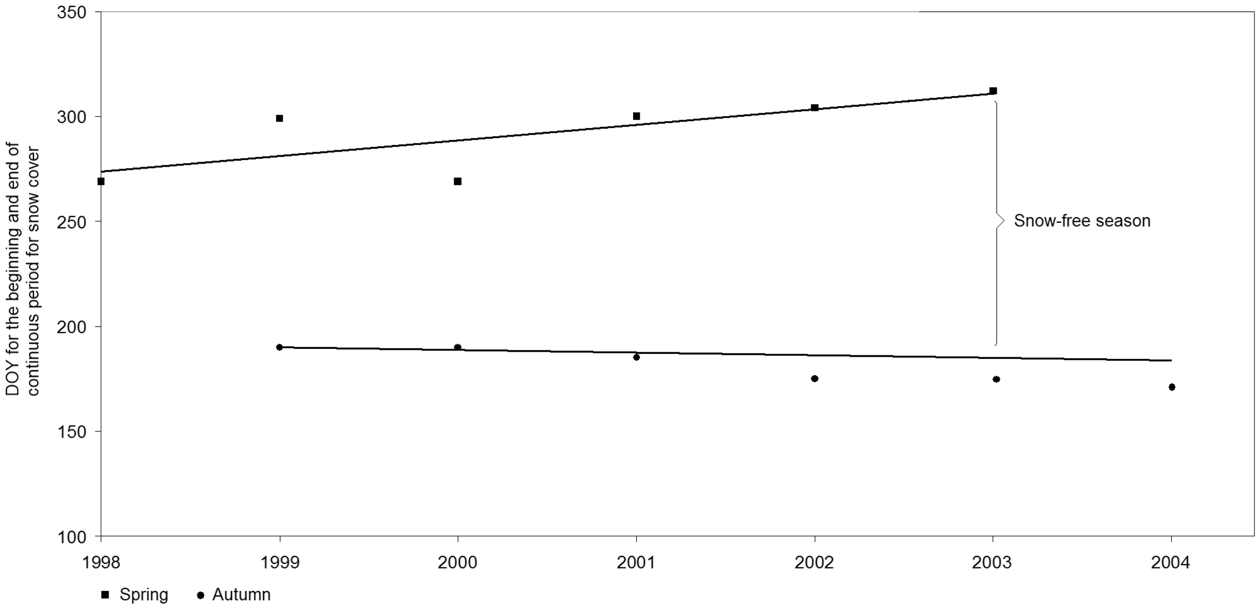

Figure 4: Day of year (DOY) for the beginning and the end of the continuous period for snow cover (1998–2004) at Station Nunatak. The area between the two trend lines indicate the snow-free season.

5.2.2 Air temperature and degree day

The Mittivakkat Glacier catchment mean annual air temperature (MAAT) is -1.7°C (1998–2004) (derived by spatial simulations in MicroMet), -2.4°C (2 m) and -2.2°C (4 m) at Station Nunatak (1994–2004), and -1.1°C (2 m) at Station Coast (1998–2004). The mean air temperature values cover a variation in MAAT from 1998 to 2004, showing increasing MAAT in the upper glacier area (0.06ºC y^{-1}) (Station Nunatak) and decreasing values in the coastal area (-0.13ºC y^{-1}) (Station Coast) (Figure 5a). The difference in MAAT between the stations has decreased from -1.6°C in 1998 to 0°C in 2003 (Figure 5a). This probably emphasizes a shift in continental and maritime conditions. Mean minimum air temperature in February is -9.2°C for Station Nunatak and -7.1°C for Station Coast in contrast to the average warmest month which is July at the nunatak (6.2°C) and August at the coast (4.9°C). A difference in warmest months between the stations, both in value and time, is probably due to e.g., albedo and heat capacity of the water, the Sermilik Fjord, near Station Coast, and the high frequency of dense clouds or thin sea fog. At Station Coast, positive mean monthly air temperatures occur from May to September and at Station Nunatak from June to September, however maximum mean monthly air temperatures is 7.4°C at the nunatak and 6.3°C at the coast (Figures 5b and 5c).

Mean monthly air temperature lapse rates for the Mittivakkat Glacier catchment are shown based on data from the two meteorological stations (Figure 5d). The mean annual air temperature lapse rate was approximately -0.3°C 100 m^{-1} (1997–2004), with an average range between the coldest and warmest mean monthly lapse rate of around 1.0°C 100 m^{-1}. February had the lowest average lapse rate (-0.6°C 100 m^{-1}), while July had the highest (0.4°C 100 m^{-1}) (Figure 5d). The positive average air temperature lapse rates from June to August are highly controlled by the wind regime; during the summer, sea breezes governed by local temperature differences in the heating of sea and land prevail, but they mostly only affecting coastal areas. The same yearly trend is present for periods without the occurrence of dense clouds or thin fog at the coastal (Mernild et al., 2005). The trend in monthly lapse rates is almost similar to other arctic coastal areas e.g., the Zackenberg River catchment (74°N), East Greenland.

