POPULAR SUMMARY
HJZ, August 15, 2001

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35A164

Submitted to Annals of Glaciology 35, 06/2001

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Abstract

Firn-temperature profiles are calculated in a thermal model using continuous surface temperatures derived from Automatic Weather Station (AWS) data and passive microwave data in the Greenland Summit region during the period 1987-1999. The results show that significant interannual variations of mean summer (June to August) and annual temperatures occur in the top 15 m, in addition to the normal seasonal cycle of firn temperature. At 5 m depth, the seasonal cycle is damped to 13% of the surface seasonal amplitude, but even at 15 m about 1% or 0.6° C of the seasonal cycle persists. Both summer and mean annual temperatures decrease from 1987 to 1992, followed by a general increasing trend. Interannual variability is 5° C at the surface, but only is only dampened to 3.2 ° at 10 m depth and 0.7° at 15 m depth. Dampening of the interannual variability with depth is slower than dampening of the seasonal cycle, because of the longer time constant of the interannual variation. The warmer spring and summer temperatures experienced in the top 5 m, due to both the seasonal cycle and interannual variations, affect the rate of firn densification, which is non-linearly dependent on temperature. During the 12 year period 1987- 1999, the mean annual surface temperature is –29.2° C, and the mean annual 15 m temperature is –30.1° C, which is more than 1° C

warmer than a 15-m bore-hole temperature representing the period of about 1959 and warmer than the best-fit temperature history by Alley and Koci (1990) back to 1500 A. D.

Introduction

Snow surface temperature and near-surface air temperatures on polar ice sheets show pronounced seasonal cycles and significant interannual variations. These short-term variations are significantly dampened with depth, while decadal and longer temporal variations are maintained as a climatic record of temperature. For example, previous analysis of the temperature-depth variation with depth at Summit showed a minimum temperature of – 31.5° C at 130 m, corresponding to an age of about 1659 A. D. (Alley and Koci, 1990). Seasonal and interannual variations in firn temperature also drive changes in the rate of firn densification, which causes changes in the snow-surface, as detected by satellite radar altimeter (Zwally and Li, submitted; Li and Zwally, in Press). In this paper, we use the continuous surface temperature record composted from AWS and passive microwave data by Shuman and others (2001) for the Greenland summit region over the period 1987-1999 to derive the corresponding firn temperature evolutions with depth.

The Model

We follow the standard time-dependent heat-transfer equation (Paterson 1994, p.224), which in one dimension can be written:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho\, c}\frac{\partial^2 T}{\partial z^2} + \frac{1}{\rho\, c}\frac{\partial k}{\partial T}\left(\frac{\partial T}{\partial z}\right)^2 - w\frac{\partial T}{\partial z} + \frac{f}{\rho\, c} \qquad (1)$$

where $\frac{\partial T}{\partial t}$ is the change in firn temperature T with time t at depth z, ρ is density, c is heat capacity, k is thermal conductivity, w is vertical velocity and f is internal heating. Thermal properties of ice and firn used in the model are computed from the relations given by Paterson (1994, p.205). Thermal conductivity (k) for firn is calculated from Schwerdtfeger (1963) by using the empirical density-depth relation (Schytt, 1958)

$$\rho(z) = \rho_i - (\rho_i - \rho_s)\exp(-C \cdot z) \qquad (2)$$

where $\rho(z)$ is density at depth z, ρ_i the density of ice (917 kg m^{-3}), ρ_s the density of surface snow (350 kg m^{-3}) and the constant C is taken as 0.029 m^{-1} to give the best fit to the field data collected at the Summit of Greenland region (Bolzan and Strobel, 1994; Gow and others, 1997).

Vertical velocity (W) is calculated according to the Dansgaard and Johnsen (1969) model by using a constant accumulation rate of 0.25 m a^{-1} (Zwally and Li, submitted). Internal heating (f) is neglected in this analysis by assuming that f is smaller than the coefficients of $\frac{\partial T}{\partial t}$ by at least three orders of magnitude (Van Ommen and others, 1999).

