Ice-sheet elevation changes caused by variations of the firn compaction rate induced by satellite-observed temperature variations (1982–2003)

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ABSTRACT. Changes in the surface elevation of the Greenland and Antarctic ice sheets and ice shelves caused by variations in the rate of firn compaction are calculated with a time-dependent firn densification model driven by two decades (1982–2003) of satellite-observed monthly surface temperatures. The model includes the effects of melting and refreezing, both the direct changes in density and the subsequent effects on the densification rate. As previously shown, the temperature-dependent rate of densification is largest in summer, but changes in winter temperatures also have a significant effect. Over the last decade, climate warming has enhanced the rate of compaction and lowered the average surface elevation of Greenland by 1.8 cm a^{-1} and most of West Antarctica by 1.9 cm a^{-1}. In East Antarctica, a small cooling raised the average surface elevation by 0.14 cm a^{-1}.

INTRODUCTION

Studies of firn densification processes (e.g. Alley, 1987) and the rate of firn compaction have received increasing attention in recent years because of their effects on the interpretation of elevation changes observed by airborne and satellite altimeter surveys (Arthern and Wingham, 1998; Reeh and others, 2005; Zwally and others, 2005). Although the rate of densification is dependent on firn temperature as well as the accumulation rate in some manner in most models, the results of Zwally and Li (2002) showed a much stronger dependence on firn temperatures than previous models. The stronger temperature dependence causes a significant seasonal cycle in the surface elevation, due to faster compaction in summer (Li and Zwally, 2002; Dibb and Fahnestock, 2004), and also causes a faster response time to interannual changes in surface temperature and accumulation rates. Such changes on seasonal to decadal timescales are superimposed on the long-term changes due to past temperature and surface mass imbalance of the ice sheets.

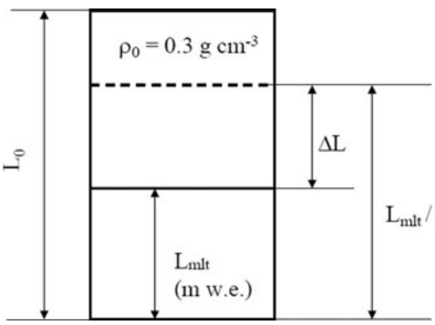

Fig. 1. Schematic diagram showing the method of calculating mean snow density ρ_m (cf. Equation (6)) and changes in the layer thickness L (cf. Equation (4)) caused by surface melt. L_0 and ρ_0 are the initial firn layer thickness and density. Here we take $L_0 = A/\rho_0$. A is the accumulation rate at each time-step in water equivalent. L_{mlt} is the melt rate in water equivalent. L_{mlt}/ρ_0 represents the thickness of the melt at the density of ρ_0. ΔL is the melt-induced thickness change.

Interpretation of ice-sheet elevation changes (dh/dt) observed by satellite altimetry requires determination of the elevation change caused by variations in firn compaction during the observation period, which requires knowledge of the temperature variations during and prior to the period of altimeter measurements. Observations from satellite and ground stations show evidence of climate warming in the past two decades over Greenland (Comiso and Parkinson, 2004) and West Antarctica, with a general cooling over East Antarctica (Comiso, 2000; Kwok and Comiso, 2002), suggesting a probable impact on the rate of firn compaction and observed elevation changes. In this study, we drive our densification model with monthly surface temperatures compiled from a two-decade record (1982–2003) of continuous surface temperatures derived from the Advanced Very High Resolution Radiometer (AVHRR) infrared measurements. The model also includes the densification effects of surface melting and refreezing (Reeh and others, 2005; Zwally and others, 2005). Results of our model calculations were used to correct the dh/dt observed by satellite altimetry for approximately the period

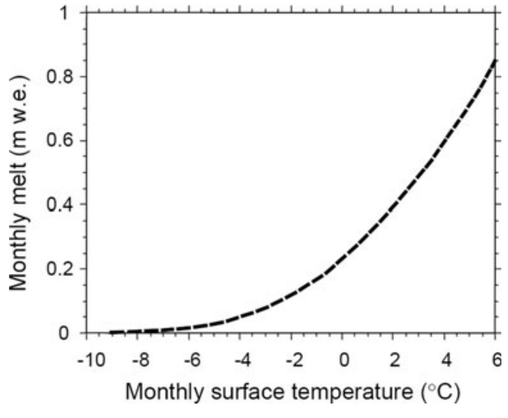

Fig. 2. The melting–temperature relationship taken from Braithwaite and Zhang (2000).