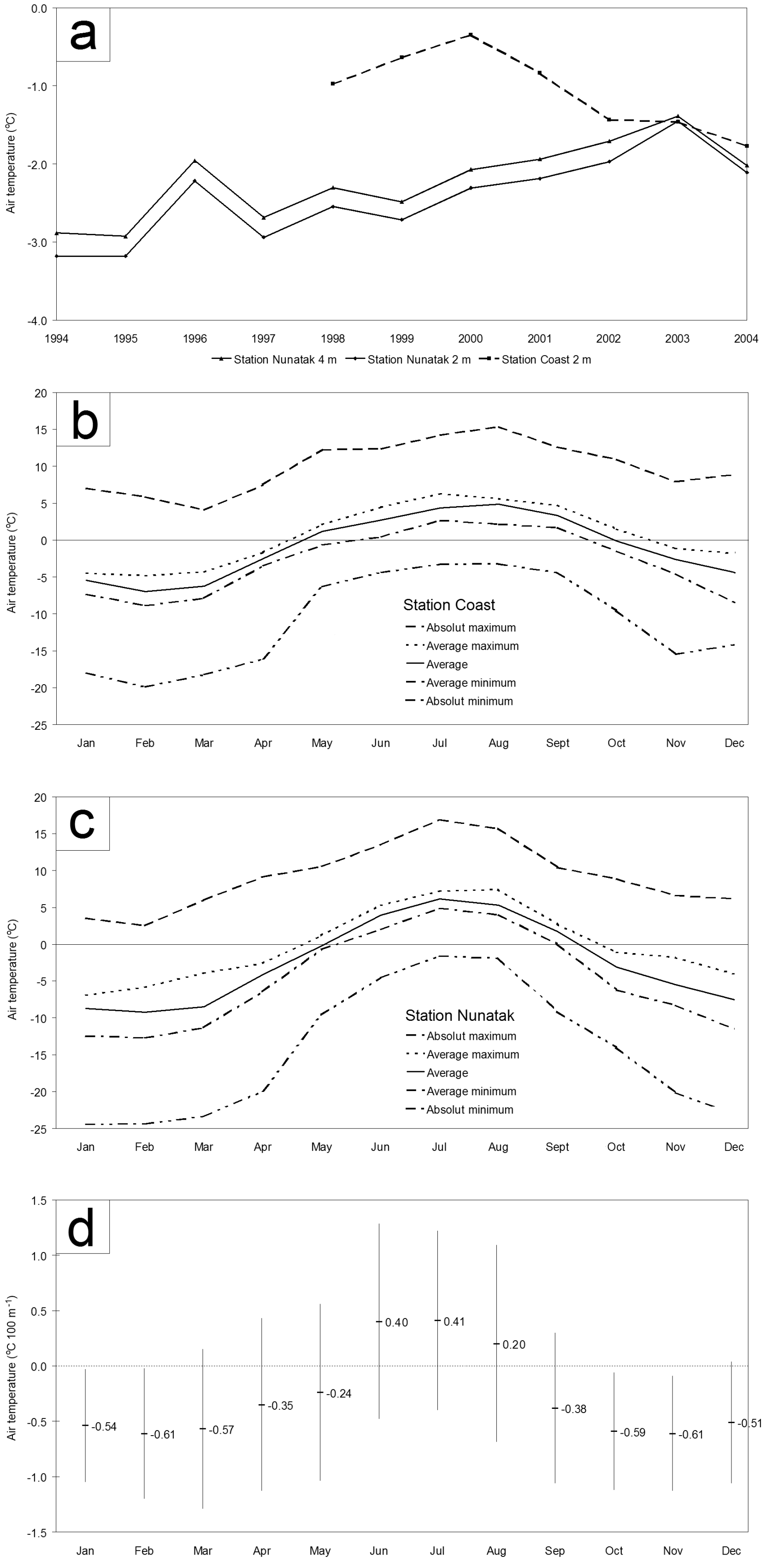

Figure 5: (a) Mean annual air temperature (MAAT) at Station Coast (2 m) (1998–2004) and at Station Nunatak (2 and 4 m) (1994–2004); (b) Station Coast maximum, mean, and minimum monthly mean air temperatures (2 m) for the time period (1998–2004); (c) Station Nunatak maximum, mean, and minimum monthly mean air temperatures (2 m) for the time period (1998–2004); and (d) monthly lapse rates based on air temperature (2 m) from Station Coast and Station Nunatak (1998–2004).

The lower part of the Mittivakkat Glacier catchment; the proglacial valley and the coastal area are highly dominated by the inversion. In summer time (June through August), inversions are present in approximately 85% of the observations (conducted in July 2006), where around 50% of the time inversions occur at 300 m.a.s.l., based on the radio sonde observations. In winter the present of inversion is expected to increase, as the amount of solar radiation and surface temperature decrease and snow and ice cover increase. For Zackenberg, NE Greenland, inversion are present 47–79% of the time in winter and 10–46% in summer/autumn (Mernild *et al.*, 2007c) The same trend is described by Serreze *at al.* (1992) for the Eurasian Arctic, and might also hold true for the Mittivakkat Glacier catchment.

A lateral transect of air temperature variation occurs through the catchment from the coast to the glacier terminus. That indicates a mean higher horizontal air temperature of 2°C and 4°C approximately 1,300 m from the coast (almost half way between the coast and the glacier terminus) compare to the coastal area and the glacier terminus air temperature respectively. This, due to cold sea breezes and katabatic winds (*piteraq*): cold air with a high density which flows towards the Mittivakkat Glacier edge (Mernild *et al.*, 2006b). Horizontal and altitudinal data which are required to account for the spatial variation of numerous variables used in snowmelt, glacier melt, and hydrological modeling at the catchment scale.

For Station Nunatak the trend lines on Figure 6 indicate a longer summer thawing period. In autumn the thawing season was extended by 31 days and in the spring by 10 days; resulting in a net thawing increasing period of 41 days (1993–2004). At Station Coast a decreasing thawing period occurred, with 12 and 6 days shorter autumn and spring thawing period, respectively. At Station Coast the net

