Instruments and Methods

Snow density for measuring surface mass balance using the stake method

Shuhei TAKAHASHI, Takao KAMEDA

Snow and Ice Research Laboratory, Kitami Institute of Technology, Koen-cho 165, Kitami 090-8507, Japan
E-mail: shuhei@mail.kitami-it.ac.jp

ABSTRACT. A measure of snow density is required to estimate water equivalent ice-sheet surface mass balance (SMB) from stake measurements. Previous studies have utilized the snow density at different depths within the snow. By considering the snow densification process in the time interval between stake height measurements, we find that use of the snow density at the base of the stake is more appropriate. We assume the stakes are firmly anchored at the bottom and that Sorge's law holds, i.e. the density–depth profile does not change with time. Applying this method to the data for 36 snow stakes on Dome Fuji, the SMB in 2003 was 36.5 kg m^{-2} a^{-1}, 27% larger than the previous estimate, which used surface snow density. Correct selection of the snow density for SMB estimations is important, especially for Antarctic inland areas where accumulation is low (e.g. Dome Fuji, Vostok, Dome C and South Pole) and where the snow density near the surface varies markedly.

1. INTRODUCTION

Studies of water equivalent ice-sheet surface mass balance (SMB) are important to determine the global contribution of ice sheets to the water cycle, and for ice-core studies, especially ice-core dating. The SMB has been measured using several methods. These include annual-layer counting in snow pits (e.g. Koerner, 1964), ice-core analysis of stable isotopes (e.g. Hammer and others, 1978), snow deposition measurement over a set time interval from stake height differences ('stake method'; e.g. Takahashi and others 1994; Kameda and others, in press) and ultrasonic sensor detection of the snow surface (e.g. Reijimer and Van den Broeke, 2003).

Among these methods, the stake method has been used widely for SMB measurements because of its simplicity and ease of measurement. Stakes are set to a certain depth in the snow, and the stake height from the snow surface is measured over a given time interval. The snow density is required to calculate the water equivalent value of the SMB. Previous studies have used different approaches to establish the most appropriate snow density value to use.

At the South Pole, Giovinetto and Schwerdtfeger (1966) used the mean density of the upper 125 cm of the firn cover in the snow-stake network, ignoring the rate of snow settling. Radok and Lile (1977) observed snow accumulation at intervals of ~5 days over a 5 × 5 snow-stake farm at Plateau Station, Antarctica. They used surface snow density to obtain water equivalent accumulation. Hagen and Reeh (2004) summarized SMB measurement techniques, but did not discuss stake method snow density estimates.

In east Dronning Maud Land, East Antarctica, Fujiwara and Endo (1971) and Takahashi and others (1994) used the snow density through the upper 2 m (which they found to be a function of surface elevation) for SMB calculations. In the same area, Kameda and others (1997) and Satow and others (1999) used densities from the surface to near the annual snow accumulation depth. However, no study has sufficiently investigated the most appropriate snow density value to use for conversion to SMB values. We examine several snow density measures that can be used for this conversion. Investigating the snow densification during the period between the two stake measurements, we suggest a quantity, 'snow density for SMB calculation', ρ_{SMB}, that we believe is most appropriate for estimation of SMB, and which has been utilized in recent studies in East Antarctica.

2. DENSITY PROFILE

Figure 1 shows the snow density data for Dome Fuji station, east Dronning Maud Lnd, from measurements made on 18 February, 18 April and 15 October 1995, and on 18 January 1996. These densities were measured at intervals of 5–10 cm using a rectangular sampler (total volume: 97.4 cm^3, 59.6 mm × 55.2 mm × 29.6 mm (width × length × height)) and an electronic weight-balance (A&D Co. Ltd, Japan, Type DX-4000; maximum weight 4000 g, resolution 0.01 g). The snow density at the surface is <300 kg m^{-3} and it increases with depth to nearly 400 kg m^{-3} at 3 m depth.