To solve Equation (1) two boundary conditions are needed: the upper boundary (the driving temperature), the temperatures at the snow surface and the lower boundary (at which the temperature is considered to be constant), a known temperature at a certain depth. Figure 1 shows the driving surface temperature used in this study. This time series of the temperature over the period 1987-1999 was derived from AWS and passive microwave data for the Greenland Summit region (Shuman and others 2001). For the lower boundary, we chose the measured GISP2 borehole temperature at the depth of 30 m (-31.4 °C, Alley and Koci 1990). This depth choice is sufficient to avoid any effect of penetration of the surface temperature wave during the 12 years on the lower boundary condition, as confirmed by several numerical tests.

Results and discussion

The surface driving temperature for the Summit region of Greenland over the period of 1987-99 is shown on daily basis in Figure 1. The temperature fluctuates within the maximum range between approximate –60 °C and close to 0 °C, exhibiting clear annual cycles with average amplitude about 55 °C. A distinct cooling period occurs in 1992. In this period the mean annual temperature (T_m) and mean summer temperature (June 1-Aug. 31) is more than 4 °C lower than the average. T_m is averaged from September 1 to August 31 of the following year. The temperature decreases from 1987 and reaches the minimum in 1992 and then gradually increases until 1999. The cooler temperatures in 1992 in Greenland have been attributed to a cooling associated with the Mt. Pinatubo eruption (Abdalati and Steffen, 1997). The mean annual temperature and summer temperature averaged from 1987-1991 approximately are –28.4 and –12.8° C in comparison with –29.3 and –15.0 °C for 1993-99.

Driven by above surface temperature variation, Figure 2 illustrates the modeled firn temperature changes at several selected depths over the corresponding period. At 3 m depth, the amplitude of the firn temperature is attenuated to only 25% of the surface value. As expected, the amplitude of the seasonal variation significantly reduces with depth from the 27.7 ° C at 1m to 0.61° C at 15 m (Table 1). Nevertheless, the residual amplitudes of 1.66° C at 10 m and 0.61° C at 15 m indicates that significant corrections to measured bore-hole temperatures at these depths are required to obtain the mean annual surface temperature. Over the period 1987-1999, the mean annual surface is –29.29° C. At lower depths the means are –29.88° C at 10 m, –30.12° C at 15 m, and –31.4 ° C at 30 m, which approaches the fixed and colder lower-boundary condition obtained from the bore hole measurement.

Table 1. Dampening of amplitudes of seasonal variations in temperature and interannual variations (1987-1999) in temperature with depth.

Depth	0m	1m	2m	3m	4m	5m	7m	10m	15m
Seasonal Amplitude (T° C)	55.16	27.71	18.58	13.59	9.95	7.26	3.95	1.66	0.61
Interannual Amplitude (T° C)	4.95	4.28	3.82	3.70	3.50	3.24	2.61	1.55	0.73

Interannual changes of mean summer firn temperature are shown in Figure 3 at several depths together with the values from the surface temperature. The summer temperatures are an important in firn densification, which has been found to be a dominant factor in the seasonal surface elevation change (Zwally and Li submitted). From 1992 to 1999, a clear warming trend with the rate of approximate + 0.3° /yr is indicated by each regression lines through the data for the top 5 m firn. The results show that the interannual variations of the surface summer temperature are large above 5m, and significantly damped below 10 m.

Table 1 shows that the amplitude of the interannual variations in T_m at 5 m depth are about 65% of the amplitude at the surface, and are damped approximately linearly with depth to about 30% at 10 m and 15 % at 15 m. In contrast, above 5 m the damping of the seasonal variations with depth is much faster than the damping of interannual variations.

Figure 4 shows the modeled firn temperature at 10 m depth (solid line) together with mean annual surface temperature T_m. Although the variation is small (<2° C), both sets of data still show that the temperature dropped about 2 °C from 1987 to 1992 followed by a general warming trend. The clear seasonal variation shown by the solid line and the discrepancy between the two sets of data seems indicating that 10 m temperature is significantly affected by both the seasonal cycle and interannual variations in temperature.