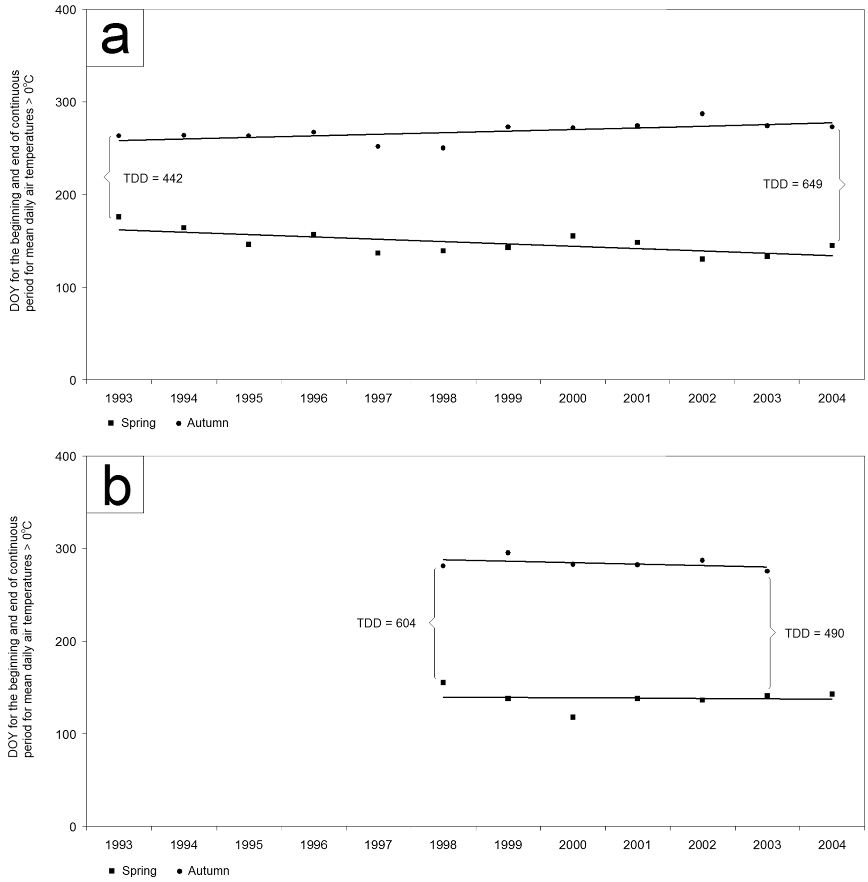

Figure 6: Day of year (DOY) for the beginning and the end of the continuous period for mean daily air temperatures above 0°C for: (a) Station Nunatak (1993–2004); and (b) Station Coast (1998–2004). The trend lines (linear regression) indicates longer thawing season at Station Nunatak, and a shorter thawing season at Station Coast. Furthermore, increasing Thawing Degree Day (TDD: the accumulated number of TDD is the sum of values of positive mean daily air temperatures) occur for Station Nunatak, and decreasing TDD for Station Coast.

thawing period decreased by 18 days (1998–2004). Furthermore, from 1993 to 2004 the yearly TDD increased at Station Nunatak from 442 to 649 (47% increase). No changes in mean TDD day^{-1} on 5.1 from 1993 to 2004 was observed. The opposite occurred for Station Coast, where yearly TDD decreased from 604 (1998) to 490 (2003) (19% decrease). The mean TDD day^{-1} decreased from 4.8 (1998) to 3.7 (2003) (Figure 6).

5.2.3 Wind direction, wind speed, and relatively humidity

Wind directions at both stations are highly dependent on the orographic conditions. At Station Nunatak cold katabatic fall winds, especially from the E, dominate all months around 30% of the time. The presence of the katabatic winds also results in the almost total lack of calms periods. During winter (illustrated by January in Figure 7c) and summer (illustrated by July) the main wind directions are from N to E at Station Nunatak. At Station Coast the wind direction is significantly influenced by the surrounding topography. A valley northeast of the station channels cold katabatic winds, especially in the winter (approximately 50% of the time the wind comes from north (Figure 7c)). 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 (Figure 7c); This is governed by local temperature differences between the heating of sea and land.

The mean annual wind speed is 3.8 m s^{-1} at 2 m and 4.0 m s^{-1} at 4 m at Station Nunatak (1994–2004), and 4.0 m s^{-1} at 2 m at Station Coast (1998–2004). Wind speed data shows a trend of increasing velocities during the period (Figure 7a). The wind speed is highest in the winter time (Figure 7b), with mean monthly velocities around 6 m s^{-1} and gusts values up to more than 30.0 m s^{-1}. Furthermore, the highest velocities occur from the dominating wind directions. Strong winds (*neqqqjaaq*, 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 relatively humidity is 87% (1998–2004) (derived by spatial simulations in MicroMet), covering a variation showing highest average values at Station Nunatak in winter (83%) due to the relatively lower air temperature, and highest average values at Station Coast in summer (86%) due to the sea breezes (Figure 7c).

5.2.4 Precipitation

The mean annual precipitation at Station Nunatak is 1,784 mm w.eq. y^{-1} (1997–2004), 1,347 mm w.eq. y^{-1} at Station Coast (1997–2004) (Figure 8b), and 1,491 mm w.eq. y^{-1} for the whole of the Mittivakkat Glacier catchment (Figure 8a) (derived by spatial simulations in MicroMet). The total annual solid (snow) precipitation at Station Nunatak is 1,629 mm w.eq. y^{-1} (1999–2004), calculated after applying a wind speed and winter glacier mass balance correction due to the exposed location at the nunatak (e.g., Hasholt and Mernild, 2004; Mernild *et al.*, 2006a), and at Station Coast it is 1,143 mm w.eq. y^{-1}. This indicates a positive orographic effect of 99 mm w.eq. per 100 m for SWE precipitation (Figure 8b) (Mernild *et al.*, 2006a). The 99 mm w.eq. per 100 m precipitation increase between the two meteorological stations is assumed to be closely related to the orographic influence of Ammassalik Island. Comparing the corrected precipitation at the DMI station in Tasiilaq with the adjusted precipitation at Station Nunatak, the orographic precipitation increases 121 mm w.eq. per 100 m (10% per 100 m) during 1997 to 2004. This is almost identical with gradients found and used in mountainous areas of Norway (Young *et al.*, 2006). Previous Ammassalik Island studies (1997/98), Hasholt *et al.* (2003) showed orographic precipitation increases as high as 14% per 100 m. 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 8c). 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.*, 2006b).

