

GLOBAL WARMING AND THE GREENLAND ICE SHEET

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Abstract. The Greenland coastal temperatures have followed the early 20th century global warming trend. Since 1940, however, the Greenland coastal stations data have undergone predominantly a cooling trend. At the summit of the Greenland ice sheet the summer average temperature has decreased at the rate of 2.2 °C per decade since the beginning of the measurements in 1987. This suggests that the Greenland ice sheet and coastal regions are not following the current global warming trend. A considerable and rapid warming over all of coastal Greenland occurred in the 1920s when the average annual surface air temperature rose between 2 and 4 °C in less than ten years (at some stations the increase in winter temperature was as high as 6 °C). This rapid warming, at a time when the change in anthropogenic production of greenhouse gases was well below the current level, suggests a high natural variability in the regional climate. High anticorrelations ($r = -0.84$ to -0.93) between the NAO (North Atlantic Oscillation) index and Greenland temperature time series suggest a physical connection between these processes. Therefore, the future changes in the NAO and Northern Annular Mode may be of critical consequence to the future temperature forcing of the Greenland ice sheet melt rates.

1. Introduction

Air surface temperature trends in the polar regions are of special interest for several reasons. During the previous interglacial period (the Eemian, ~ 125 k y before present) the sea level was about five to six meters higher than today (Stirling et al., 1998; Vezina et al., 1999). It is interesting to note that a melting of either the Greenland or the West Antarctic ice sheet would produce a similar sea level increase. Indeed, it has been suggested (Mercer, 1978; Cuffey and Marshall, 2000) that the difference between the current and the Eemian sea level may more likely be due to the melting over Greenland than the West Antarctic ice sheet during the past interglacial. Consequently, during the current phase of climate change marked by an increasing atmospheric concentration of greenhouse gases and increasing global temperature, it is important to ask whether there is any indication that the Greenland ice sheet is melting. The melting ice sheet would lead to an increase



in sea level, and possibly also to a reduced intensity of the Atlantic thermohaline circulation (Clark et al., 2002; Dickson et al., 2002).

A hypothetically stable ice sheet is produced by a long term balance between negative components (melting, sublimation and ice/water discharge) and positive components (precipitation and water vapor deposition). It is also interesting to note that with warmer temperatures, more of the precipitation at low elevations (where most melting occurs) will be rain instead of snow. The wetting of the snow leads to reduced surface albedo and can contribute to an earlier than normal onset of melt. On the other hand, the thinning of an ice sheet may occur without increasing the temperature and melting if there is a decrease in the precipitation and/or an increase in the ice outflow. In fact, the results of Bromwich et al. (2001) indicate that surface height reductions measured by laser altimeter (Krabill et al., 1999) are strongly correlated with regions of decreasing precipitation trend. In relation to global warming, it is the surface air temperature that provides the most direct link between an anthropogenically induced global warming and a possible melting of polar ice sheets.

An increase in the global average surface air temperature in recent decades has been estimated by a wide body of researchers (e.g., Hansen et al., 1999; Christy, 2001). The average increase of the global surface air temperature for the last century is likely to be between 0.4 to 0.8 °C. Although the internal variability of the climate system (Hurrell, 1996; Hurrell and van Loon, 1997) and the solar influence on climate (Willson and Mordvinov, 2003) are not yet fully understood, it is believed that the observed global temperature increase is, at least partially, due to the increasing atmospheric concentration of carbon dioxide and other greenhouse gases (IPCC, 2001). The atmospheric General Circulation Models (GCMs) generally predict that the warming due to greenhouse gas increases will be amplified at higher latitudes. Although this warming enhancement at higher latitudes has indeed been observed on long time scales (Cuffey et al., 1995), its validity on a decadal time scale has been questioned (Polyakov et al., 2002). The temperature changes over Greenland are of prime importance in assessing the stability of the current climate. The global warming induced melting of the Greenland ice sheet would mean a major catastrophe for coastal regions all over the world.

The purpose of our paper is to point out the Greenland natural climate variability, its dependence on the phase of the NAO, and its difference from the global trend.

2. Greenland Ice Sheet Mass Balance

Determining the long-term mass balance of the Greenland ice sheet has been a subject of intense observational and modeling research (e.g., Ohmura et al., 1999; Dahl-Jensen, 2000; Thomas et al., 2000, 2001). The results are inconclusive for the ice sheet as a whole, owing to the large uncertainties when balancing very large,

difficult to measure, offsetting quantities (Reeh, 1999). Even the direction in which the mass of the Greenland ice sheet is currently changing is in dispute.

The current network of stations, including the automated observing stations, do not provide time series of sufficient length for reliable long-term mass balance assessment. Large scale atmospheric modeling demands increased horizontal resolution to resolve steep Greenland topographical features at the ice margin where substantial seasonal melting occurs and to improve the parameterizations of processes important for ice sheet mass balance like meltwater retention by percolation and refreezing. There have been reports of regional warming in the Arctic region (Serreze et al., 2000), increase in snowpack melt on the Greenland ice sheet (Mote and Anderson, 1995) and a regional thinning of the Arctic sea-ice (Rothrock et al., 1999). However, a host of measurements do not indicate a melting of the Greenland ice sheet. The following review illustrates the continuing high level of uncertainty in the Greenland ice sheet mass balance measurements.