These data can be fitted (Fig. 1) by the curve

$$\rho(z) = 408 - 118\mathrm{e}^{-\frac{z}{1.72}}, \qquad (1)$$

where $\rho(z)$ (kg m^{-3}) is snow density at depth z (m). The correlation coefficient is 0.63. In accordance with Sorge's law (Bader, 1954) in which the snow densification is calculated in the case of constant annual accumulation, we assume the density profile does not change with time.

3. BASIC CONCEPT

Figure 2 is a schematic diagram of the initial depth–density profile (Fig. 2a) in which the cross-hatched area indicates the snow mass from the surface to the stake base, and the situation a year later (Fig. 2b–d). We assume the same profile at both times, and that the base of the snow stake is anchored ('stake base'). The measured stake height difference over the 1 year period is Δh (Fig. 2c), and L_1 is the initial depth of the stake base. In this figure, to facilitate

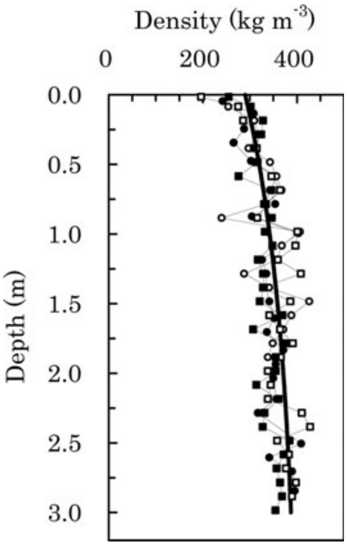

Fig. 1. Snow density measured at Dome Fuji on 18 February 1995 (solid circles), 18 April 1995 (open circles), 15 October 1995 (open squares) and 18 January 1996 (solid squares). The fitted curves are also shown.

comparison, the initial and 1 year snow-stake bases are set at the same level. However, given steady-state ice-sheet flow, the stake base has vertical downward displacement (compression) by Δh over the course of a year.

Note that the snow layer, from the surface to the stake base (i.e. over the length of the stake), is compressed and the surface after 1 year is lowered by ΔL (Fig. 2b) relative to the stake base. In Figure 2b, the new snow mass is the hatched area above the old first-year surface at a height of $\Delta h + \Delta L$. This snow mass, b_1, is

$$b_1 = \int_0^{\Delta h + \Delta L} \rho \, \mathrm{d}z = \rho_1(\Delta h + \Delta L), \tag{2}$$

where ρ_1 is the average density from the surface to a depth of $\Delta h + \Delta L$. Equation (2) is a valid estimate of the SMB at the second year. However, whereas Δh is easy to measure, ΔL is not. Thus it is difficult to estimate SMB using this method.

In Figure 2c, the first-year density profile (as in Fig. 2a) overlaps that for the second, *with the same stake base level*. The area difference shown as the hatched area (b_2) is the SMB, which has two parts, the surface part with a depth of Δh and lower part with a depth of L_1, as follows:

$$\begin{aligned} b_2 &= \int_0^{\Delta h} \rho \, \mathrm{d}z \left(\int_{\Delta h}^{\Delta h + L_1} \rho \, \mathrm{d}z - \int_0^{L_1} \rho \, \mathrm{d}z \right) \\ &= \rho_2 \Delta h + \Delta\rho L_1, \end{aligned} \tag{3}$$

where ρ_2 is the average density from the surface to a depth of Δh and $\Delta\rho$ is the average density increase through the depth of L_1. The density increase $\Delta\rho$, which depends on depth, is difficult to estimate.

In Figure 2d, the first-year density profile overlaps that of the second year *with the same snow-surface level* (i.e. it has been raised by Δh). The density profile, then, is from the surface to a depth of $L_1 + \Delta h$, and the difference in the area is

$$b_3 = \int_{L_1}^{L_1 + \Delta h} \rho \, \mathrm{d}z = \rho_3 \Delta h, \tag{4}$$

where ρ_3 is the snow density at the stake base (the average density from L_1 to $L_1 + \Delta h$).The three above methods all give the same SMB ($b_1 = b_2 = b_3$), but b_3 is the easiest to calculate.

