THE EVOLUTION OF THE ENGLACIAL TEMPERATURE DISTRIBUTION IN THE SUPERIMPOSED ICE ZONE OF A POLAR ICE CAP DURING A SUMMER SEASON

Wouter Greuell and Johannes Oerlemans
Institute of Meteorology and Physical Oceanography
University of Utrecht
The Netherlands

ABSTRACT

The aim of the present investigation was to provide more insight into the processes affecting the evolution of the englacial temperature distribution at a non-temperate location on a glacier. Measurements were made in the top 10 m of the ice at the summit of Laika Ice Cap (Canadian Arctic) during the summer 1975 (by Blatter et al.). This location is in the superimposed ice zone. The model simulation includes calculation of the surface energy fluxes, of radiation penetration, of the englacial temperature and density distribution, and of the formation, penetration and refreezing of melt water.

In the first kind of experiments the energy fluxes from the atmosphere were tuned in such a way as to obtain the right amount of ablation. With these energy fluxes as a boundary condition the consequences of melt water penetration and refreezing for the englacial temperature distribution were proofed to be considerable. In the second kind of experiments the measured temperature at the interannual surface was used as boundary condition, and to start with the temperature below the interannual surface could only be affected by conduction. The measured and the calculated temperatures match until melt water penetrates to the interannual surface. Thereafter, calculations give too low temperatures. Most of this energy deficiency will probably be due to radiation penetration, whereas a minor part of it may be caused by melt water penetration into open veins or an error in the assumed interface temperature.

1. INTRODUCTION

Two kinds of parameters determine the ablation at a glacier surface. On one hand there are the meteorological elements like incoming radiation, temperature, humidity and wind velocity. On the other hand temperature, density and structure of the upper snow and ice layers affect the mass balance. In fact, most of the parameters of both groups are interrelated

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and affected by the melting process. If a computer model is constructed for the simulation of mass balance the number of variables and of their relations has to be restricted, of course. In most cases the energy fluxes between atmosphere and glacier are calculated from standard meteorological quantities and additional assumptions concerning the state of the snow or glacier ice are made. Albedo and the roughness lengths are generally prescribed and the temperature of the snow or ice is assumed to be 0°C over the entire depth of the glacier at the location to which the calculation should apply. The validity of this last assumption for alpine glaciers was tested in previous work (Greuell and Oerlemans, 1986). It appeared that in the Alps the "zero degree assumption" hardly affects the calculated mass balance at lower elevations, say below the equilibrium line. However, larger errors are made at higher elevations with the error increasing with elevation.

The englacial temperature and density distributions affect the mass balance in two ways. Firstly, the long wave outgoing radiation and turbulent fluxes depend on the surface temperature. Secondly, melt water formed at the surface may penetrate and refreeze at lower depths depending on temperature and density distribution. In that case the melt water does not run off and therefore does not contribute to the ablation. The amplitude of the cold wave penetrating into the snow of alpine glaciers during the winter season or during nighttime in the summer season increases with elevation. More melt water is then needed to eliminate the cold wave.

The purpose of the present study is to obtain more insight into the evolution of the englacial temperature profile. This is done by means of a data set and a computer simulation. As location for the simulation the summit of Laika Ice Cap (Canadian Arctic, 75°53' N, 79°10' W, 530 m a.s.l.) was chosen. This location is in the superimposed ice zone. Here the temperature profile down to a depth of 10 m was measured during the summer season 1975 (Blatter, 1985). To start with the computer simulation will show to what extent we are able to simulate the evolution of the temperature profile with the mere knowledge of some standard meteorological variables. Then a sensitivity experiment will be done to estimate the effects of penetrating and refreezing melt water.

Finally, instead of the calculated energy fluxes at the atmosphere-glacier interface, the measured temperatures at the interannual surface will be used as a boundary condition. The comparison of the calculated and the measured temperature distribution below the interannual surface leads to some considerations about the roles of penetrating radiation and of melt water penetration into veins in the ice below this surface. Another purpose of the experiments presented here is to test the computer model that we primarily developed for mass balance studies (Greuell and Oerlemans, 1986), but which is also suitable for the present study as it includes a calculation of the temperature and density profile.

2. THEORY

In the general case the evolution of the temperature distribution in a glacier is described by the following equation:

$$\rho c \frac{dT}{dt} = \nabla \cdot (K \nabla T) + W \tag{1}$$

where ρ , c and K are the density, the specific heat and the conductivity of snow/ice, t is time, T is temperature and W the generation of energy per unit volume and per unit time. W includes the following processes:

- The energy fluxes between atmosphere and glacier. Nearly all of this energy will be absorbed in or emitted from the uppermost centimeters of the snow or ice. Only the short wave radiation will partly penetrate and be absorbed deeper.
- The formation and refreezing of melt water are sink and source of energy, respectively.
- Deformational heat
- The energy flux between glacier bed and glacier.
- Cooling and/or freezing of rain water adds energy to the glacier.