Using the Seasat and Geosat satellite mission data, Zwally et al. (1989) concluded that the southern part of the Greenland ice sheet, south of 72° N, grew at the rate of about 23 cm/year during the years 1978 to 1986. It has been suggested (Zwally, 1989) that a generally warmer polar climate and the anticipated increase in precipitation might be a possible cause of this ice sheet mass growth. Seasat and Geosat altimetry data from 1978 to 1988 were re-analyzed by Davis et al. (1998a). Inclusion of additional satellite orbit-related corrections lead to the conclusion that the southern Greenland ice sheet grew only at a rate of 1.5 cm/year between the years of 1978 and 1988. The latter growth rate was considered to be too small relative to the uncertainties to determine with confidence if the Greenland ice sheet was undergoing a long-term change in response to changing global climate (Davis et al., 1998a). The discrepancy between the Zwally et al. (1989) and Davis et al. (1998a) results indicates that a few more decades of measurements are needed before a definite statement concerning the mass balance of the Greenland ice sheet can be made (Zwally et al., 1998; Davis et al., 1998b). More recently, McConnell et al. (2000) argued that large melt layers formed in 1977 and 1978. These layers then modified the usual Seasat and Geosat radar signatures at the snow-air interface and lead to an overestimate of thinning and an underestimate of thickening in the region for the subsequent decade. Using a physical model of firn densification together with snow accumulation records at 12 ice core sites, McConnell et al. (2000) have shown that the satellite record of the Southern Greenland ice sheet elevation changes during the years 1978–1988 agrees with the expected changes induced by variable snow accumulation and that such changes are well within the long-term natural variability. The aircraft-based laser altimetry over southern Greenland between 1993 and 1998 (Krabill et al., 1999) indicates a thickening over most of the southwestern part of the ice sheet at the rate of more than 10 cm/year and a significant thinning rate exceeding 100 cm/year near the south east coast. It has been suggested (Krabill et al., 1999) that the observed changes are caused by increased rates of ice flow rather than by melting.

Paterson and Reeh (2001) compared the elevation of about 300 sites on a 1200 km long traverse across northern Greenland (between 77 and 78° N) measured by the British North Greenland Expedition of 1953–1954 with the radar altimetry results from the ERS-1 satellite data collected during 1994–1995. They found no significant change in ice sheet elevation (perhaps a slight thickening) in the eastern part between 25 and 50° W. In the western part, between 60 and 65° N they found a significant thinning at the rate of about 30 cm/year. In the area of this thinning, Krabill et al. (2000) found a slight thickening during the years of 1994–1999.

The extent of snow melt on the whole Greenland ice sheet between the years 1979 and 1991 was deduced from the passive microwave satellite data by Abdalati and Steffen (1997). The mean ice sheet melt area as determined from the passive satellite data at 19 and 37 GHz (Abdalati and Steffen, 1995) was correlated to the average temperature changes at four Greenland coastal stations: Thule, Godthåb, Danmarkshavn and Ammassalik (the Godthåb temperature was really an average of the Godthåb and two other nearby stations). For the years 1979–1991, the correlation coefficient was 0.78 and suggested that a 1 °C temperature increase in the average of the four coastal stations is accompanied by an increase of $73 \times 10^3 \text{ km}^2$ in the melt area. It has been proposed that the expected greenhouse related temperature increase will lead to a significant spatial increase of melt on the Greenland ice sheet (Abdalati and Steffen, 1997).

3. The Greenland Ice Sheet and Sea Level

Possible changes of the Greenland ice sheet and the accompanying effect on sea level caused by increasing greenhouse gas concentrations has been investigated using coupled atmosphere-ocean GCMs. Ohmura et al. (1996) investigated the effect of doubling the atmospheric CO₂ concentration. Over the Greenland ice sheet, the model suggests a decrease in precipitation and an increase in ablation at the rate of 2 mm/year and 200 mm/year, respectively. In their simulations, the annual average surface air temperature over Greenland increased by about 2 °C in lower coastal regions and by about 4 °C at higher elevation on the ice sheet. This pattern results from the fact that at high elevations, there is little or no summer melting, while at low elevations, temperature variability is stabilized by the melting heat sink effect whereby temperatures remain near 0 °C during the melt season. The simulated Greenland ice sheet contribution to sea level change was approximately 1.1 mm/year (Ohmura et al., 1996). This contribution could be partially offset by an expected increase in precipitation over Antarctica. The net sea level contribution from the two ice sheets, 0.2 mm/year is within the uncertainty of the assumptions and models used.

A similar conclusion for the doubled CO₂ scenario was obtained by Thompson and Pollard (1997). They estimated the Greenland contribution to sea level change

would be 1.2 mm/year while the contribution from Antarctica was -1.3 mm/year, leaving again the net sea level change to be decided by other factors. Gregory and Oerlemans (1998) used GCM output as a driving mechanism for a more detailed glacier model. Taking a 1% per year increase in atmospheric CO_2 concentration, they obtained a global average temperature increase of between 2.7 and 3.3 °C over the 1990 to 2100 time span. Their result suggests that the Greenland contribution to sea level rise is considerably smaller, between 0.30 and 0.35 mm/year. This was again brought within the uncertainty of the model by a positive mass balance of the Antarctica contribution to the sea level change at the rate of -0.30 mm/year.

Zuo and Oerlemans (1997) employed an alternative approach to estimate the ice sheet and glacier contributions to global sea level change by determining ice mass sensitivity to temperature and precipitation changes. The available instrumental records suggested that changes in air temperature have resulted in a net positive contribution of ice melt to global sea level change. Their estimate of ice melt contribution from 1865–1990 was 5.7 cm (2.7 cm from glaciers and 3.0 cm from Greenland). Greenland melting accelerated during a warm period beginning in the 1920s and between 1965–1990 melted at a significantly smaller rate, associated with regional cooling. Much of the observed melt in Greenland and other ice masses is thought to be a response to warming since the neoglacial maximum (little ice age) conditions (Weidick, 1984; Grove, 1988). This and the fact that the recent temperatures are higher than in the earliest part of the record explain why Zuo and Oerlemans get a continually positive sea level contribution from the Greenland ice sheet.

Future sea level change will also be significantly influenced by other factors besides ice sheet mass balance, i.e., solid earth (crust and mantle) responses to deglaciation (Peltier, 1998; 2002), thermal expansion of sea water (IPCC, 2001) and melting of relatively small mountain glaciers (Dyurgerov and Meier, 1997).

Concerning the history of the Greenland ice sheet, Cuffey and Marshall (2000) pointed out that the relationship between the temperature change and the $^{18}\text{O}/^{16}\text{O}$ ratio might have been different for different states of climate, and that consequently the surface air temperature over the Greenland ice sheet during the previous interglacial period (Eemian) might have been higher than usually assumed. Hence the melting of the Greenland ice sheet might have been a major contributor, along with the partial disintegration of the West Antarctic ice sheet, to the higher sea levels during the Eemian.