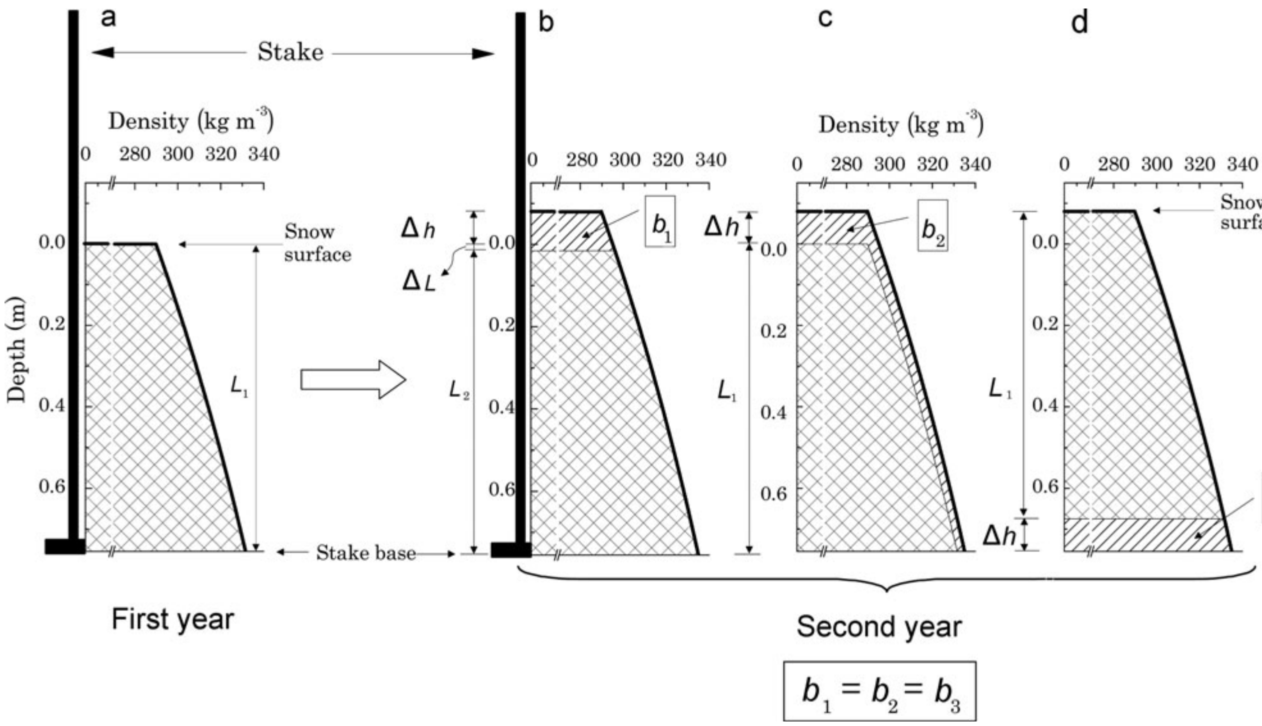

Fig. 2. Schematic diagram of the initial depth–density profile (a) in which the cross-hatched area indicates the snow mass from the surface to the stake base, and a year later (b–d). The base of the snow stake is anchored ('stake base'). The SMB after 1 year is shown as the hatched areas b_1, b_2 and b_3 ($b_1 = b_2 = b_3$). The measured stake height difference over the 1 year period is Δh (c) and L_1 is the initial depth of the stake base. ΔL is the surface lowering after 1 year. See text for further details.

