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THE HEAT AND MASS BALANCE OF SNOW DUNES ON THE CENTRAL ANTARCTIC PLATEAU

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Abstract. The heat-balance components of the faces of snow blocks were measured at "Plateau" station on the Antarctic plateau using micro-meteorological instrumentation. Heat-balance considerations and sublimation observations indicate considerable mass loss from the sloping snow surfaces during summer but little loss from horizontal surfaces. This process tends to level the irregularities of the snow surface. The conclusions are applicable to the snow dunes forming the general accumulation pattern on the Antarctic plateau.

Résumé. *Bilan d'énergie et de masse des dunes de neige sur le plateau central antarctique.* Les composants du bilan d'énergie des faces de blocs de neige ont été mesurés à la station "Plateau" au centre de l'Antarctique en utilisant l'intrumentation de micro-météorologie. Des considérations de bilan d'énergie et des observations de la sublimation indiquent des pertes de masse considérables sur les surfaces inclinées de la neige pendant l'été mais peu de pertes sur les surfaces horizontales. Ce processus tend à niveler les irrégularités de la surface de la neige. Ces conclusions sont applicables aux dunes de neige formant les figures générales d'accumulation sur le plateau antarctique.

Zusammenfassung. *Der Wärme- und Massenhaushalt von Schneedünen auf dem antarktischen Zentralplateau.* Die Komponenten des Wärmehaushalts von Schneeblockoberflächen wurden an der "Plateau-Station" auf dem antarktischen Plateau mit mikrometeorologischem Instrumentarium gemessen. Betrachtungen zum Wärmehaushalt und Sublimierungsbeobachtungen deuten während des Sommers auf erheblichen Massenverlust bei geneigten Schneeoberflächen, jedoch auf geringen Verlust bei horizontalen Oberflächen hin. Dieser Vorgang tendiert auf die Einebnung der Unregelmässigkeiten der Schneeoberfläche. Die Schlussfolgerungen sind auf die Schneedünen, die wesentliche Akkumulationsform auf dem antarktischen Plateau, anwendbar.

Introduction

The annual accumulation of snow on the Antarctic plateau is small, roughly 7 cm water equivalent at the South Pole and 3 cm water equivalent at "Plateau" station. The accumulation occurs largely in the form of large-scale features such as snow dunes and sastrugi which characterize the surface structure during the winter but are considerably reduced in size in the summer months. This is evidenced by the stratigraphical work of Gow (1965) at the South Pole, which shows good horizontal layering without major irregularities. Gow attributed this levelling to a sublimation†–deflation process in summer when considerable mass loss occurs from sloping surfaces but not from the hardened horizontal surface. The mass loss occurs through large sublimation crystals developing on the sloping faces of the dunes or sastrugi which are subsequently stripped off even by light winds, a process referred to by Gow as deflation. Orheim (1968) has carried out similar observations at "Plateau" station where softening and sublimation from artificial and natural snow features was observed as well as hardening of horizontal surfaces. Like Gow, he attributed the process to absorbed radiation, the inclined faces absorbing considerably more energy. The horizontal and inclined surfaces would hence have totally different heat balances.

The present study attempts to analyse quantitatively the heat balance of horizontal and inclined snow surfaces at "Plateau" station which is situated at lat. 80° S., long. 40° E. on the central Antarctic plateau at an altitude of 3 600 m. For this purpose, snow blocks in the form of truncated pyramids with 45° slopes were cut out and placed on a flat, horizontal snow surface and the individual heat-balance components were measured over the various faces. The measurements were made during a period of good weather with clear skies and light winds between 1 and 10 January 1968. Solar elevations during that period were 32° at midday and at midnight 12° above the horizon. The results obtained should be valid for all large-scale features on the snow surface which have sloping faces, including sastrugi and snow dunes.

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† Throughout this paper sublimation will mean phase transitions from solid to vapour only.

Heat-balance Components

The heat balance of a non-melting snow surface can be expressed by the following equation:

$$R+S+Q+E = 0 \tag{1}$$

where R is radiation balance at the surface, S is heat-flux in the snow, Q is eddy or sensible heat-flux at the surface, and E is latent heat-flux at the surface. The sign convention is as follows. Positive terms: surface acts as a heat source, i.e. heat-flux is away from the surface. Negative terms: surface acts as a heat sink, i.e. heat-flux is towards the surface. The symbolism and sign convention used is similar to that defined by Dalrymple and others (1966).