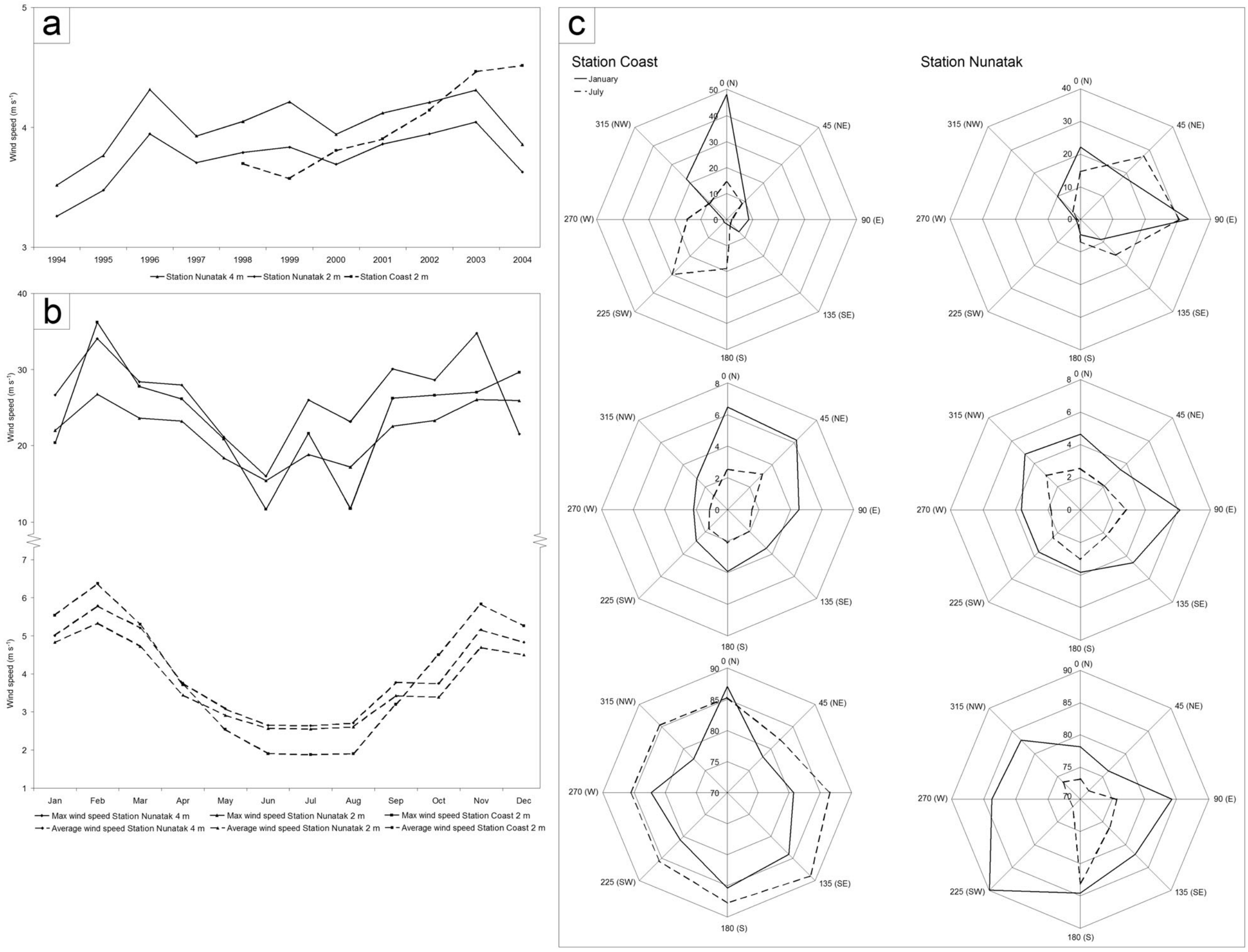

Figure 7: (a) Temporal trends in wind speed as average yearly values (1994–2004) for Station Nunatak (2 m and 4 m above terrain) and Station Coast (2 m); (b) temporal trends in maximum and average wind speed as mean monthly values for Station Nunatak (1993–2005) and Station Coast (1997–2005). Notice the change in scale on the ordinate; and (c) frequency (%) of wind direction, wind speed (m s^{-1}) related to wind direction, and relatively humidity (%) related to wind direction for average January and July for Station Nunatak (1993–2005) and Station Coast (1997–2005).

