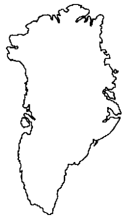

A newly detected ablation phenomenon in Dronning Maud Land, Antarctica

Carl Egede Bøggild and Jan-Gunnar Winther

From November 1993 to February 1994 members of the Geological Survey of Greenland (GGU) participated in a Nordic research effort in Antarctica. The Nordic Antarctic Research Programme (NARP) involves Norway, Sweden and Finland, which are all Antarctic Treaty Consultative Partners; Denmark as an observer has participated only since 1992 (Thomsen, 1994; Bøggild *et al.*, 1995). The member countries of NARP have traditionally carried out research in Dronning Maud Land. This region of Antarctica has recently gained new research interest, including survey for a joint European deep drilling programme planned for 1995/96. Future Norwegian climate studies on blue ice will therefore be closely related to the joint European deep drilling programme.

Of the two ice sheets in the world, Greenland and Antarctica, only the Greenland ice sheet displays significant surface melting, since the climate in Antarctica is generally too cold for large scale melting. However, different types of melt phenomena have been observed in blue ice fields in Antarctica. GGU was invited to participate in the Norwegian Antarctic Research Expedition 1993/94 in order to study physical melt processes in Dronning Maud Land in an environment which is similar to near equilibrium areas in the high Arctic regions of the Greenland ice sheet. Only sparse information on such areas exists from the Greenland ice sheet.

To the best of our knowledge the first recorded sub-surface melt phenomenon within clear blue ice was discovered during the 1993/94 expedition; numerical modelling shows this to be a consequence of solar radiation penetration and absorption, i.e. the 'solid-state greenhouse effect'. This discovery may contribute to the understanding of runoff from high polar regions of both the Antarctic and Greenland ice sheets.

The Jutulgryta blue ice area

Occurrences of blue ice in Jutulgryta, Dronning Maud Land, are primarily restricted to isolated areas which are intersected by snow fields (Fig. 1). They are often related to convex surface shapes where exposure to wind is most prominent (Takahashi *et al.*, 1988). The surface topography undulates along the gentle north-westerly slope that leads down to the Jutulgryta depression, and blue ice fields are common and constitute about 70% of the slope region. The present studies were restricted to an area about 3 km in radius at an altitude of approximately 140 m a.s.l. (Fig. 1).

Sub-surface melting

Since average air temperatures in Antarctica are well below freezing point, past observations of melting have been reported only in nunatak areas where blue ice is in contact with bedrock, rocks in the ice, or with other material which increases heat absorption (Autenboer, 1962; Paige, 1968). However, the sub-surface melting observed in the Jutulgryta depression cannot be explained by these processes in as much as local climatic conditions related to nunataks can be discounted; the nearest nunatak is more than 50 km away. Moreover, no impurities were found which could lead to internal melting (Bøggild *et al.*, 1995).

Brandt & Warren (1993) summarise studies of snow temperatures with special emphasis on the occurrence of a maximum temperature below the surface (the 'solid-state greenhouse effect') that results from solar radiation penetration and absorption inside the snow, and the fact that long-wave radiative cooling is restricted to the surface. Factors such as radiative heating of sensors, dirt inside ice or a dark layer beneath the snow are reasons for the past reportings of this 'solid state greenhouse effect' in snow (Brandt & Warren, 1993). Although the idea of a 'solid state greenhouse effect' is attractive, and has been described theoretically by several authors (e.g. Schlatter, 1972; Brandt & Warren, 1993), Brandt & Warren state that it is rather questionable within snow, but may in theory occur within blue ice due to the lower extinction coefficient and albedo values compared to those for snow.