The T_m for all 12 years except 1992 (T_m = - 32.0) are warmer than the maximum temperature of -31.25° C measured at 15 m depth in the 1989 bore-hole (Alley and Koci, 1990). In 1989, the depth of 15 m corresponded to a time about 30 years prior to the drilling, or about 1959. While the measured bore-hole temperatures ranged from the

-31.5 °C minimum measured at 130 m depth to the -31.25° C measured at 15 m (a difference of 0.25° C), the range in the best-fit surface-temperature history is larger at about 2° C (Alley and Koci, 1990). From their temperature reconstruction, Alley and Koci (1990) concluded that the indicated warming falls within the range of natural variability and provides no clear evidence of a greenhouse signal. However, during the 12 year period 1987- 1999, the mean annual surface temperature is –29.2° C, and the mean annual 15 m temperature is –30.1° C, which is more than 1° C warmer than a 15-m bore-hole temperature representing the period of about 1959 and warmer than the best-fit temperature history by Alley and Koci (1990) back to 1500 A. D. Even though the middle of the 1987 to 1999 period was affected by the atmospheric cooling effects of the Mt. Pinatubo volcanic eruption, the period was on average significantly warmer by at least 1° C than recent century-scale average temperatures.

The continuous temperature data shown by Figure 1 have provided the most detail and complete near surface temperature record for the Greenland summit region during 1987 – 1999. Therefore, it is especially useful in the analysis of surface elevation data retrieved from satellite radar altimeter (ERS1-2) for the period 1992-99. This temperature record is assumed to be the snow temperature at the surface in the present analysis. Indeed, more precise calibration using some of field firn temperature measurements made during this period should be given to ensure the modeled firn temperatures with depth are in agreement with field data.

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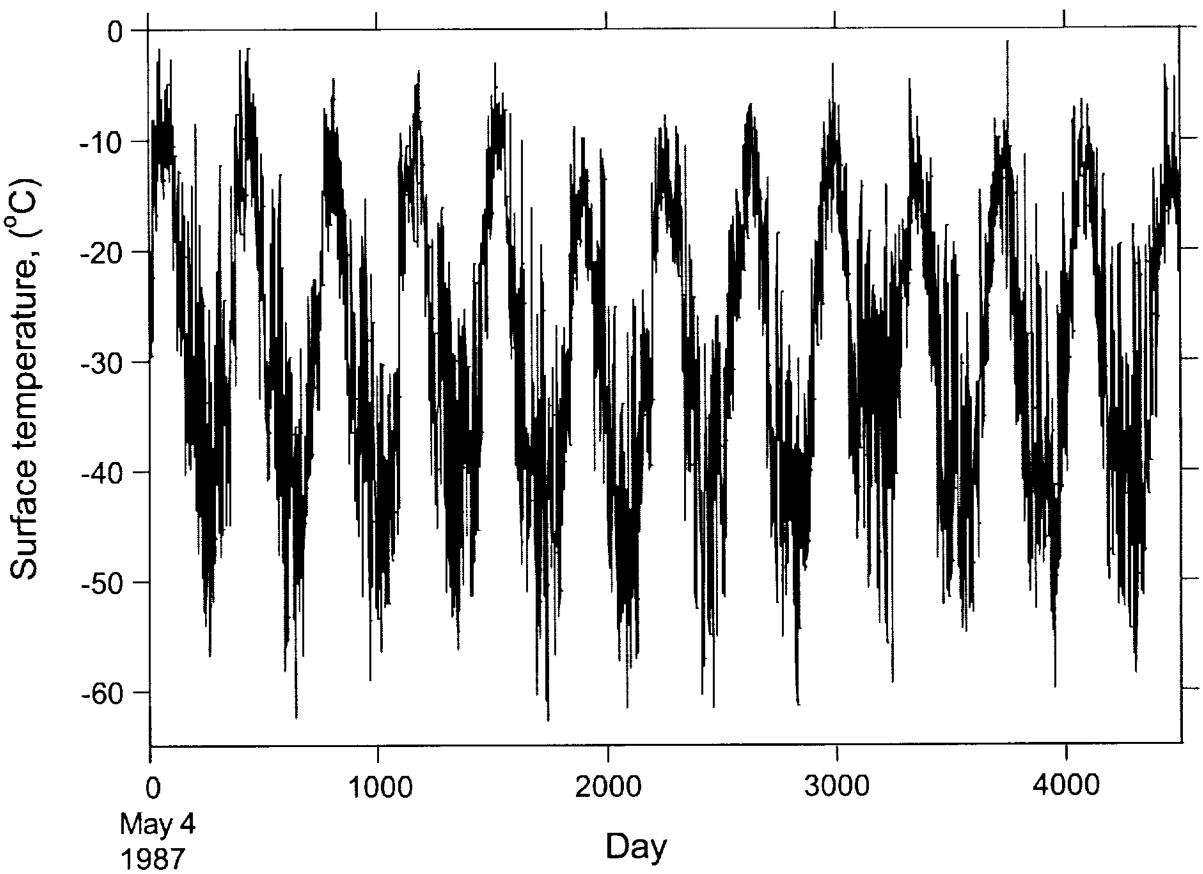
Figure Captions