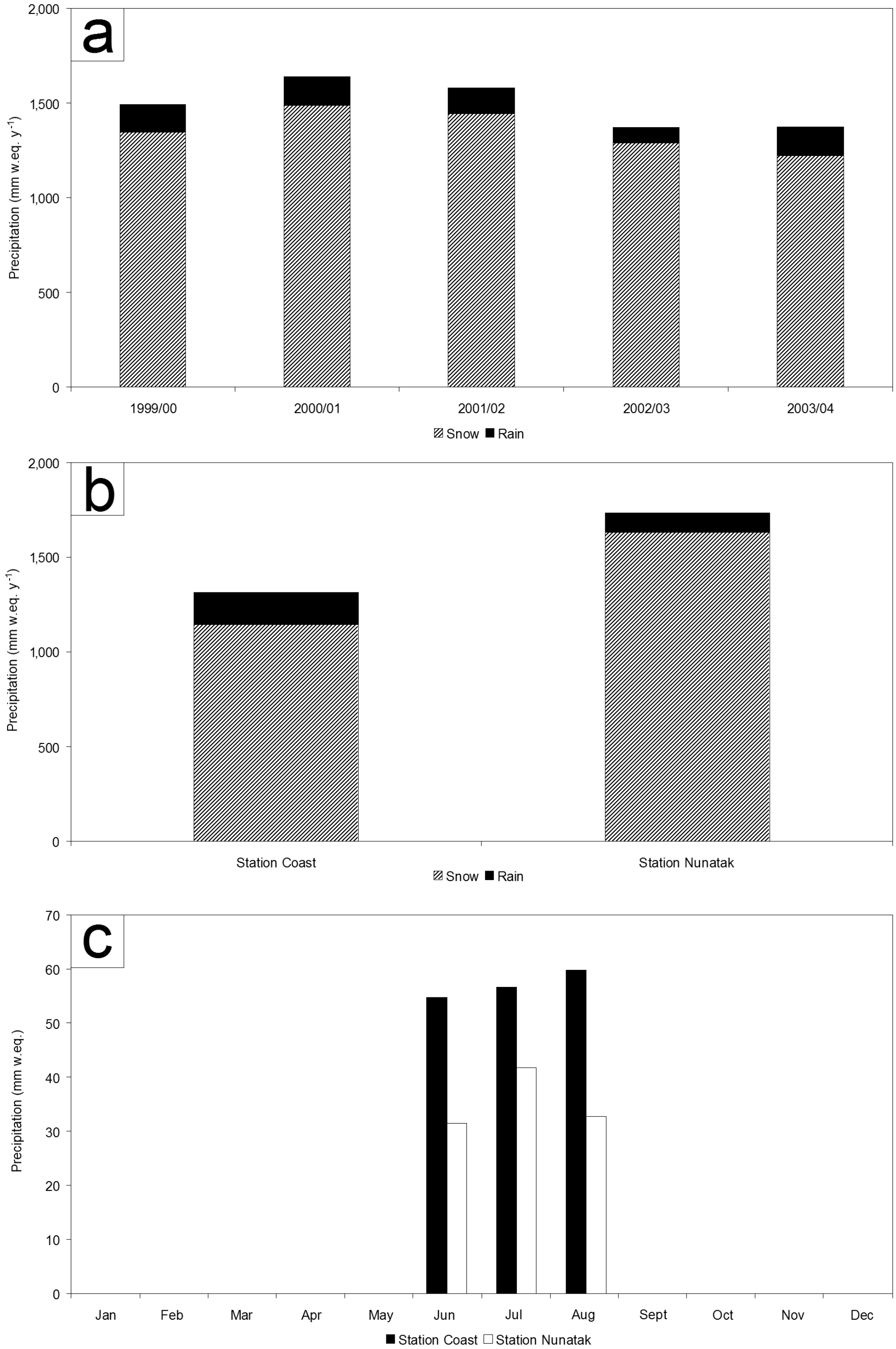

Figure 8: (a) Average annual (September to August) Mittivakkat glacier catchment snow and rain precipitation (1999/2000 to 2003/2004) (derived from Snow and Micrometeorological Model (SnowModel/MicroMet) (Liston and Elder, 2006a; 2006b)); (b) average annual (September to August) snow and rain precipitation at Station Coast (1998/1999 to 2003/2004) and at Station Nunatak (1998/1999 to 2003/2004); and (c) monthly June, July, and August average rain precipitation at Station Coast (1998–2004) and at Station Nunatak (1994–2004).

5.3 Glacier mass balance and runoff conditions 1993–2004

This period of continuous Mittivakkat Glacier mass balance observations since 1995/96 has been one of almost increasing (linear trend) glacier recession (Table 1). Only 1995/96 and 2002/02 had a positive net mass balance of 0.01 m w.eq. y^{-1} and 0.35 m w.eq. y^{-1}, respectively. The average observed winter mass balance (1995 through 2003), summer mass balance (1995 through 2003), and glacier net mass balance (1995 through 2004) are, respectively, 1.27±0.17, -1.80±0.40, and -0.59±0.51 m w.eq. y^{-1}, showing a negative net mass balance (Table 1). Further, an average increasing negative net mass balance occur since the first continuously observations in 1995/96. During the period of observation the Mittiakkat Glacier lost in average 0.59 m w.eq. y^{-1}, corresponding to 8.5×10^6 m^3 y^{-1} based on 78% (14.4 km^2) glacier cover in the catchment, and further corresponding to a 0.4% y^{-1} loss of volume based on 1994 determined glacier volume of $2{,}024\times10^6$ m^3 y^{-1}. This was measured by radio-echo sounding (Knudsen and Hasholt, 1999). The observed net mass balance from 1999 to 2002, based on 100-m-altitudal intervals observations, indicate that the ELA was located around 500–550 m a.s.l., except for 2000/01 where it was above 800 m a.s.l. (Mernild *et al.*, 2006a).

Table 1: Observed winter, summer, and net mass balance for the Mittivakkat Glacier (1995/1996 to 2003/2004) based on data in Knudsen and Hasholt (2004) and Mernild *et al.* (2006). Winter mass balance observations are carried out in late May and early June and summer mass balance observations in late August. (†) Calculated based on observations from 1995/96 to 2002/03. (*) Calculated based on observations from 1995/96 to 2003/04. The Mittivakat Glacier covers approximately 80% of the catchment area (18.4 km^2).

Year	Observed winter mass balance (m w.eq. y^{-1})	Observed summer mass balance (m w.eq. y^{-1})	Observed net mass balance (m w.eq. y^{-1})
1995/1996	1.51	-1.50	0.01
1996/1997	1.41	-1.81	-0.40
1997/1998	1.14	-2.31	-1.17
1998/1999	0.98	-1.75	-0.77
1999/2000	1.23	-2.06	-0.83
2000/2001	1.18	-2.14	-0.96
2001/2002	1.28	-1.78	-0.50
2002/2003	1.40	-1.05	0.35
2003/2004	No data	No data	-1.06
Average and standard deviation	1.27±0.17 (†)	-1.80±0.40 (†)	-0.59±0.51 (*)

At the Mittivakkat Glacier catchment the simulated date of river break-up at the catchment outlet has varied from year to year between 10 May (1998) and 10 June (2003) during the period 1994 and 2004 (Table 2 and Figure 9). The river simulated discharge varies between 1,326 mm w.eq. y^{-1} (corresponding to a runoff of 24.4×10^6 m^3 y^{-1}) for 1999 and 2,282 mm w.eq. y^{-1} (corresponding to a runoff of 42.0×10^6 m^3 y^{-1}) for 2001 (Mernild and Hasholt, 2006). The mean annual simulated river discharge for the period 1994–2004 was 1,973±281 mm w.eq. y^{-1} (corresponding to a runoff of 36.3×10^6 m^3 y^{-1}). High annual runoff peaks occur throughout the runoff season, mainly after periods with high air temperatures and subsequent surface melt (snow and glacier ice melt) and rain events (Figure 9). For example in 2004, where two main runoff peaks: a July 10 peak (11.6 m^3 s^{-1}) caused by a precipitation event, and an August 13 (11.0 m^3 s^{-1}) event due to melt events occurred. Maximum hourly observed river discharge (40.3 m^3 s^{-1}) so far at the catchment outlet was on 4 September 2000 after 36 hours with a mean air temperature of 8.7ºC coupled with 34 mm of precipitation (derived from MicroMet) (a peak discharge not seen clearly on Figure 9, due to the daily time step).