Wahr et al. (2001) determined a -5.8 mm/year vertical crustal motion in southwestern Greenland, which is consistent with archeological and historical evidence that the region has been subsiding over the last 3 k years. This result is, however, inconsistent with estimates of Earth's continuing viscoelastic response to melting ice prior to 4 k y before present. One possible explanation of this pattern was suggested to be an advance of the nearby ice margin by 50 km in the last 3 k years.

Recent geodetic research has further elaborated the complexity and uncertainty of the Greenland ice sheet mass balance. Mitrovica et al. (2001) suggest that the sea level rise will not be distributed evenly among the oceans. Regional sea levels are also affected by the gravitational force between the water and the ice sheet. As the ice sheet melts the gravitational force decreases and the result is a regional decrease in sea levels within several thousand km surrounding the melting ice sheet. Thus, the melting of the Greenland ice sheet would produce a sea level drop over the northern and middle Atlantic and a major sea level rise over the South Pacific with the maximum sea level increase near the southern part of South America (Mitrovica et al., 2001). The melting of continental ice sheets was suggested (Weaver et al., 2003) as a means of communication between the Arctic and Antarctic regions.

4. Greenland Surface Air Temperature Record

Temperature records from Arctic regions are of a special interest because most climate change simulations with enhanced greenhouse forcing predict that global warming will be amplified in the polar regions. This expectation can be complicated by regional changes of atmospheric or ocean circulation; either natural or anthropogenically induced. The temperature field of the Arctic region is not uniform; surface air temperatures are currently persistently lower in the western part of the Arctic, especially in winter (Overland et al., 1997). Observed decadal scale temperature trends are equally non-uniform. An analysis of Arctic winter temperature records for the years 1979–1997 (Rigor et al., 2000) suggested a general warming pattern over the eastern Arctic Ocean (at the rate of about 1 °C/decade) and a similar cooling (at the rate of –1 °C/decade) over the western part of the Arctic Ocean. Over land, the warming occurs predominantly during winter and spring. The spring warming (which reached up to 2 °C/decade in the eastern Arctic) was attributed to an increase in the length of a melting season, rather than to changes in the peak temperatures (Rigor et al., 2000; Chapman and Walsh, 1993). Positive temperature trends may not exist for ice covered regions in summer if melting is already occurring, owing to the fact that additional heat may go predominantly into ice melt. One major explanation of Arctic regional temperature anomalies over semidecadal to decadal scales is the strength in the intensity of the Arctic circulation, and particularly for the case of Greenland, the variation in the strength of the North Atlantic westerlies (Wallace and Thompson, 2002).

A history of recent temperature changes at the GISP2 site on the Greenland ice sheet near Summit has been reconstructed using the automatic weather station data from the Cathy, Kenton, GISP2 and Summit sites combined with the satellite Special Sensor Microwave Imager brightness temperatures (Shuman et al., 1996; 2001). The record of the re-constructed daily temperatures covered the period from May 1987 to October 1999. On an annual basis, the record shows high temperature variability, particularly in winter and autumn, when some temperature changes over

a few days are as large as 20 to 30 °C, equal in magnitude to a typical summer to winter temperature difference. On a decadal scale Shuman et al. (1996, 2001) found a general temperature decline from 1987 till 1992 followed by a temperature increase from 1992 to 1999. Although the minimum temperature recorded in 1992 is generally attributed to the Mt. Pinatubo eruption, the fact that the cooling trend started in the late 1980s, several years before the eruption, suggests that other factors also significantly affect the temperature changes over the ice sheet. Later in this paper, we investigate trends in an extended summit temperature series, i.e., through December 2001 based on the latest observations from the Greenland Climate Network (GC-Net) (Steffen and Box, 2001; Box, 2002).

Stroeve and Steffen (1998) investigated the use of the AVHRR satellite surface temperature retrieval to track the surface temperature changes over the Greenland ice sheet. They found a reasonable correlation between the ice sheet temperature changes derived from the AVHRR data and the temperature records at the Summit and the ETH/CU camp stations. A major problem in using the satellite data to monitor the ice sheet temperature emerged because of the difficulty in detecting clouds over ice and snow surfaces. The presence of undetected thin cirrus can cause a significant error (of several °C) in surface temperature retrievals.

Precipitation over the Greenland ice sheet seems to be affected more by changes in atmospheric circulation than in temperature (Bromwich et al., 1993; Chen et al., 1997).

The period 1963–88 has been studied using a model of synoptic activities at 500 hPa and compared with the observed accumulation data from the Summit area (Bromwich et al., 1993). A significant negative trend in precipitation in the southern regions was observed between the years 1963 and 1979 followed by a positive trend between 1979 and 1988. The precipitation changes are in phase with changes in specific humidity. A much lower variability with the prevailing negative trend was obtained for a representative northern interior location. The increase of the precipitation during the years 1979–88 agrees qualitatively with the analyses of Zwally et al. (1989), Zwally (1989), and Davis et al. (1998a) who found, using satellite radar data, that the Greenland ice sheet was growing.

The ECMWF and the NCEP-NCAR analysis were used by Hanna et al. (2001) to analyze the patterns of Greenland temperature and precipitation over two decades 1979–98. They found no statistically significant trend in the average Greenland temperature, precipitation or snow accumulation between the years 1979–1998. On a regional basis, they found a significant precipitation and accumulation increase in the southeast and northwest of Greenland accompanied by a precipitation and accumulation decrease in the southwest and northeast. The results were validated using the accumulation records from several Greenland ice sheet sites. The authors bring to attention the fact that changes in the ECMWF parameterization of surface and boundary layer processes lead to an increase of the modeled Greenland temperature by 9 °C. Also the ECMWF Greenland temperatures were about 3 to 4 °C higher than the corresponding NCEP-NCAR data.

Table I
Temperature trends at Greenland's coastal stations in °C/10 y

| Station | Summer | Annual | Winter | Time interval |
|-------------|--------|--------|--------|---------------|
| Godthåb | -0.30 | -0.30 | -0.41 | 1940–2000 |
| Ammassalik | -0.23 | -0.20 | -0.16 | 1940–2000 |
| Egedesminde | -0.13 | -0.23 | -0.37 | 1950–2000 |

To investigate the hypothesis that melting the Greenland ice sheet at lower elevations is a result of greenhouse gas induced global warming, first we analyze the record of surface air temperature measurements at Greenland coastal stations. Box (2002) found a notable correlation ($r = 0.53, 0.57, 0.60, 0.64, 0.67$) between the surface air temperature at five coastal stations and the temperature at DYE-2, at 2332 m elevation on the ice sheet. Abdalati and Steffen (1995) found a notable correlation between the temperature of the coastal stations and the ice sheet melt area.