The term R (the radiation balance) is obtained simply by the use of a net radiometer. For the purposes of this study a miniature version of the C.S.I.R.O. net radiometer (Funk, 1962) was employed. The instrument was mounted 5 cm above the surface and could in effect only "see" the surface of the snow block. Calibration factors corrected for temperature, as supplied by the C.S.I.R.O., were used. A second miniature radiometer was mounted 5 cm above and its sensing plane parallel to the sloping snow-block surfaces and moved to a new face every 24 h. Results are given in Figure 1.

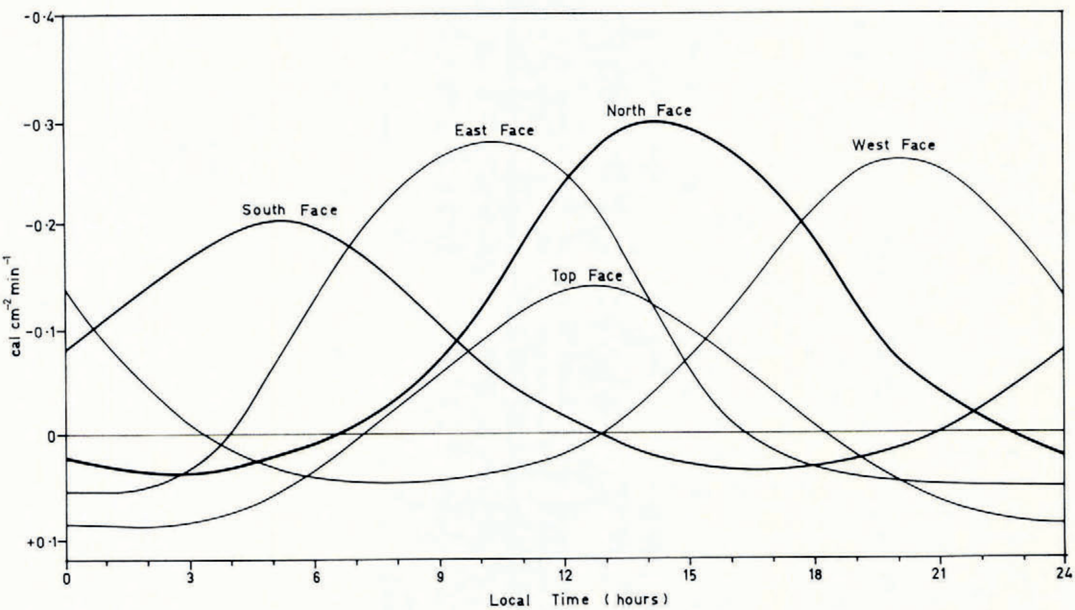

Fig. 1. The radiation balance of all five faces of the snow block.

To obtain the term S (the snow heat-flux) a thermocouple probe with copper-constantan temperature sensors painted white to reduce radiation errors was in use under a flat horizontal surface. This probe had sensors at 5, 15, 30 and 50 cm depth. The surface temperatures were extrapolated from air-temperature profiles as shown below. Snow-temperature profiles at 3-hourly intervals could thus be constructed (Fig. 2) and from the change in heat content of the snow the heat-flux

$$S = \rho c \int_{-50}^{0} \Delta T(z)\, \mathrm{d}z \tag{2}$$

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in the upper 50 cm of the snow could be computed. In a study reported elsewhere (Weller and Schwerdtfeger, unpublished), the thermal conductivity of the snow was derived and the heat-flux below 50 cm depth during the above measurements was obtained as 0.0055 cal cm^{-2} min^{-1} or 8 cal cm^{-2} d^{-1} (32.94 J cm^{-2} d^{-1}) from the temperature gradient at 50 cm depth. The values of the density ρ and the specific heat c were 0.32 Mg m^{-3} and 0.435 cal g^{-1} deg^{-1} (1.818 J g^{-1} deg^{-1}), respectively, the latter figure being the value quoted by Dorsey (1940) for a temperature of -35°C.