Table 2: Yearly observed and simulated accumulated discharge from the Mittivakkat Glacier catchment, together with maximum observed discharge and simulated date for river break-up (Mernild and Hasholt, 2006). The period goes from September to August followed by the Mittivakkat Glacier mass balance.

	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 proglacier valley)
1993/1994	30 Jun – 28 Aug	1,307	9.3	2,144	22 May
1994/1995	1 Jul – 31 Aug	1,896	11.7	2,091	27 May
1995/1996	No data	No data	No data	1,864	28 May
1996/1997	No data	No data	No data	2,126	17 May
1997/1998	No data	No data	No data	1,914	10 May
1998/1999	22 Jun – 31 Aug	937	11.7	1,639	23 May
1999/2000	8 Jun – 17 Sept	2,010	6.9	2,145	11 May (13 May)
2000/2001	18 Jun – 15 Sept	1,726	6.1	2,282	23 May (26 May)
2001/2002	10 Jun – 5 Sept	1,871	7.9	1,987	27 May (28 May)
2002/2003	7 Jun – 20 Aug	927	5.7	1,326	8 Jun (10 Jun)
2003/2004	14 Jun – 27 Aug	1,907	10.0	2,190	25 May (26 May)
Average	--------	--------	8.7	1,973	23 May

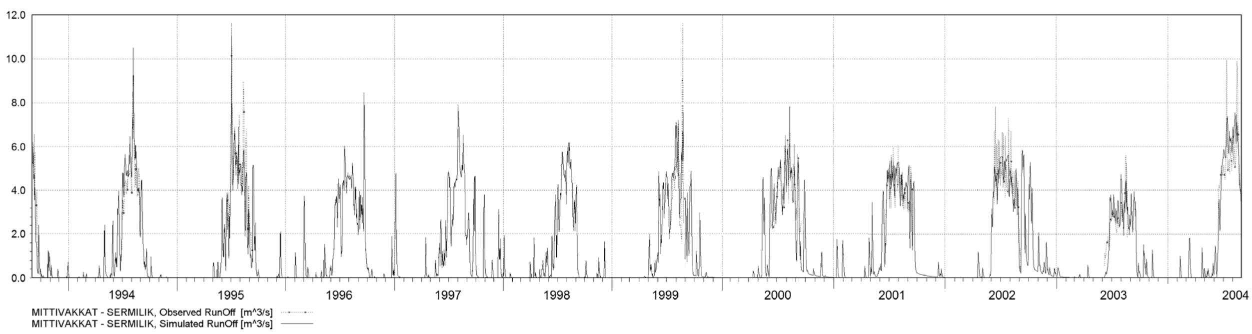

Figure 9: Daily observed and simulated discharge from the Mittivakkat Glacier catchment, Ammassalik Island, from September 1993 to August 2004. However, observed dicharge was missing from 1996, 1997, and 1998. Discharge was simulated by the NAM model; $R^2 = 0.77$ (Mernild and Hasholt, 2006).

5.4 Air temperature, glacier balance, and runoff in a 106 years perspective

Figure 10 illustrate the mean annual air temperature variation from 1898 to 2004 for the Mittivakkat Glacier catchment (obtained by linear regressions of air temperatures between the Tasiilaq and Sermilik stations). During the 106 year period warming, cooling, and constant air temperatures occurred in different intervals. General periods of warming was observed from 1918 (the end of the Little Ice Age) to 1935 and 1978 to 2004, in accordance with observations from the Arctic in generel by Serreze *et al*. (2000). Air temperature cooling at the Mittivakkat Glacier catchment occurred from 1955 to 1978, and approximately constant temperature conditions from 1898 to 1918 and 1935 to 1955, however the air temperature over the last 106 years has increased statistically significant by 1.3°C. This in contrast to the mean global air temperature increase by 0.3 to 0.6°C (e.g., Maxwell, 1997; Kane, 1997). All four seasons 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 year period within the last 106 years was the period from 1936–1946 (-1.8°C), while within