The studies in the Jutulgryta area show that observed melting is confined to a zone between 0.5 and 1 m depth below the blue ice surface, and that this melt layer was consistent throughout the one month of observations (Bøggild *et al.*, 1995). Measurements of sub-surface temperatures in exposed as well as snow-covered blue ice, clearly documents that a melting zone is only present below the surface where blue ice is exposed. Ice temperatures are

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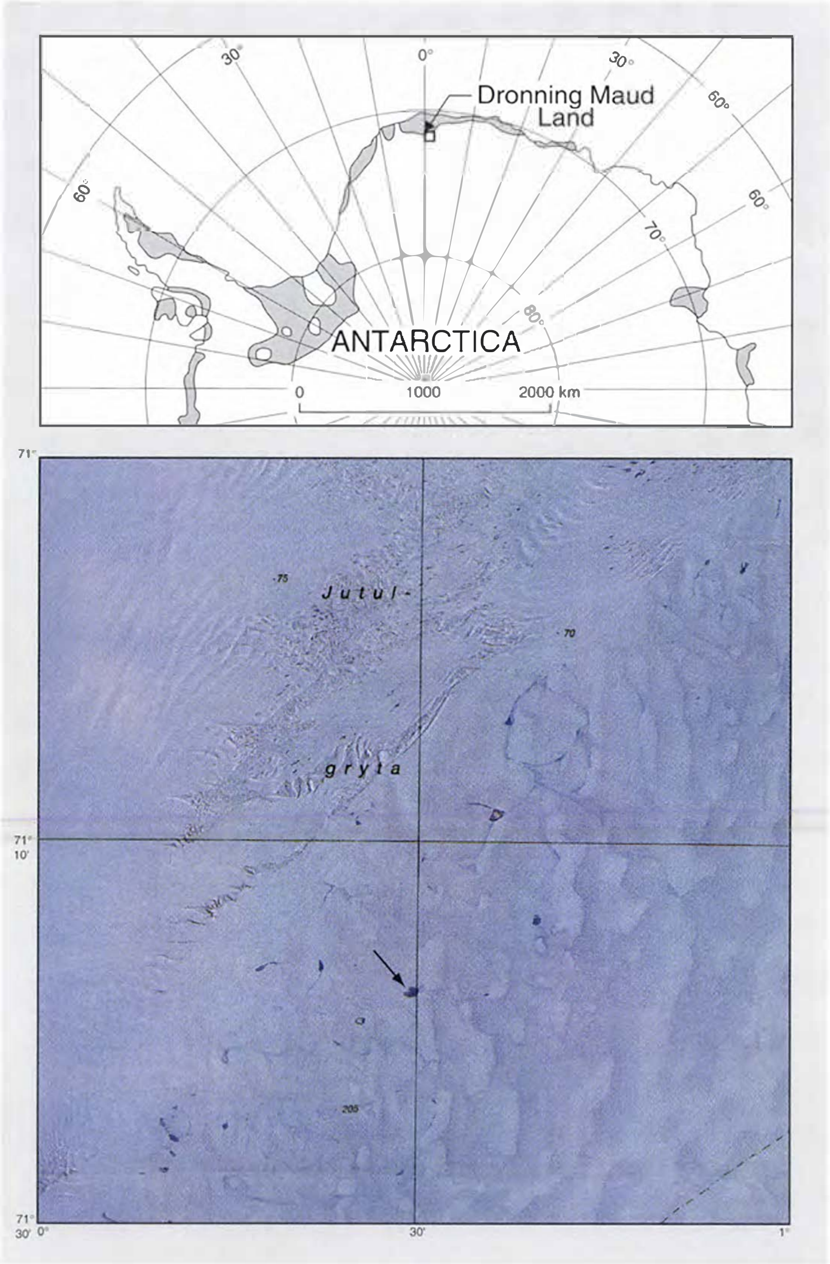

Fig. 1. Part of a satellite enhanced map covering the blue ice region in Jutulgryta. The dark areas are blue ice fields which are intersected by bright snow fields. The darkest spots are lakes. The location of the camp was 71°23′55″S, 0°29′55″E, altitude 140 m a.s.l., indicated with an arrow.

generally 6° C higher than temperatures in snow covered profiles (Fig. 2).

Modelling experiments

A number of numerical modelling experiments have been carried out in order to reconstruct the sub-surface melt phenomenon and, when positive, sensitivity experiments have been performed to find the parameters which control the formation of a sub-surface melt layer.