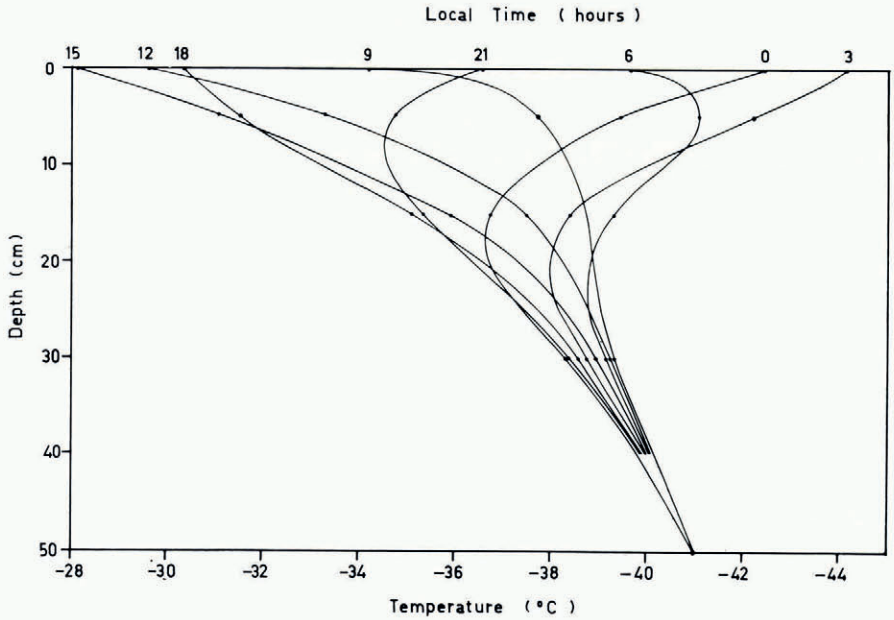

Fig. 2. Snow temperatures down to 50 cm depth at 3-hourly intervals.

From the heat-balance equation (1), the combined flux of sensible and latent heat ($Q+E$) was obtained as a remainder term for 3-hourly intervals. These results are plotted for the top and north faces (Fig. 3), assuming the term S to be equal for both faces.

The Bowen ratio approach, assuming similarity between the mechanisms of vertical transfer for heat and moisture, can now be used to separate the components. The eddy heat-flux can be written:

$$Q = -\alpha_i(\theta_i - \theta_o) \tag{3}$$

where θ_o is the temperature at the snow surface, θ_i the temperature at the height i where the heat transfer coefficient α_i is valid. Similarly, for the latent heat-flux:

$$E = -\frac{0.623L}{pc_p}\alpha_i(e_i - e_o) \tag{4}$$

where L is the latent heat of sublimation or hoar-frost deposition, p the atmospheric pressure, c_p the specific heat at constant pressure, e_i the vapour pressure at height i, and e_o the vapour pressure at the snow surface. The Bowen ratio r_B can thus be written:

$$r_B = \frac{Q}{E} = \frac{c_p(\theta_i - \theta_o)\,p}{0.623L(e_i - e_o)}. \tag{5}$$

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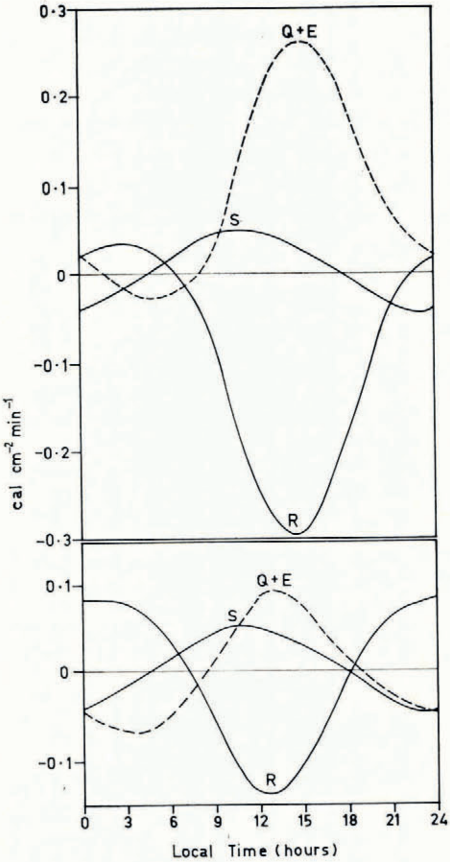

Fig. 3. The heat-balance components for the sloping north face (upper) and the horizontal top face (lower).

Temperature profiles were measured by ventilated copper-constantan thermocouple sensors at 50, 15 and 5 cm above the surface. Mean profiles at 3-hourly intervals for the period 1–10 January are shown in Figure 4. They reflect a logarithmic structure of the temperature profile near the surface and were extrapolated to an assumed roughness parameter of the snow surface of 0.01 cm to give the snow-surface temperature. During the day there are lapse conditions over the snow which change to inversions during the night.

From the mean temperature profile for the whole period and, assuming the relative humidity at 50 cm height to be 75% (from Rusin (1961, table 46), where the monthly means of four stations in the Antarctic interior are quoted) and the air at the snow surface to be at saturation, the Bowen ratio becomes 8.7. When using a relative humidity of 65%, the ratio is 7.3. The Bowen ratio method has obvious limitations. At best it must be said that the method can give approximate values only. With the limited data available, however, at least it allows a rough estimation of the latent and sensible heat-flux components. This is carried out accepting a value of $r_B = 8$. Integrating the daily values of all components, the values of Figure 5 are obtained. This figure establishes a remarkable dissimilarity of the heat balances of the two faces.