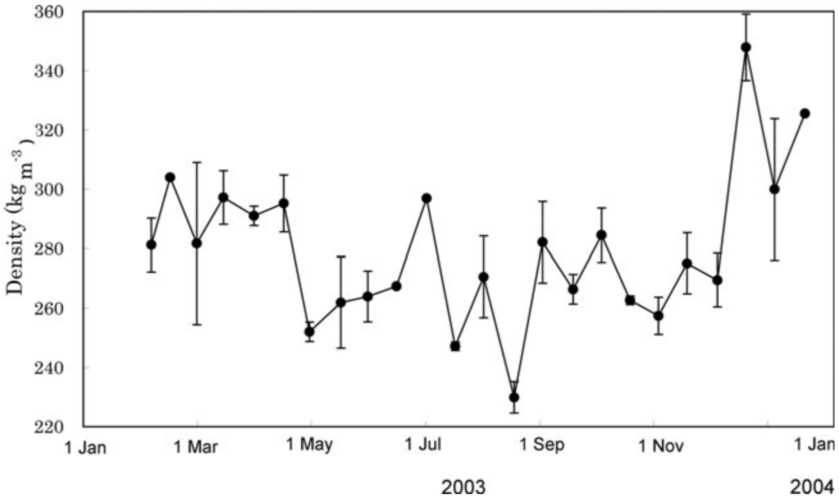

Fig. 3. Snow density from the surface to 10 cm depth at Dome Fuji in 2003. The average value was 280 kg m^{-3}.

Alternatively, Equation (4) can be derived from the difference in the snow mass above the snow-stake base as

$$\begin{aligned} M_1 &= \int_0^{L_1} \rho_t \, \mathrm{d}z, \; M_2 = \int_0^{L_1+\Delta h} \rho_{t+\Delta t} \, \mathrm{d}z \\ \Rightarrow b &= M_2 - M_1 = \int_0^{L_1+\Delta h} \rho_{t+\Delta t} \, \mathrm{d}z - \int_0^{L_1} \rho_t \, \mathrm{d}z, \end{aligned} \tag{5}$$

where M_1 and M_2 are the snow mass above the stake bottom initially and after 1 year, respectively, and ρ_t and $\rho_{t+\Delta t}$ are the density profiles initially and after 1 year, respectively. Here, if we assume the density profiles, ρ, are the same every year, then

$$b = M_2 - M_1 = \int_{L_1}^{L_1+\Delta h} \rho \, \mathrm{d}z = \rho_3 \Delta h, \tag{6}$$

which is the same as Equation (4). If we have measured density profiles from surface to stake base along with each stake reading, Equation (5) will produce a more accurate estimate of the SMB, but it is difficult to obtain a density profile with every stake measurement.

When we have a representative density profile in the observation area, we know the density at the stake base, ρ_3, and can estimate the SMB from stake height change, Δh, using Equation (4). Hence, we call ρ_3 the 'snow density for SMB calculation', ρ_{SMB}.

As detailed above, the calculation assumes a steady-state density profile and that the snow stake is anchored in the snow at the base. Over short periods, the rate of stake height change will not be constant; it is sometimes negative, due to intermittent precipitation or migration of snow by drifting. In this case, the density profile is not steady and Equation (4) is not appropriate for SMB estimation. Application of Equation (4) is better suited to longer periods (at least >1 year) which should include the season of stake readings. This will avoid seasonal changes in the density profile, especially in the near-surface layer.

4. THE 2003 SURFACE MASS-BALANCE ESTIMATION AT DOME FUJI

A 36-stake farm within a 100 m × 100 m square area with a 20 m grid interval was installed ~300 m northeast of the main station buildings at Dome Fuji station on 25 January 1995 (Azuma and others, 1997). Measurements have been ongoing. The stake heights have routinely been measured at 11–21 day intervals (average interval 15.3 days) during the four overwintering observation periods (January 1995, January 1997, January 2003 and January 2004), and once annually in the other years (Kameda and others, in press).

The average change ± standard error in stake height between 13 January 2003 and 15 January 2004 was 103 ± 8 mm. During this period, the average depth of the 36 stakes ranged from 1.37 to 1.47 m. According to the depth–density profile shown in Figure 1 (Equation (1)), ρ_{SMB} at this depth is 356 kg m^{-3} and, using Equation (4), the SMB at Dome Fuji station during the 2003 season is estimated to be 36.5 ± 3.0 kg m^{-2} a^{-1}.