In the coastal region of southern and central Greenland, there are three meteorological stations (Godthåb, Egedesminde and Ammassalik) that have an almost uninterrupted temperature record between 1950 and 2000. The summer (June, July, and August), the annual and the winter (December, January, and February) temperature time series are shown in Figure 1. The summer temperatures, which are most relevant to Greenland ice sheet melting rates, do not show any persistent increase (Table I) during the last fifty years. The superimposed decadal scale temperature oscillations in western and southern Greenland (Figure 1) are strongly correlated with the NAO and the observed 1992–1998 warming is linked to a positive NAO phase.

The answer as to why Greenland coastal temperature trends are in contrast to the global average is that there is a regional anomaly with its origins in the strength of the north polar vortex (Wallace and Thompson, 2002). Over the 30-year period from 1968–1997, average sea level pressure over the Arctic Ocean decreased 6–8 hPa, resulting in a persistent pattern of cold Canadian polar air advection over western and southern Greenland. Variations in this polar pressure trend have been determined using principle component analysis of northern Hemisphere pressure fields (Thompson and Wallace, 1998, Wallace and Thompson, 2002). The dominant principle component is closely related to the strength of the North Atlantic westerlies. This oscillation of the dominant principle component has been referred to as the Northern Annular Mode (NAM). A major manifestation of the NAM teleconnection pattern is the North Atlantic Oscillation (NAO). During the little ice age, the NAO/NAM was apparently reversed (Shindell et al., 1999, 2001), giving an opposite regional temperature anomaly, i.e., cold in Europe and warm in western

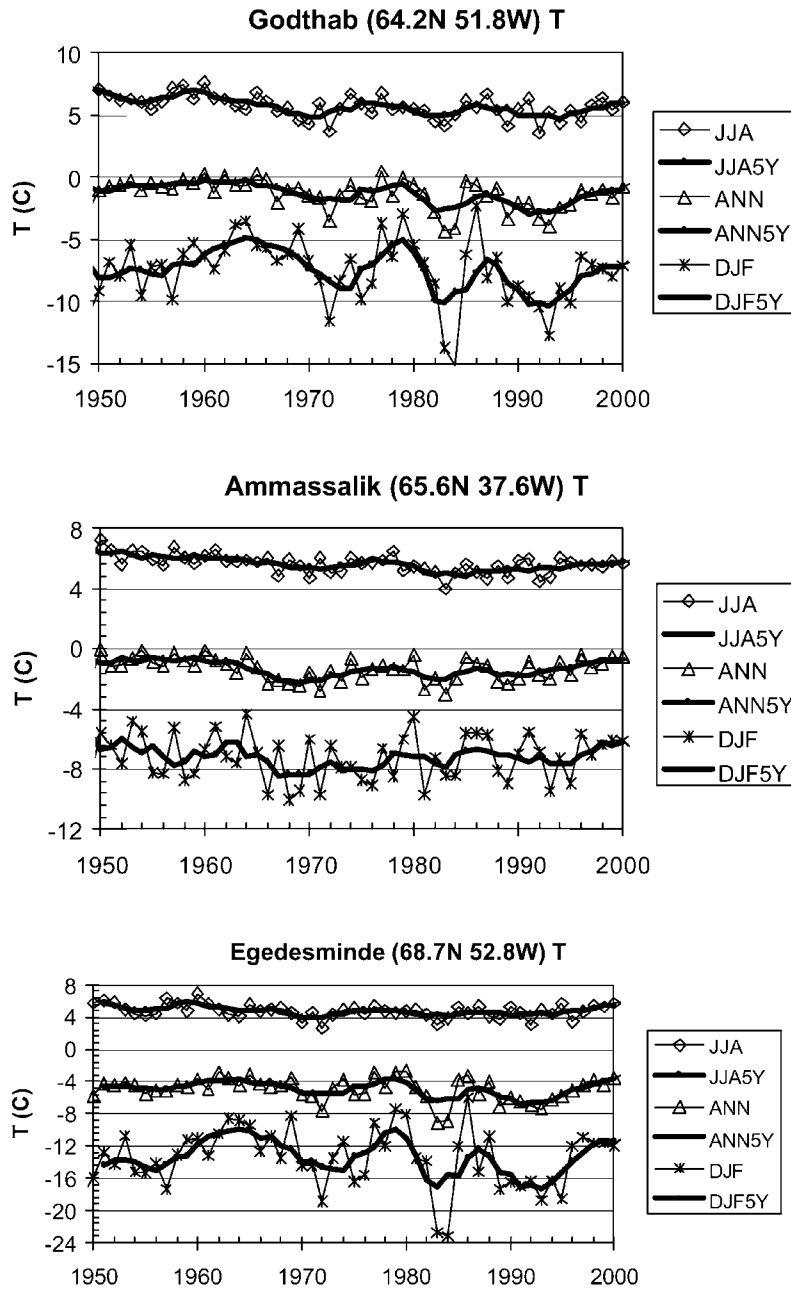


Figure 1. The summer (diamonds), annual (triangles) and the winter (crosses) temperature (<http://www.giss.nasa.gov/data>) and their five year running means at Greenland stations. The slope of the least squares linear fit to each 1950–1999 data set suggests generally decreasing summer temperature at each of the stations (Table 1).

Greenland. This, however, is in contrast to the borehole temperature measurements of Dahl-Jensen et al. (1998).

The two Greenland meteorological stations that have the longest uninterrupted temperature records are Godthåb and Ammassalik. Their temperature records start in the second half of the 19th century. The records (Figures 2 and 3) show increasing temperatures at the beginning of the century, with the peak temperatures in the 20th century occurring between 1930 and 1940, followed by a temperature decrease. The contrasting behavior of the Greenland temperature record with the global warming trend is shown in Figure 4. While the current global average temperature is about 0.5 °C above its 1940 value, the Greenland coastal stations temperatures are about 1 °C below their 1940 values. The predominantly cooling trend observed at the Greenland coastal stations during the second half of the 20th century suggests that the southern part of the Greenland ice sheet has most likely also been undergoing cooling during the last few decades.