The sensitivity studies mainly rely on input parameters and data measured in Jutulgryta during the 1993/94 expedition. When not available, they were obtained from published observations closely matching the Jutulgryta conditions. The theory and numerical scheme behind this non-stationary, combined radiative and thermodynamic model is described in detail by Bøggild (1990, 1991) and Bøggild *et al.* (1995).

Numerical modelling shows development of a sub-surface meltlayer (a 0° C zone) in blue ice after only five days of ice exposure (Fig. 3). The solid black line refers to a situation where the snow cover has remained and would

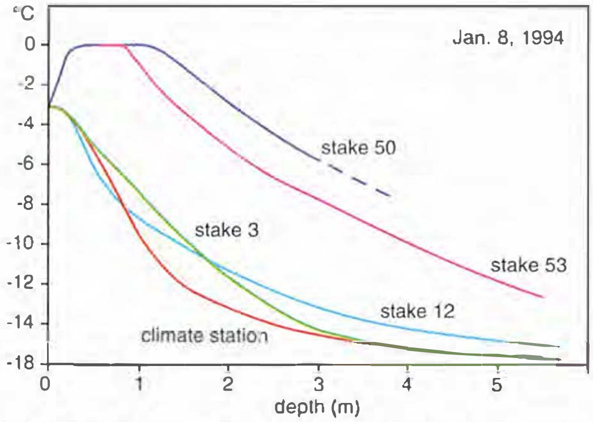

Fig. 2. Sub-surface temperatures recorded on 8 January, 1994. Measurements from stake 50 and 53 are from exposed blue ice. Stake 3, 12 and the climate station are from similar, but snow covered profiles.

disable radiative penetration. The maximum just below surface stems entirely from diurnal fluctuations of surface temperatures. The formation of a melt layer is strongly controlled by penetration and absorption of radiation, which in turn is governed by the surface reflectance (albedo) α, the transmittance β and the extinction coefficient κ (Fig. 3).

The development of steady state temperatures below the melt layer takes longer to establish with increasing distance from the surface. To simulate temperature evolution over periods of several years it has been necessary to modify the existing model by coarsening the grid resolution to 0.5 m (to overcome the demand for computer time). Figure 4 shows how temperatures develop within blue ice after simulation runs of 1, 2, 4 and 8 years duration, respectively. The snow profile temperatures from stake 3 (Fig. 2) have been used as initial conditions, although with thermal and optical properties as for blue ice. Air temperatures and global radiation are monthly mean values over 10 years measured at the German Georg von Neumayer (GvN) station (Helmes, 1989). From 927 air temperature time series, Fortuin (1992) concludes that air temperatures in Antarctica are only significantly dependent on elevation and latitude. The GvN research station is located at approximately the same elevation and latitude as the Jutulgryta area, but some 250 km to the west. The annual cycle of air temperatures in Jutulgryta can therefore be assumed to be similar to observations from GvN, omitting the need for the complex transfer function necessary in Greenland when extrapolating a temperature signal over a similar distance (Bøggild *et al.*, 1994).

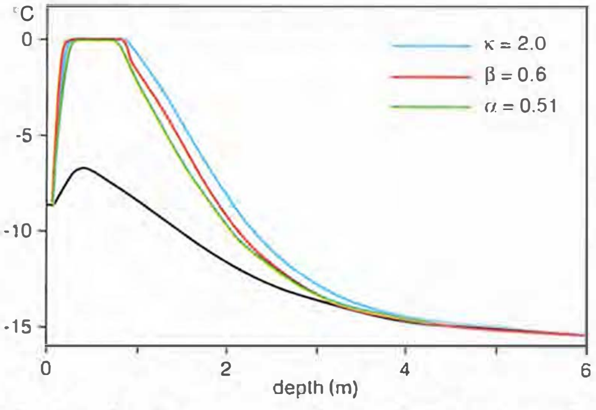

Fig. 3. Simulated temperature profiles based on 5 day runs. α is surface reflectance, β is radiation transmittance and κ is extinction coefficient. From the figure it appears that all the three parameters α, β and κ can independently cause the formation of a sub-surface meltlayer. The adjustment of α is based on own observations, whereas κ and β are adjusted within observed limits suggested by Grenfell & Maykut (1977). The three curves show that a sub-surface meltlayer can develop by adjusting one parameter within natural limits and keeping the others constant. A detailed discussion of parameters is found in Bøggild *et al.* (1995).