Figure 1. Variations of surface air temperature for the Summit of Greenland during May, 1987-October, 1999 (after Shuman and others 2001).

Figure 2. Variations of firn temperature computed at several depths above 15 m for the summit of Greenland during May, 1987-October, 1999.

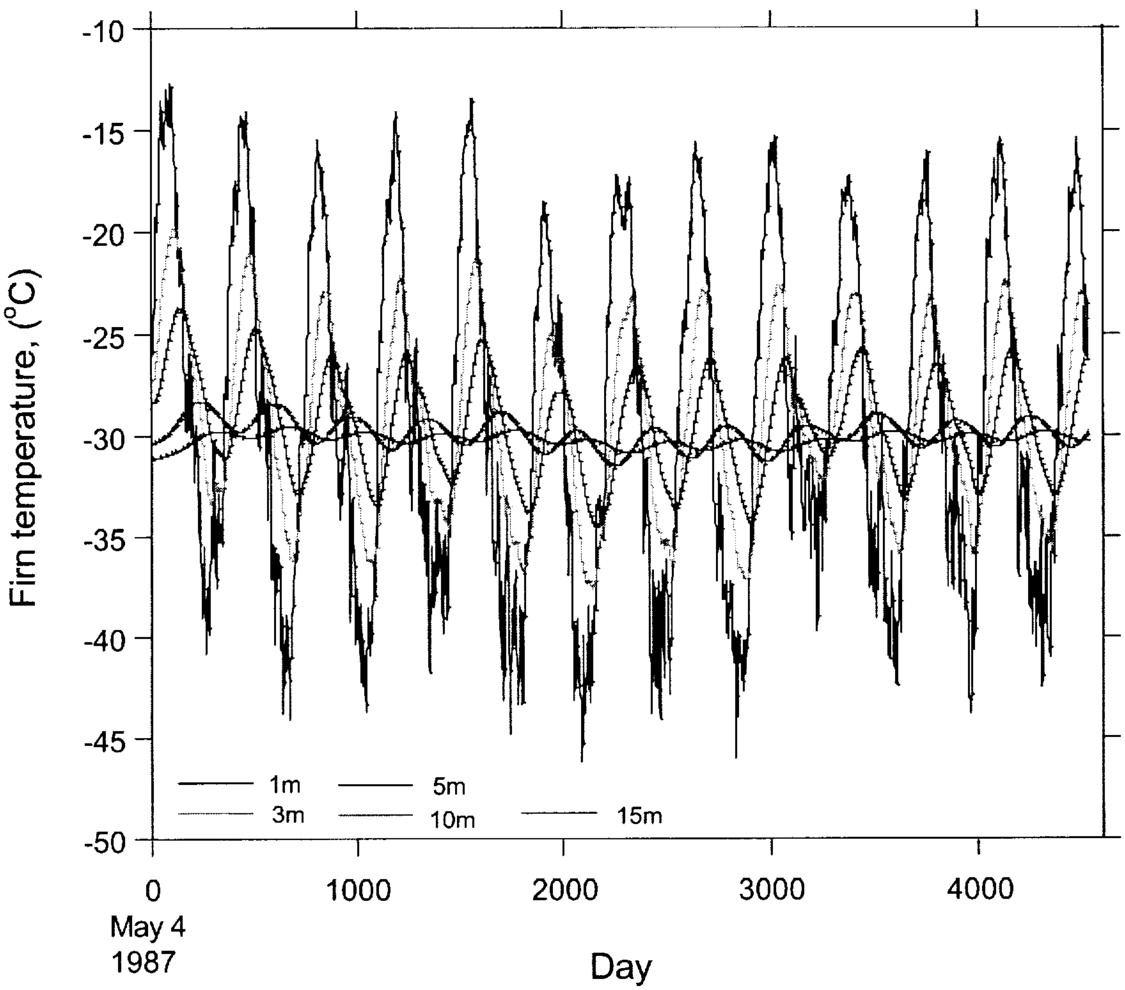
Figure 3. Interannual variations of summer mean firn temperatures (Jun.-Aug.) at several depths above 15 m in Summit of Greenland during May, 1992-October, 1999. Fitted lines at each depth showing warming trend between 1992-99 with + 0.3 °C a^{-1}at the surface.