5. Great Greenland Warming of the 1920s

A significant and a rapid warming occurred between 1920 and 1930. This warming was observed at all Greenland stations that had a temperature record covering the 1920s. The five-year running averages of annual temperatures (Figure 5) show a rise of between 2 and 4 °C. The 1920s Greenland warming is also seen in the $^{18}\text{O}/^{16}\text{O}$ record (Figure 6) of the Summit ice core (Steig et al., 1994; Stuiver et al., 1995; White et al., 1997). The warming of 1920s could have affected the state of the Greenland ice sheet at that time, since the warming occurred during all seasons, including summer when the surface air temperatures reach over 0 °C over a significant fraction of the ice sheet. Since there was no significant increase in the atmospheric greenhouse gas concentration during that time, the Greenland warming of the 1920s demonstrates that a large and rapid temperature increase can occur over Greenland, and perhaps in other regions of the Arctic, due to internal climate variability such as the NAM/NAO, without a significant anthropogenic influence. During the Greenland paleoclimate history a similar warming, induced by the NAO oscillation, probably occurred several times before. The uniqueness of the 1920–1930 warming is that it has been observed during the time of instrumental records.

6. Greenland Temperature and the NAO

The weather and climate of southern and western Greenland and their changes on varying time scales are affected by the NAO (North Atlantic Oscillation). To characterize the mode and the strength of the NAO an index is calculated using the surface pressure difference between the Azores and Iceland. The station data needed for the NAO index are available for approximately the last 135 years.

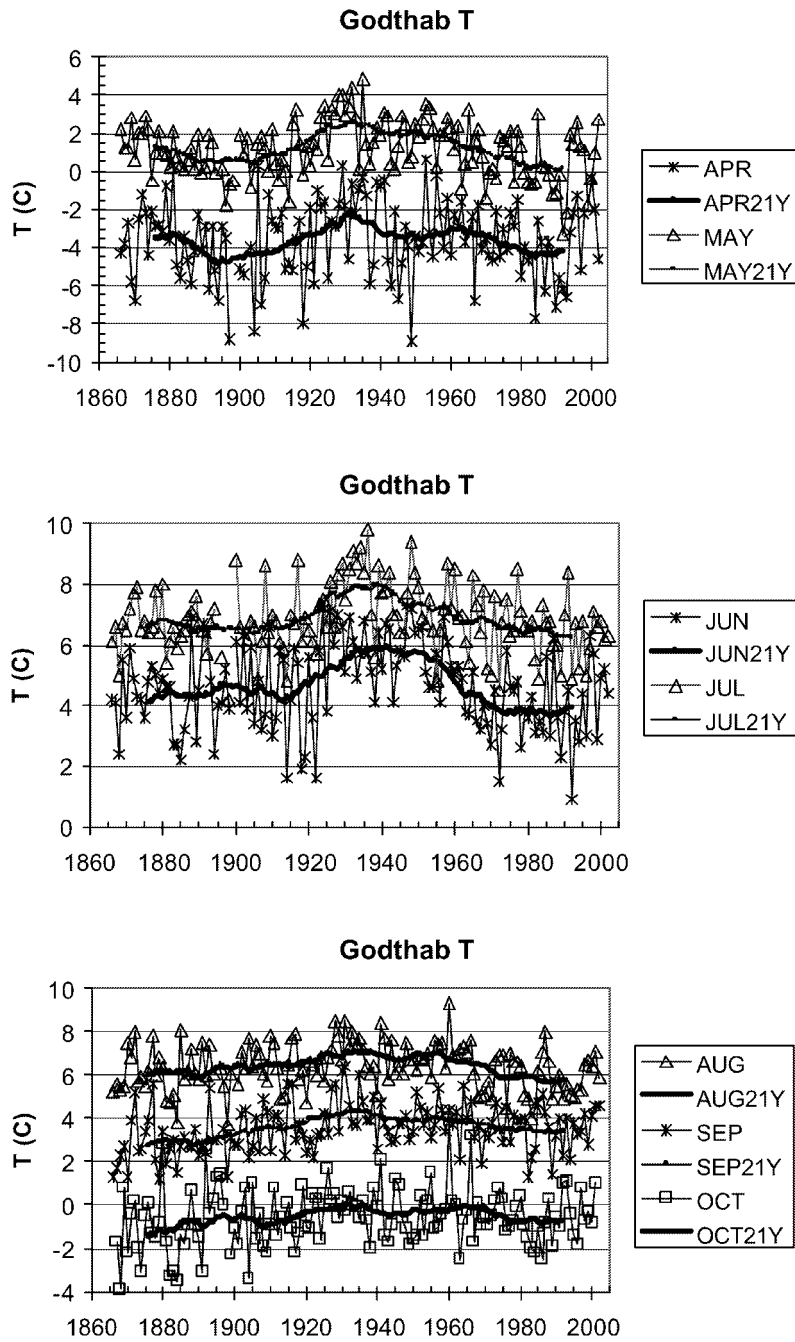


Figure 2. The temperature record of the Godthâb station shows a persistent temperature decrease during the whole melting season (April to October) after the temperature peak reached between 1930 and 1940. The annual data (<http://www.giss.nasa.gov/data>) and a 21 year running average are shown.