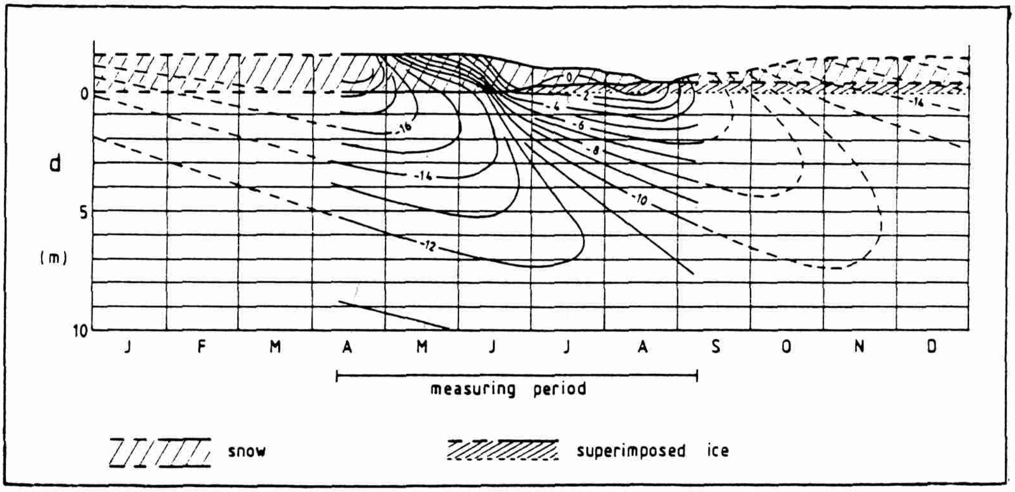

Figure 1. Evolution of the englacial temperature distribution in the top 10 m at the summit of Laika Ice Cap during 1975 as based on measured data (from Blatter, 1985).

3. MEASUREMENTS

In the summer season of 1975 the evolution of the temperature profile on the summit of Laika Ice Cap, situated on Coburg Island in the Canadian Arctic was measured (Blatter, 1985). This was done as part of a glaciological program carried out by members of the North Water Project team. The measurements covered the uppermost 10 m of the vertical column at the summit of the ice cap. A hole of this depth was drilled by hand with the aid of a SIPRE core drill in early April 1975. A cable with thermistors (accuracy ± 0.2°C) was inserted and the hole filled with snow and water. The temperature stabilized some 2 weeks later. Measurements were taken 17 times with the first measurement on April 16 and the last one on September 5.

The evolution of the temperature profile is shown in Figure 1. In the ice under the interannual surface the penetration of the winter cold wave has a time lag roughly proportional to depth, and the amplitude of the variation decreases with depth. The evolution of the temperature distribution in the layer above the interannual surface is more complicated. Schematically the following periods can be distinguished (dates are calculated with the computer model, see next sections):

a. At the beginning of the measurements the layer is about 1.5 m deep and has a mean density of about 400 kg m^{-3}.
b. Until June 9: gradual warming of the surface layers.
c. June 9 - June 15: melt water is formed at the surface, penetrates and refreezes completely in the "cold" snow of the layer above the interannual surface thereby raising temperature and density of this layer. On June 15, for the first time, the layer is warmed up to 0°C over its full depth.
d. June 15 - August 17: this is the ablation season proper. The layer continually looses energy, by conduction to the ice underneath, and thus tends to cool down. During a few short periods this cooling down is reinforced by a negative energy flux from the atmosphere. However, this flux is positive on most days and melt water is formed, part of which is used to keep the layer at 0°C. The rest runs off. At the bottom of the layer the density attains the density of ice after a while. The ice formed that way is called superimposed ice and the layer formed by it gradually thickens. On many days during this period snowfall takes place.
e. August 17 - September 5: melt water formation stops. In fact, the accumulation season starts.

Mass balance measurements at the same site give a winter accumulation for 1974-1975 of 69 cm w.e. (=water equivalent). Summer ablation amounted to 37 cm w.e. Thus, the net mass balance was 32 cm w.e. (Müller, 1977), which is close to the annual mean of 30 cm w.e. (Blatter, 1985). Aerial photographs taken in 1959 and 1971 show that the total mass balance of Laika Ice Cap is strongly negative (Blatter, 1985).