Conclusions

The heat balance of the various faces has been shown to be controlled by different processes. For the two faces selected for analysis, it has been assumed that the snow heat-flux will

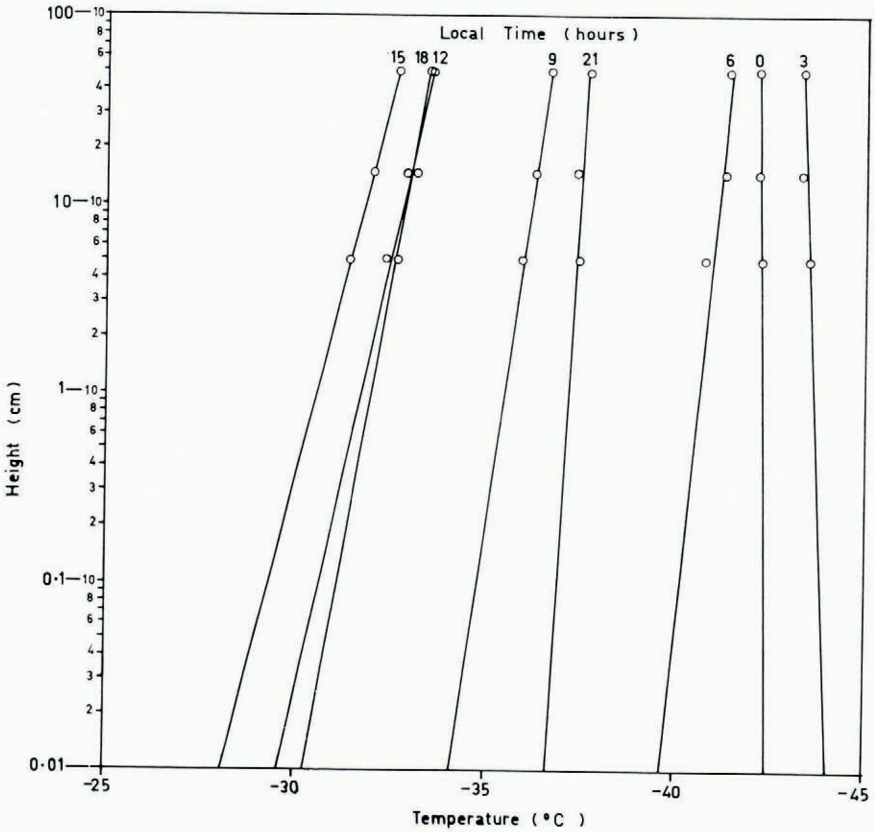

Fig. 4. Mean air-temperature profiles at 3-hourly intervals for the period 1–10 January 1968.

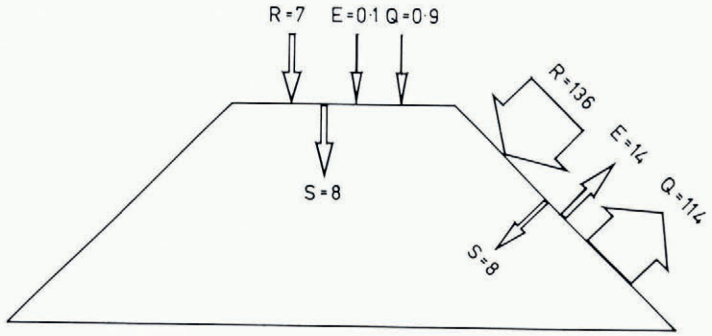

Fig. 5. The daily integrated heat-balance components for the top and north faces. Figures are in cal cm^{-2} d^{-1}. R = radiation balance, S = heat-flux in the snow, Q = eddy heat-flux, E = latent heat-flux.

be similar in amplitude and phase. Strictly, the higher amount of radiation absorbed on the sloping face probably means higher snow-surface temperatures. This will increase the amplitude of the diurnal heat-flux but it should not affect the heat-flux below 50 cm, the depth of penetration of the diurnal heat-flux. For the other faces, also, similar heat-fluxes should be obtained, since the amounts of radiation received by all surfaces do not vary greatly as shown in Figure 1.