If we use the surface (0–10 cm) snow density (Kameda and others, 1997; Satow and others, 1999), $\rho_0 = 280$ kg m^{-3} observed at Dome Fuji station twice a month in 2003 (Fig. 3), the resulting SMB is 28.7 ± 2.3 kg m^{-2} a^{-1}. The SMB using Equation (4), 36.5 kg m^{-2} a^{-1}, is 27% larger than this estimation.

Using Equation (4), Kameda and others (in press) estimate the annual SMB at Dome Fuji from 1995 to 2006. The average SMB over 12 years was 27.3 kg m^{-2} a^{-1}, in which the snow-stake depth changed from 0.76 to 1.69 m and ρ_{SMB} increased from 334 to 363 kg m^{-3}. This result agrees well with the annual SMB from AD 1260 to 1993 (26.4 kg m^{-2} a^{-1}) estimated from volcanic signals in the Dome Fuji ice core.

Over a period of ~40 years, the Japanese Antarctic Research Expedition (JARE) has observed SMB along many traverse routes in a wide area of east Dronning Maud Land from the coast to inland areas including the Dome Fuji area. Fujiwara and Endo (1971) and Takahashi and others (1994) plotted snow (0–2 m) densities and SMB as a function of elevation. The average surface density at the elevation of Dome Fuji (3800 m) was 338 kg m^{-3}, which is close to our result for ρ_{SMB}, 356 kg m^{-2} a^{-1}, over the snow depth interval 1.37–1.47 m.

JARE snow stakes are 2.5 m long, 15–25 mm diameter bamboo poles. Generally, snow stakes are initially buried to 0.8 m depth (stake height above the surface = 1.7 m), and reset when the stake depth is >1.7 m (i.e. if ≤0.8 m is above the surface). Therefore, the average stake depth is 1.2–1.3 m. If we are unable to obtain detailed snow-stake depth data, it is best to measure the density at the average depth, 1.2–1.3 m. The density profile however, depends upon elevation and regional characteristics.

5. POSSIBLE ERROR SOURCES

5.1. Seasonal change in the density profile

The density profile implied by Sorge's law is based on the assumption of unchanging accumulation and temperature. Under actual conditions, the accumulation rate and temperature change seasonally, and the density profile will vary seasonally. As shown in Figure 3, the surface snow density in 2003 was higher in summer (evaporation prevails) and lower in winter (condensation and accumulation prevail), which seems a typical variation for this inland area. However, if seasonal perturbations are the same from year to year, Equation (4) is valid when measurements are made in the same season. If we measure stake heights in the same season, the density profile near the surface will be the same and Equation (5) will be valid. Conversely, if we measure stake height at different seasons, the integrals M_2 and M_1 in Equation (5) will be over different ranges and therefore will not be valid.

5.2. Snow stakes

Equation (4) is based on the assumption that the stake base is anchored in the snow. If the snow catches or freezes to the stake, the stake can shift downward due to the densification of the snow layer above the base. The surface of a bamboo stake is smooth and it is unlikely that snow will catch or freeze on it. In addition, a bamboo stake has an average bulk density of $\sim$340 kg m^{-3}, close to the density of snow near the surface. Thus the penetrating effect due to the weight of the stake is negligible. A much heavier stake could sink lower, resulting in a measurement error.

6. CONCLUSION

It is important to select the correct snow density for SMB in water equivalent estimates, especially in areas of inland Antarctica (e.g. Dome Fuji, Vostok, Dome C and South Pole) where the accumulation is small and the snow density near the surface varies markedly. Assuming the stake base is firmly anchored in the snow and the density–depth profile from the surface is steady with time (Sorge's law), the best estimation of SMB is obtained using the snow density at the base of the stake.

Applying this method to data from 36 snow stakes, the SMB at Dome Fuji was found to be 36.5 kg m^{-2} a^{-1} in 2003, 27% larger than the previous estimate, which used surface snow density.

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