Figure 4. Comparison between modeled 10 m firn temperature and mean annual surface air temperature in Summit of Greenland showing interannual variations during May, 1987- October, 1999.



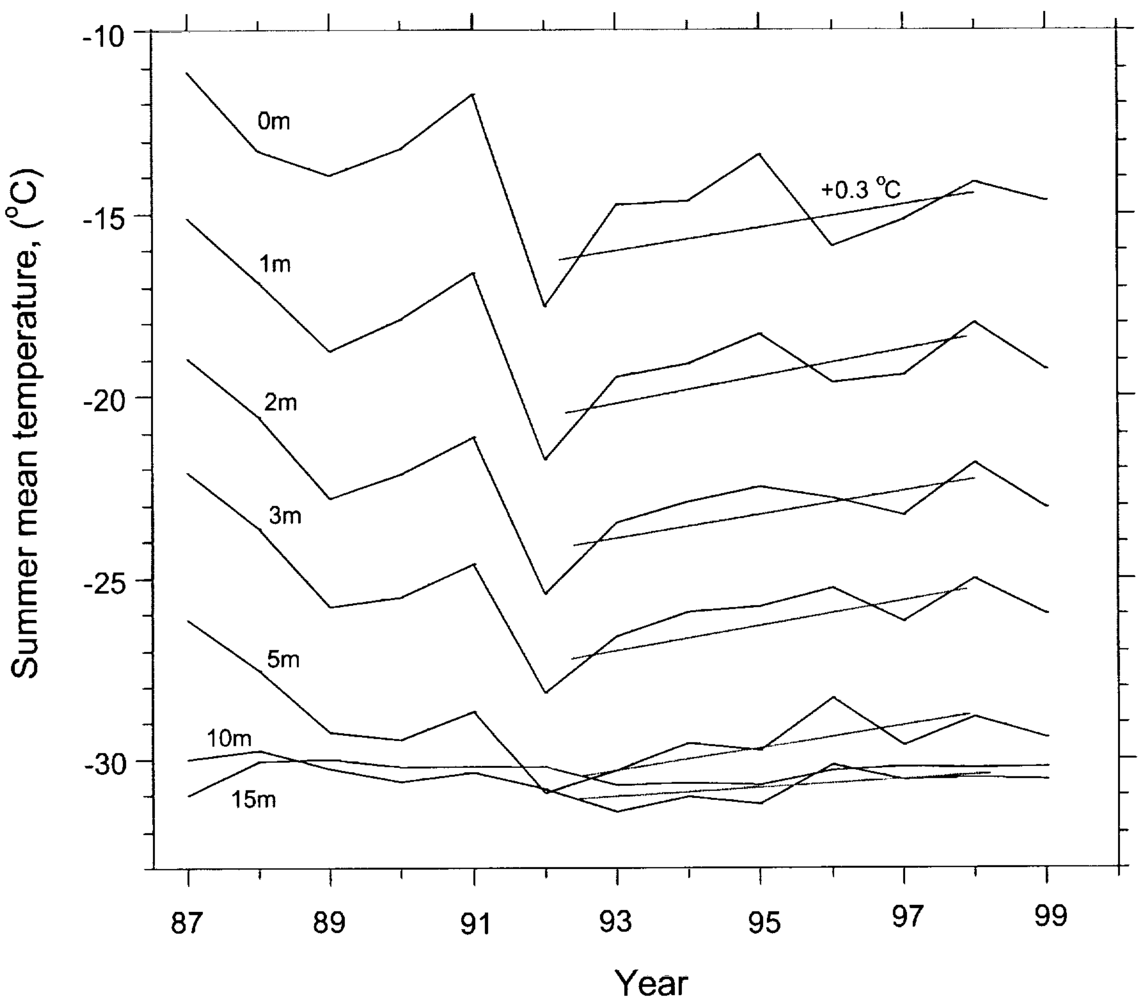
Surface temperature, (°C)
0
-10
-20
-30
-40
-50
-60
0
1000
2000
3000
4000
May 4
1987
Day