The simulations in Fig. 4 illustrate that several years of exposed blue ice are needed to produce the parallel rise of ice temperatures from the 'cold' snow covered profile to the 'warm' ice temperatures of exposed blue ice (Fig. 2). The trend is clear, but interpretation cannot be carried further due to lack of observations from winter-time. It can be stated, however, that sub-surface melting in blue ice must have occurred over many years in order to raise the temperature by 6°C in blue ice, and it probably occurs every austral summer.

Summary and outlook

The existence of a persistant sub-surface melt layer during the melt season means that runoff is not restricted to occasional events each year when air temperatures are near or above the melting point. Contributions to sea level rise are quite likely to come from Jutulgryta and similar areas, because the grounding line of the adjacent ice-shelf is highly crevassed with hydraulic contact to the sea water below the ice shelf. It should be noted, however, that the contribution from this melt phenomenon is rather small in relation to the total annual mass balance turnover of Antarctica.

The 'invisible' nature of the sub-surface melting and runoff phenomena are generally confined to a narrow range of summer mean air temperatures. An increase of air temperature will result in 'classical' surface melting, whereas a cooling will strongly reduce the formation of a sub-surface melt layer. Thus, the confined air temperature range under which sub-surface melting can occur makes this phenomenon a good potential indicator for detecting possible future climate changes.

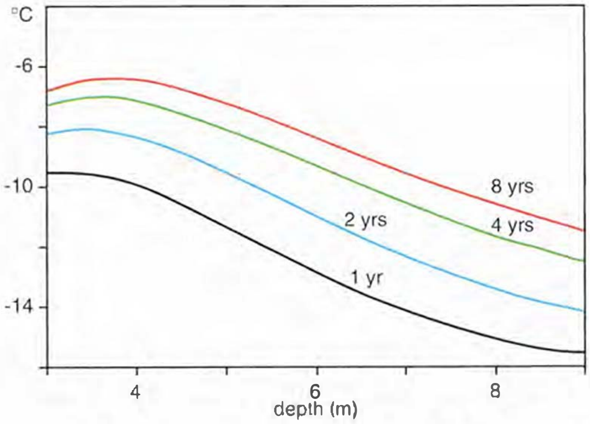

Fig. 4. Evolved temperature profiles after 1, 2, 4 and 8 years of simulations.

The effect of the reported ozone hole over Antarctica on sub-surface melting is not yet known. It is likely that increased penetration of ultraviolet (UV) radiation through the atmosphere will also enhance radiative absorption in blue ice, since the ice is most transparent to solar radiation penetration in the shortwave UV range and becomes more opaque with increasing wavelength (Grenfell & Maykut, 1977). Once the sub-surface meltlayer is established, it is likely to remain due to radiative scatter at interfaces inside the ice. New efforts should therefore be devoted to analysing the effect of the ozone hole over Antarctica on the formation of sub-surface melting and runoff. This will be possible by further development of the existing model to include spectral solar radiation and scatter properties.

Our discovery of a widespread 'solid-state greenhouse' melt layer in blue ice in Antarctica may also contribute to the understanding of runoff from the Greenland ice sheet, since similar surface features, i.e. frozen lakes and blue ice fields intersected with snow fields, have been documented near the equilibrium line in both East and West Greenland (Echelmeyer *et al.*, 1991; Reeh *et al.*, 1991).

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C. E. B., Geological Survey of Denmark and Greenland, Copenhagen

J.-G. W., Norwegian Polar Institute, Postboks 5072 Majorstua, N-0301 Oslo, Norway