The inversions over the snow surface during the night, as shown in Figure 4, confirm the negative $Q+E$ term obtained during the night (Fig. 3). Similarly, during the day when there are lapse conditions, $Q+E$ is positive. Hoar-frost deposit is thus possible during the night on horizontal surfaces but much less likely on the north-sloping face. Sublimation is indicated from both faces during the day with a considerably higher mass loss possible from the north-sloping face (Fig. 3). Similar considerations using appropriate phase corrections hold for the other sloping faces. Thus the radiation balance of the south-sloping face is at a maximum early in the morning and there will be a corresponding phase shift of the sublimation peak.

The integrated values in Figure 5 illustrate the daily net effect. The horizontal surface is hardly affected by mass losses and the exchange of sensible and latent heat between the atmosphere and the snow surface is negligible. On the other hand, the integrated daily latent heat-flux can account for a daily net loss from the sloping face of almost 1 mm of snow by sublimation alone. This certainly has to be considered as a major factor in the levelling of the snow surface irregularities. Mechanical erosion (deflation) of the sublimation crystals will increase this figure. Orheim (1968) quoted mass losses from sastrugi which are generally 3 mm d^{-1} in summer.

The difference in the integrated daily eddy heat-fluxes at the two faces requires comment. It is clear that the heat-transfer coefficient used in eddy heat-transfer studies over irregular surfaces can represent a mean value only. Large local variations of this coefficient from the mean value can occur depending on the geometry of the surface. Hofmann (1963) has stated that the heat-transfer coefficient at edges and corners, for instance, can be higher by a factor of a hundred or more from that of a level surface. Similarly, for exposed surfaces which are strongly heated, the heat loss by buoyant convection even with small friction velocities is large and indicates high effective transfer coefficients.

Figure 6 confirms the above considerations. First, it shows the sloping faces covered with large scale-like sublimation crystals, while there are only a few small crystals on the top surface, indicating little sublimation loss from that surface and possibly small deposition. Secondly, it shows spike-like hoar-frost crystals formed during the night along the edges, where the heat-transfer coefficient is one or two orders of magnitude higher.

Fig. 6. The snow block after a period of light snowdrift, with the miniature net radiometers in position.

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It is clear that the heat-balance components of the different faces are largely controlled by the amount of radiation absorbed by these faces. The present study confirms the qualitative observations made by Gow and Orheim that there is considerable smoothing of the snow dunes during the summer, resulting in a more uniform redistribution of the snow over the whole surface. Stratigraphy studies at "Plateau", of which Figure 7 is a typical example, confirm this.

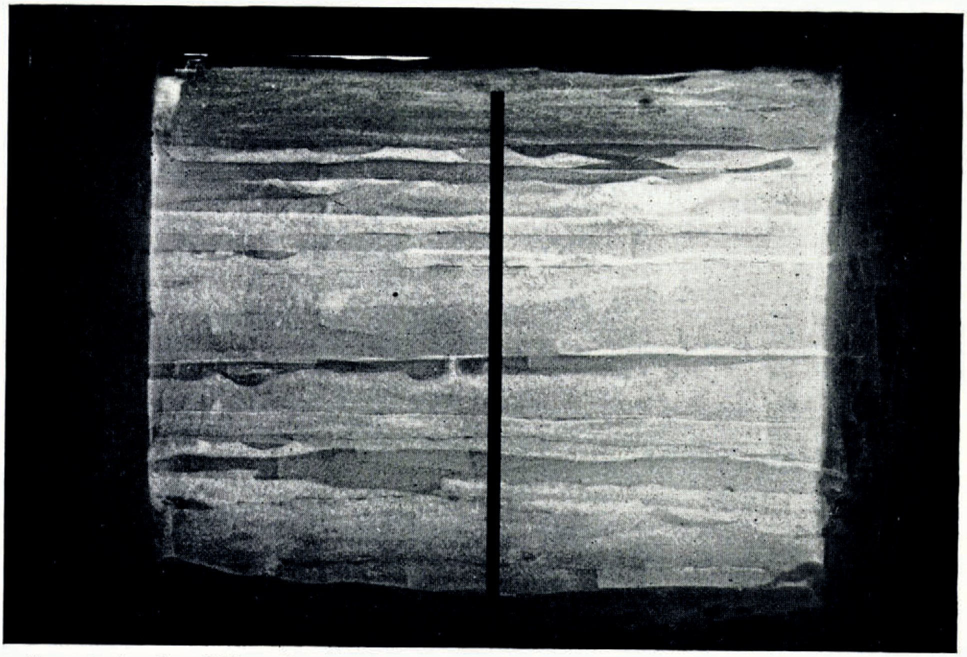

Fig. 7. Snow stratigraphy at "Plateau" station. The snow wall is 5 cm thick, the sun illuminating the other side. In the centre is a 1 m ruler.

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