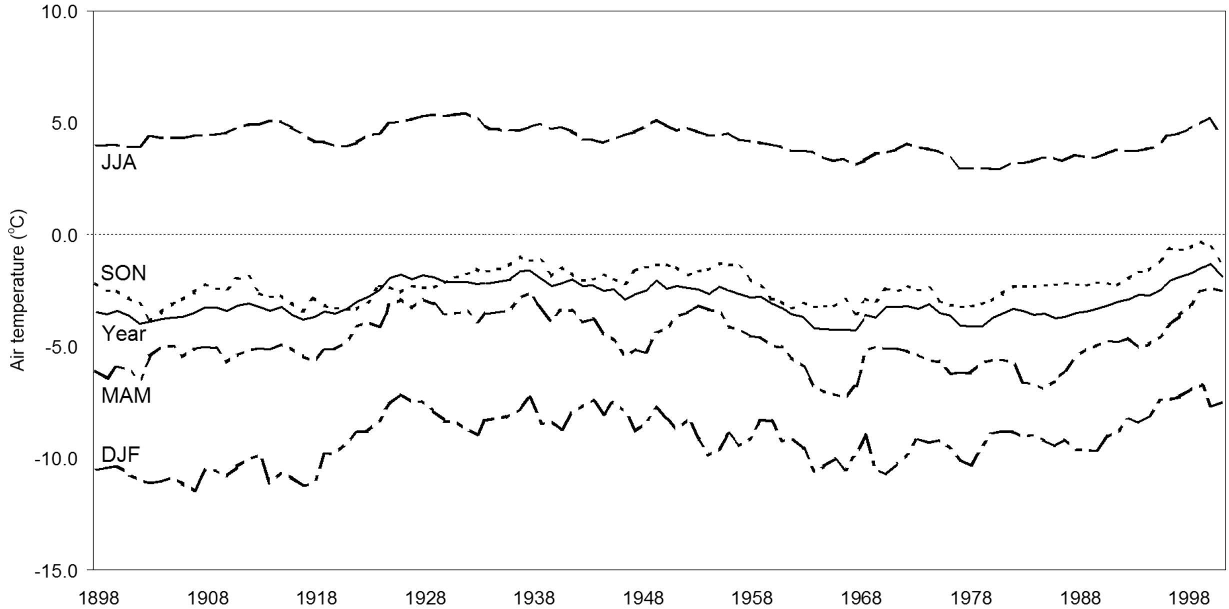

Figure 10: Five-year running mean annual and seasonal air temperature at the Mittivakkat Glacier catchment for the period 1898–2004. The abbreviations are DJM (December, January, and February), MAM (March, April, and May), JJA (June, July, and August), SON (September, October, and November), and Year (January to December). Data (from the DMI station in Tasiilaq) are missing in the period from September 1910 to August 1911 and from January 1971 to December 1972.

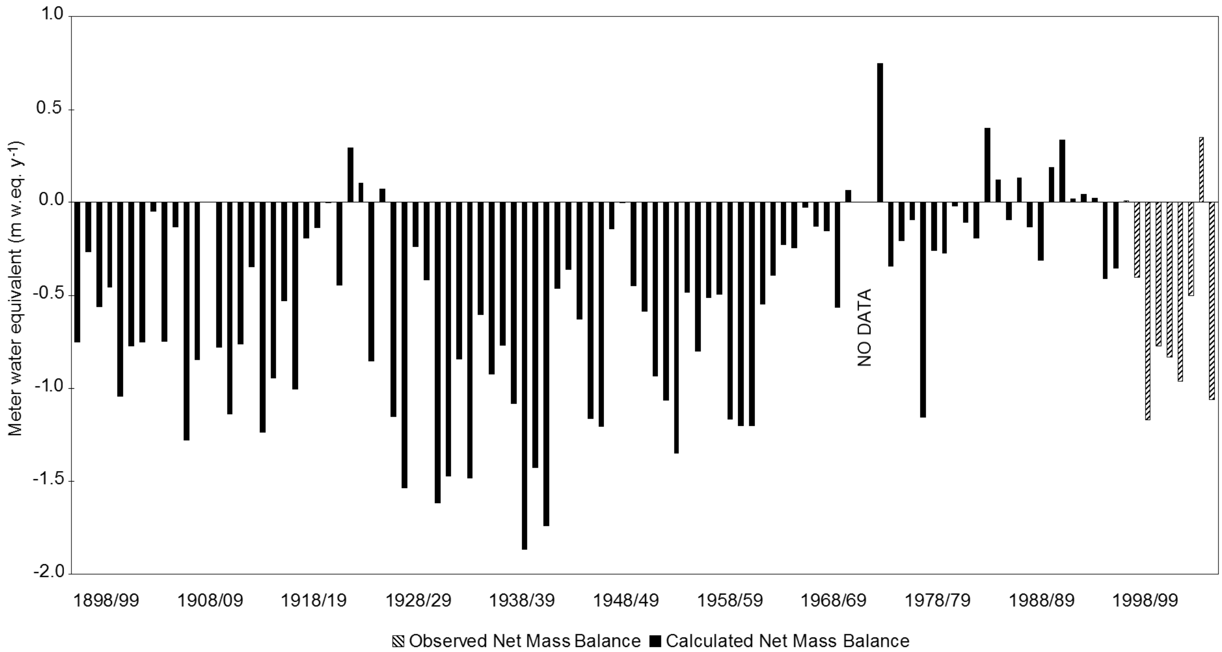

Figure 11: Yearly (September to August) observed (1995/96 to 2003/04) and calculated (1898/99 to 1994/95) glacier net mass balance (change in storage) for the Mittivakkat Glacier. The assumed accuracy of the observed net mass balance are within ±15% (Knudsen and Hasholt, 2004; Mernild *et al.*, 2006).

the last 60 years the warmest 10 year period was the period from 1995–2004 (-2.0°C) for the Mittivakkat Glacier catchment (Figure 10).

A warming climate, as just described, initiates and produce a cascade of impacts that affect glaciological and hydrological processes. Figure 11 shows the estimated Mittivakkat Glacier net mass balance from 1898 to 2004, indicating an average glacier recession of -0.55±0.53 m w.eq. y^{-1}, however maximum and minimum values of 0.75 m w.eq. y^{-1} (1972/73) and -1.87 m w.eq. y^{-1} (1939/40) occur, respectively. During the period, in 89 out of 105 balance years the Mittivakkat Glacier had a negative estimated balance, with a cumulative estimated balance of -56.7 m w.eq. The difference surface elevation based on topographic maps from 1932/33 (Geodædisk Institut 1938) and 1972 (based on aerial photographs) showed that the glacier below the 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 observed in places (Knudsen and Hasholt, 2004). Observations from 1933 indicates an almost continuous glacier margin recession on 1.2 km until 2004 (~17 m y^{-1}). The changes in location of the Mittivakkat Glacier margin since 1933 through the proglacier valley are shown on Figure 12. Together with changes in glacier size and shape, changes in internal drainage system and hydraulic response occur, all effecting the hydrological fluxes.

In the Mittivakkat Glacier catchment, the glacier net mass balance and the freshwater runoff is closely related because 78% of the catchment is covered by the Mitivakkat Glacier. Up to 90% of the yearly catchment runoff is explained by the glacier behavior. Average annual runoff was estimated to be 1,957±254 mm w.eq. y^{-1}, with a range between 2,522 mm w.eq. y^{-1} and 1,326 mm w.eq. y^{-1}, respectively (Figure 13).