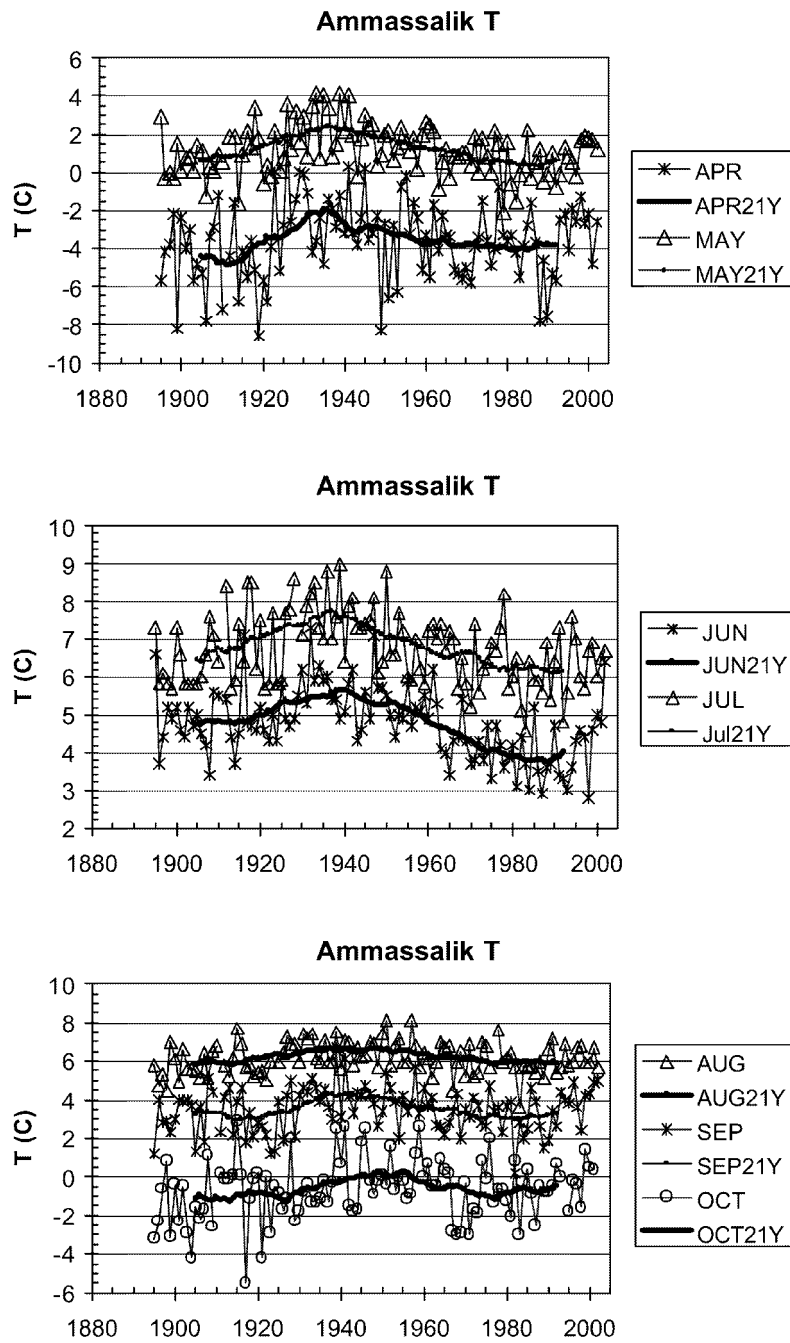


Figure 3. Same as Figure 2, however, for the Ammassalik station.

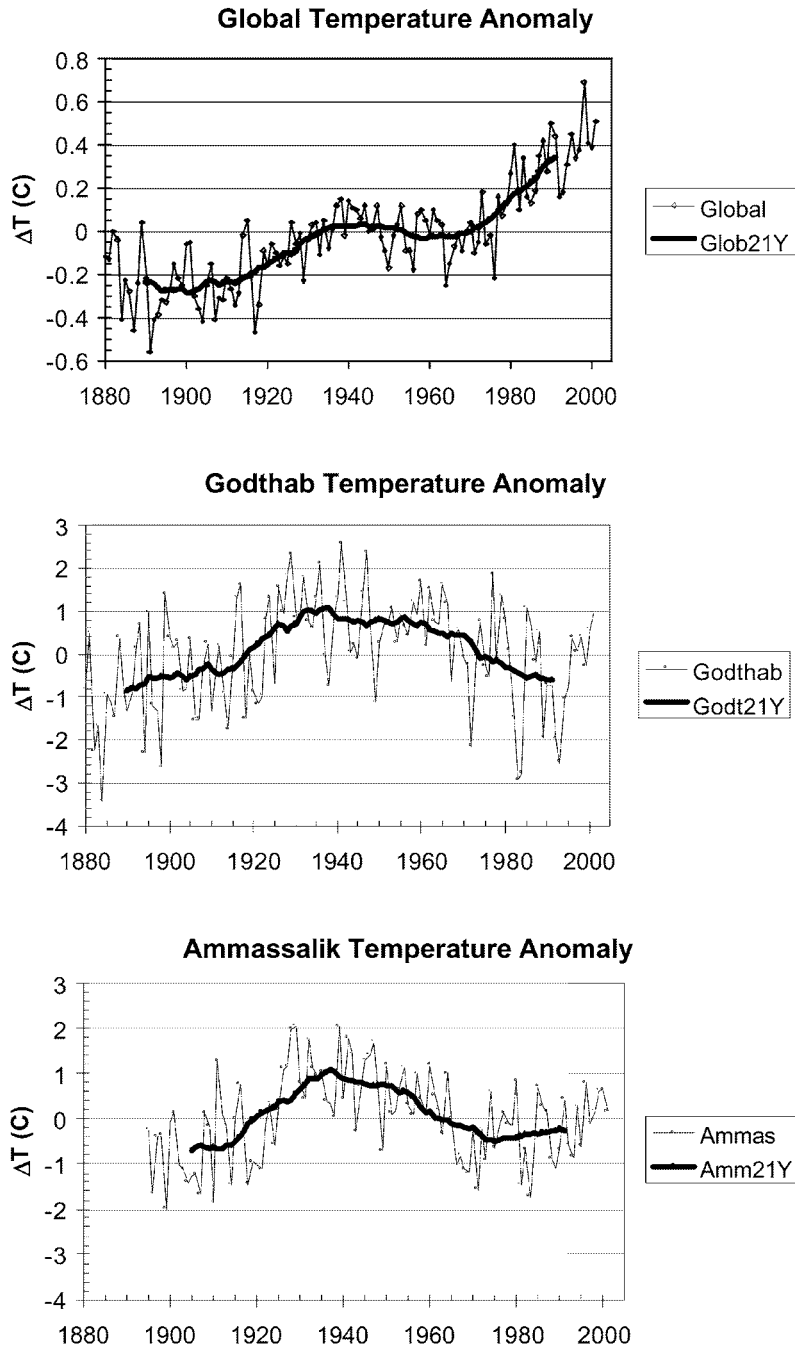


Figure 4. A contrasting behavior of the long term (21 year running averages) global (<http://www.giss.nasa.gov/data>) and Greenland temperature trends.