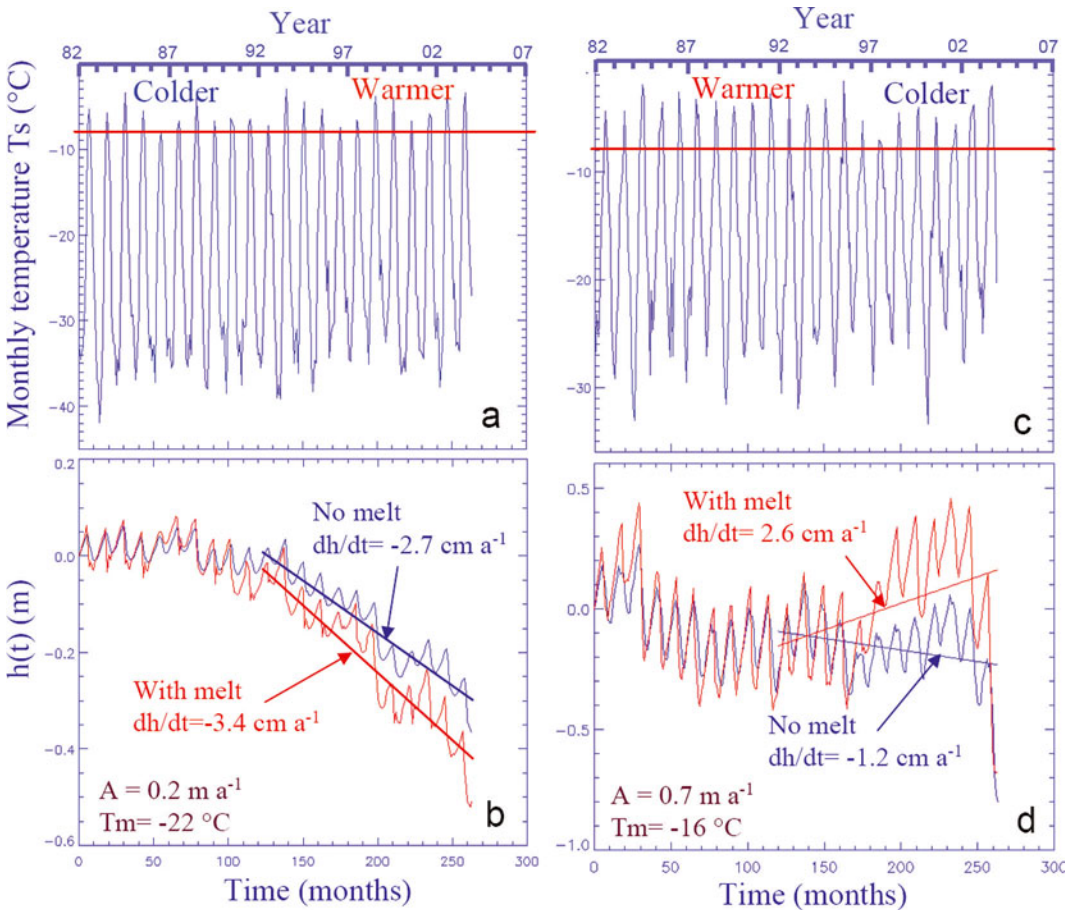

Fig. 3. Comparison of the melt effect on variations in surface height $h(t)$ for two cases with opposite variations in summer temperature (a, c) from AVHRR data, showing the importance of temperature history in the determination of surface height change. Mean annual values of accumulation A, surface temperature Tm and of $\mathrm{d}h/\mathrm{d}t$ from the fitted lines are as indicated for each case (b, d), respectively.

1992–2002 and estimate the corresponding mass changes. In this paper, we describe the methodology and results of our densification modeling in more detail. Other work in progress examines the effect of temporal changes in accumulation rates on the rate of firn compaction, and consequently on the appropriate effective density associated with surface mass-balance changes resulting from changes in accumulation rates.

MODEL FORMULATION

The model used here is a time-dependent firn densification model characterized by a stronger dependency on temperature. The initial development of the model was described in detail by Zwally and Li (2002). The model was improved by introducing the temperature gradient effect on the densification rate due to vapor transfer in the regions of low temperature and low accumulation where a firn layer remains near the surface for a long period (Li and Zwally, 2004). Considering that snow falls on an ice surface that steadily moves downwards, the rate of snow surface elevation change with time ($\mathrm{d}h/\mathrm{d}t$) is given by:

$$\frac{\mathrm{d}h}{\mathrm{d}t} = \frac{A(t)}{\rho_0} - V_{\mathrm{fc}}(t) - \frac{A_0}{\rho_\mathrm{i}}, \qquad (1)$$

where $A(t)$ is the accumulation rate that is normally a function of time, ρ_0 is the initial snow density at the surface ($0.3\,\mathrm{g\,cm^{-3}}$), A_0 is the steady-state accumulation rate and ρ_i is the density of ice ($0.917\,\mathrm{g\,cm^{-3}}$). Therefore A_0/ρ_i represents the long-term steady-state vertical velocity of ice, and $V_{\mathrm{fc}}(t)$ is the vertical velocity at the surface ($z = 0$) due to firn densification. The densification velocity at depth z is determined by firn density $\rho(z)$ and the densification rate $\mathrm{d}\rho(z)/\mathrm{d}t$ according to:

$$V_{\mathrm{fc}}(z,\ t) = \int_{z_\mathrm{i}}^{z} \frac{1}{\rho(z)} \frac{\mathrm{d}\rho(z)}{\mathrm{d}t}\, \mathrm{d}z. \qquad (2)$$

The densification rate usually depends on the physical parameters. As previously described by Zwally and Li (2002), we use the rate equation modified from Herron and Langway (1980) for the model:

$$\frac{\mathrm{d}\rho(z)}{\mathrm{d}t} = K(T(z))\hat{A}(t)\frac{\rho_\mathrm{i} - \rho(z)}{\rho_\mathrm{i}}, \qquad (3)$$

where T is firn temperature and $\hat{A}$ is the mean accumulation rate that represents the average change of overburden pressure at depth z. Equations (1–3) are coupled with the heat-transfer equation through the thermal properties of firn (Li and others, 2002).

CONCLUSIONS

The dynamic response of the snow surface elevation to the temperature variation is closely associated with the cumulative effect of temperature anomalies, and demonstrates the importance of the temperature history. This history is also important in the surface melt-induced variations for the period over which the surface elevation change is determined.

The modeled surface-elevation changes associated with seasonal temperature variations over the Greenland and Antarctic ice sheets in two decades (1982–2003) indicate surface elevation changes in Greenland and West Antarctica of approximately $-2\,\mathrm{cm\,a^{-1}}$ due to the surface warming, and a small overall increase of $1\,\mathrm{mm\,a^{-1}}$ in East Antarctica.