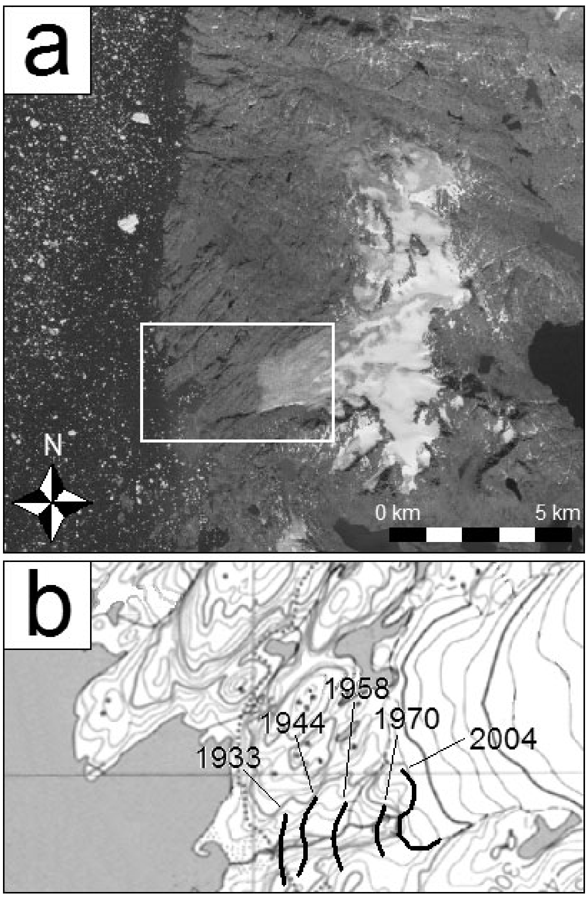

Figure 12: (a) Satellite image of the Mittivakat Glacier, Ammassalik Island August 22 (2004). The topographic map is within the white rectangle (source: www.digitalglobe.com/archive), and; (b) topographic map of the lower Mittivakkat Glacier including the margin and the proglacier valley. Lines indicate the Mittivakkat Glacier margin at different years (source: map modified after Greenland Tourism).

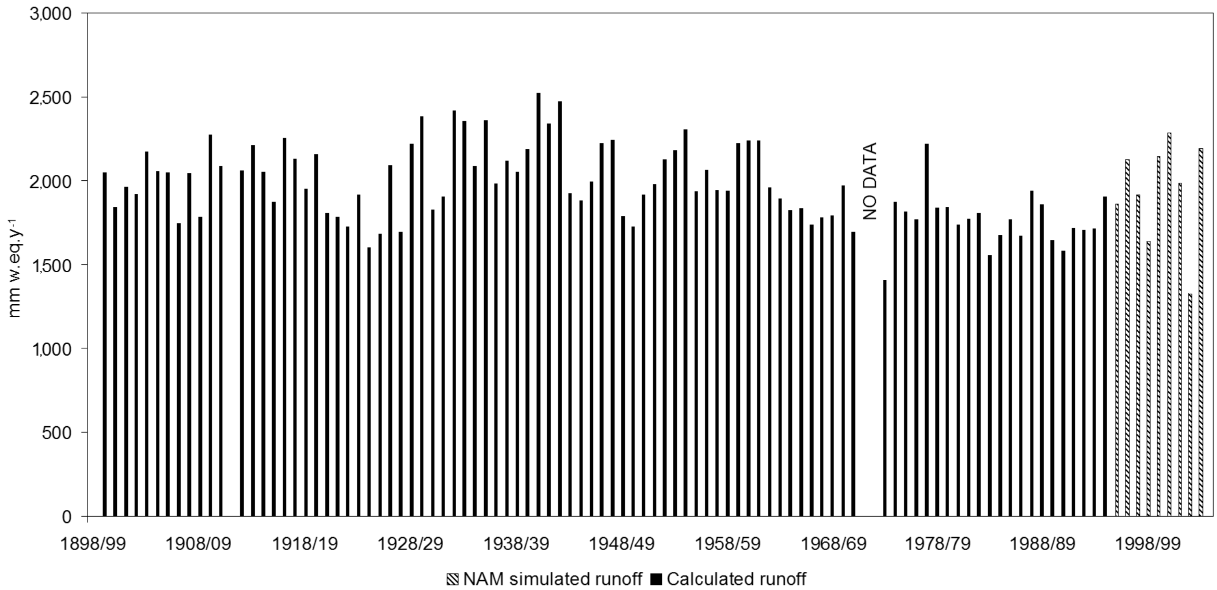

Figure 13: Yearly (September to August) simulated (1995/96 to 2003/04) and calculated (1898/99 to 1994/95) runoff from the Mittivakkat Glacier catchment. Simulated runoff values are based on NAM simulations (DHI, 2003a, 2003b; Mernild and Hasholt, 2006), calibrated and validated against observed runoff values.

6. CONCLUSION

From the above evaluation of twelve years of data (1993–2005) from meteorological stations within the Mittivakkat Glacier catchment on the western part of the Ammassalik Island, Southeast Greenland, we conclude that characteristic trends in meteorological conditions within the catchment have been noted, including increasing air temperature (0.09ºC y^{-1}) in the glacier area (at Station Nunutak) and decreasing values (-0.13ºC y^{-1}) in the coastal area (at Station Coast). Changes in air temperature, impacts both the thawing period and the snow-free period in the lower watershed and glacier net mass balance in the upper watershed. When data from the Mittivakkat Glacier catchment are compared to other data series in the area, it become clear that meteorological observations in the catchment are in line with other long term records, which make it possible to estimate data from the Mittivakkat Glacier catchment back in time to 1898. The 106 year period showed an increasing air temperature, mainly in winter season, but also that the period 1995–2004 was the warmest 10 year period within the approximately last 60 years for the Mittivakkat catchment. Since 1933 the glacier margin had retreated approximately 1.5 km.

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