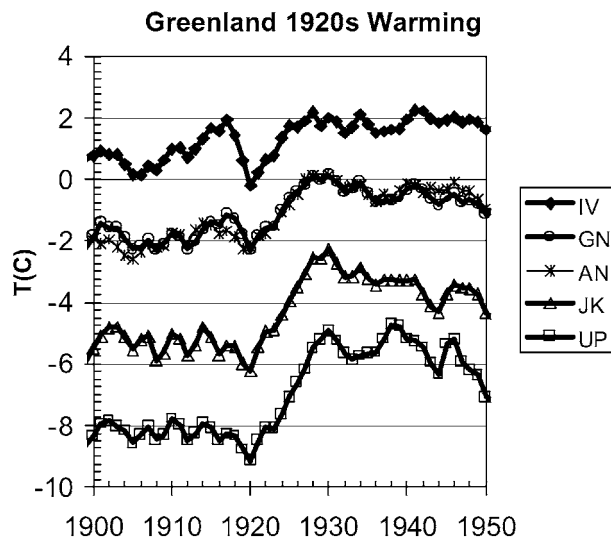


Figure 5. The rapid temperature increase of the 1920s was recorded at all Greenland stations (<http://www.giss.nasa.gov/data>) that have records for the considered time interval: Ivigtut (IV), Godthåb (GD), Ammassalik (AM), Jakobshavn (JK) and Upernavik (UP). The increase in annual temperature varied between 2 and 4 °C. The increase occurred in all seasons with a maximum increase of up to 6 °C recorded in winter.

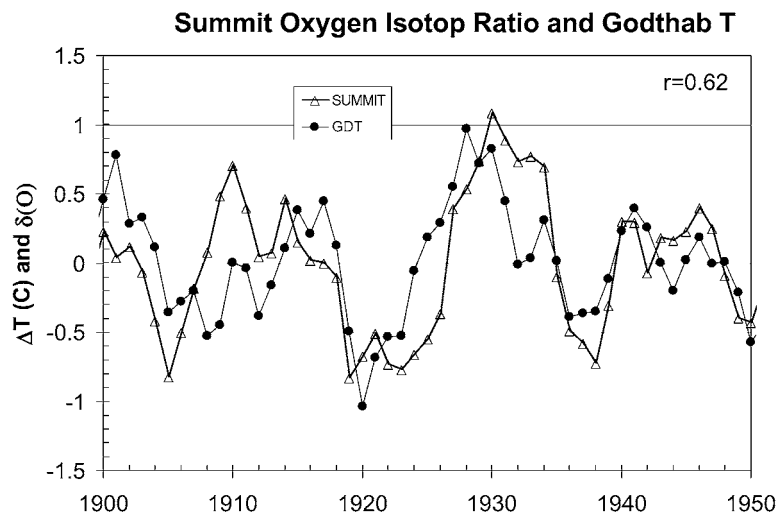


Figure 6. The oxygen $^{18}\text{O}/^{16}\text{O}$ ratio from the Greenland Summit ice cores shows that the rapid temperature increase in the 1920s also took place at the Summit. The correlation coefficient of 0.62 between the oxygen isotopic ratio and the Godthåb annual temperature suggests the Godthåb station temperature record as a suitable indicator of the temperature changes on the ice sheet. The data shown are five year running averages with a long wave component (21 years running averages) removed.

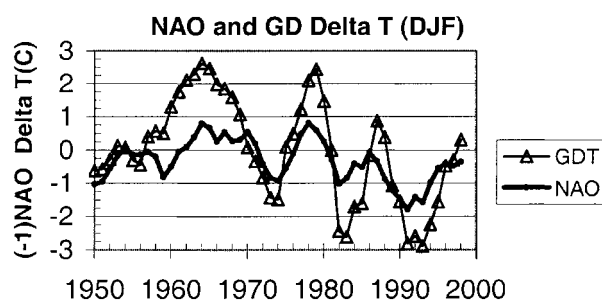


Figure 7. The five year running average of the Godthåb winter temperature anomaly (GDT), with respect to the 1950–2000 average, and the NAO index. A high correlation coefficient $r = -0.84$ suggests common physical influences affecting both variables.

To establish a long-term connection between Greenland's meteorological situation and the NAO, various proxy methods relating the NAO index to other variables available for a longer time have been developed. Among the most promising approaches to reconstruct the NAO index back in time a few hundred years are those based on the ice core accumulation data (Appenzeller et al., 1998), and the North Atlantic SST (Rodwell et al., 1999).

Snow accumulation records can be determined for a few hundreds years from the Greenland ice core analysis. Appenzeller et al. (1998) developed the NAO index proxy reconstruction for the years 1650–1994 using the annual snow accumulations at the NASA-U site in western Greenland at 73.84° N, 49.49° W and an elevation of 2370 m above sea level. After removal of a linear trend and a high frequency component, the correlation coefficient with the instrumental data NAO index (Hurrell, 1995) was $r = 0.57$ annually and $r = 0.52$ for winters.

Rodwell et al. (1999) have shown that the modern (1947–97) values of the NAO index are closely related to the changes in the North Atlantic SST. An atmospheric GCM (U.K. Meteorological Office's Unified Model) was forced by SST and the sea ice extent. The correlation between the simulated and the observed NAO index in winter (DJF) was $r = 0.41$. When the high frequency component is removed (by three runs of a three-point 1,2,1 weighted filter) the correlation (for winters of 1947–97) increased to $r = 0.74$ (Rodwell et al., 1999).

The same atmospheric and oceanic processes that are responsible for the North Atlantic Oscillations (Hurrell, 1996; Hurrell and van Loon, 1997; Wallace and Thompson, 2002) are also affecting Greenland's temperature. Figure 7 shows the winter (December, January, February) temperature at Godthåb and the NAO index (Luterbacher et al., 1999) for the second half of the past century. The anti-correlation is strong; $r = -0.84$ for five year running averages (Figure 7) and $r = -0.93$ for 21 year running averages (not shown). We find similarly high correlations at other Greenland stations. Temperature changes are thus clearly linked with the Arctic atmospheric circulation shifts.