Fig.1



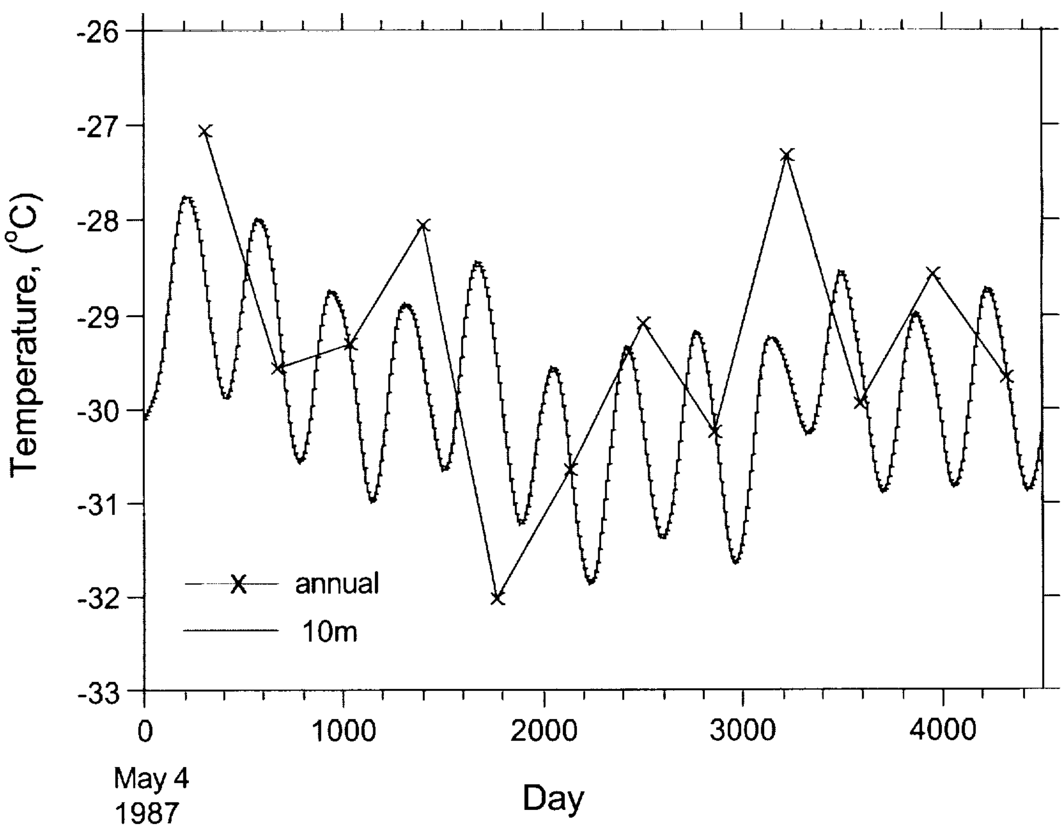
-10
-15
-20
-25
-30
-35
-40
-45
-50
Firn temperature, (^oC)
1m
5m
3m
10m
15m
0
1000
2000
3000
4000
May 4
1987
Day

Fig.2



-10
-15
-20
-25
-30
Summer mean temperature, (°C)
0m
1m
2m
3m
5m
10m
15m
+0.3 °C
87
89
91
93
95
97
99
Year

Fig.3



-26
-27
-28
-29
-30
-31
-32
-33
Temperature, (°C)
annual
10m
0
1000
2000
3000
4000
May 4
1987
Day

Fig.4