7. Recent Ice Sheet Temperature Record

A substantial decrease in the surface air temperature occurred over the Greenland ice sheet summit in summer season during the period of available measurements from 1987 to 2001. The average temperature of the warmest month and the summer average (June, July and August) temperature show a decreasing trend of 3.0 and 2.2 °C/decade between 1987 and 2001 (Figure 8). This summer cooling of the ice sheet at the Summit is accompanied by winter warming at the rate of about 2 °C per decade. The result is a substantial decrease in the annual temperature range (Figure 8) from 34 °C in 1987 to less than 28 °C in 2001. The cause of these rapid changes and decrease in temperature range is undetermined, however, a change in cloud cover is a possibility.

Comparison of the Dye 3 and GRIP borehole temperature profiles (Dahl-Jensen et al., 1998) suggest that the Dye 3 site undergoes temperature changes similar to the GRIP site, however, with an amplitude 1.5 times larger. Thus the observed summer temperature decrease at Summit (Figure 8) may represent events that occurred over a larger area of the ice sheet at lower elevations.

8. Conclusions

The Greenland surface air temperature trends over the past 50 years do not show persistent warming, in contrast to global average surface air temperatures. The Greenland coastal stations temperature trends over the second half of the past century generally exhibit a cooling tendency with superimposed decadal scale oscillations related to the NAO. At the Greenland ice sheet summit, the temperature record shows a decrease in the summer average temperature at the rate of about 2.2 °C/decade, suggesting that the Greenland ice sheet at high elevations does not follow the global warming trend either.

A significant and rapid temperature increase was observed at all Greenland stations between 1920 and 1930. The average annual temperature rose between 2 and 4 °C in less than ten years. Since the change in anthropogenic production of greenhouse gases at that time was considerably lower than today, this rapid temperature increase suggests a large natural variability of the regional climate.

High anticorrelations ($r = -0.84$ to -0.93) between the NAO index and the Greenland temperature records suggest a physical link between these processes. The recent negative shift of the NAO correlates with 1990s warming in Greenland. The NAO may play a crucial role in determining local Greenland climate during the 21st century; resulting in a local climate that may defy the global climate change. This possibility should be considered in models of ice sheet melt and future sea level rise. Forecasting changes in the NAO may be a primary factor in predicting the future Greenland ice sheet mass balance.

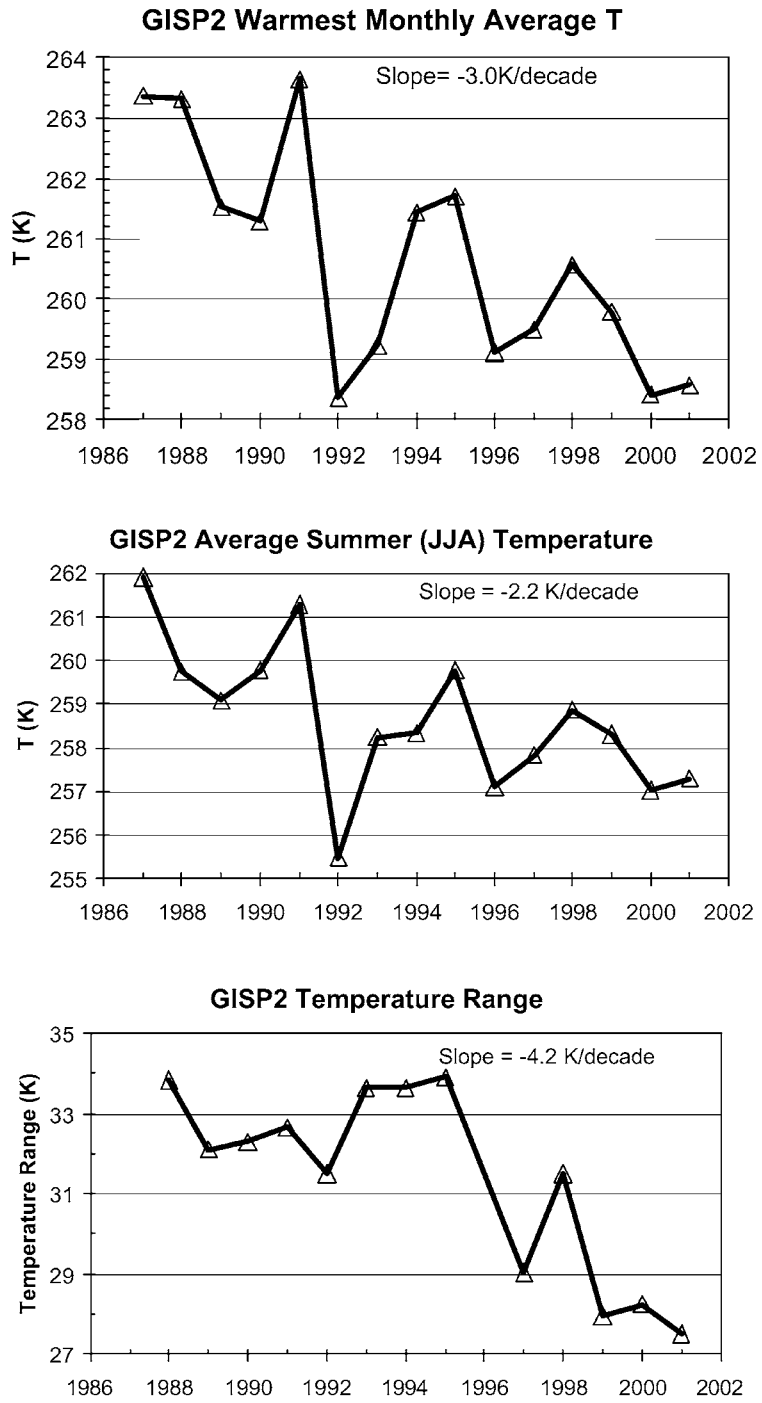


Figure 8. The average temperature of the warmest month of the year, average summer (June, July and August) temperature and the temperature range at the summit of the Greenland ice sheet decreased substantially during the available temperature record between 1987 and 2001.

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