For the simulations in the present study the following meteorological data were used:

a. Temperature (2 m), humidity (2 m), wind velocity (10 m), sunshine duration and amount and kind of precipitation. All these variables were measured with different frequencies during the whole period at Base Camp station (4 m.a.s.l.), situated near the terminus of the glacier. Although with interruptions the temperature was also measured at the site of the englacial temperature measurements (530 m.a.s.l.) and during the whole period on nearby Marina Mountain (700 m.a.s.l.).

b. No radiation measurements were available for 1975. Thus, they had to be calculated from the other parameters and suitable formalae. For the global radiation under clear skies a formula given by Meyers and Dale (1983) was used, for the incoming long wave radiation a formula from Kimball et al. (1982).

For more information about the frequency of the measurements, the assumptions used to calculate the values of the variables at the summit of the glacier and the adaption of the radiation formulae to local conditions the reader is referred to Greuell and Oerlemans (1987).

For the simulations only daily mean values of the meteorological variables were used. The amplitude of the diurnal temperature variation is about ±2°C in April and May and decreases to ±0.5 - ±1.0°C during the melt season. These variations are so small that they are obscured by larger non-periodic variations (Blatter, pers. comm.). The humidity variations do not at all coincide with the 24 hr cycle (Blatter, pers. comm.). Only the global radiation is subject to a daily cycle in dependence of the zenith angle variation.

4. THE MODEL

The model used for the calculations is described in more detail in Greuell and Oerlemans (1986). It was originally developed for the simulation of mass balance. Essentially, the surface fluxes are computed from standard meteorological variables (temperature, humidity and wind velocity at one level, and cloudiness) and from the surface temperature, the albedo and roughness lengths. In a sub-model the evolution of the englacial temperature and density distribution are calculated.

Global and incoming long wave radiation are calculated by means of the before mentioned formulae. The turbulent fluxes are calculated by means of the Monin-Obukhov similarity theory (see e.g. Businger, 1973). The values of the albedo and the roughness lengths were reconsidered, because conditions on polar ice caps are different from conditions in the Alps, the region for which the model was originally designed. For the albedo (α) we used:

$$\alpha(n) = \alpha_{n=0} + 0.06\ n \tag{2}$$

with $\alpha_{n=0} = 0.8$ in the absence of melt water at the surface, $\alpha_{n=0} = 0.54$ in the presence of melt water at the surface and n is cloudiness.

The aerodynamic roughness length z_0 varies between 0.1 mm and 1.3 mm. It increases in the presence of melt water at the surface. It also increases with density and decreases with the thickness of the snow layer. The roughness lengths for temperature and humidity are equal to 0.01 mm. The values of the albedo and the roughness lengths and the conditions for their variation were detained from the work by Holmgren (1971) about the Devon Island Expedition. It is remarkable that he found that the albedo of the frozen superimposed ice or firn below the spring snow pack at his station in the superimposed ice zone did not drastically differ from that of pure fine snow. This means that the albedo is hardly affected by a fresh snowfall event.

Penetration of short wave radiation into deeper layers may have serious consequences for the energy budget if the snow or ice is not at the melting point, so an attempt was made to include this in the model. If penetration is important, the surface layer receives less energy, the underlying layers more. This may even cause melt water production below the surface, whereas the surface itself remains frozen (see Holmgren, 1985). In snow the consequences of radiation penetration are of lesser importance, because the extinction coefficient is much larger, and penetrating and refreezing melt water may undo the different partitioning of the energy. The second effect of radiation penetration concerns the turbulent fluxes and the outgoing long wave radiation, leading to an enhanced total energy flux from the atmosphere. It should be borne in mind that this effect is only present if the temperature of the very surface is below the melting point.

Absorption and scattering of radiation in snow or ice depends on wave length. Infra-red radiation hardly penetrates; in the visible part of the spectrum the extinction coefficient is much lower. Following Holmgren (1985) short wave radiation penetration was modelled as follows: the global radiation was divided into 2 parts. One part (36%), with wavelengths larger than 0.8 µm, is completely absorbed in and reflected from the model layer at the surface (6 cm thick). The rest partly penetrates into deeper layers, according to

$$Q_s = I_s \ (1 - \alpha_s) \ e^{-\beta_s z}, \tag{3}$$

where Q is the net radiation at depth z below the surface, I the global radiation at the surface, α the albedo and β the extinction coefficient. The subscript s refers to radiation with $\lambda < 0.8$ µm. In the layer above the interannual surface β_s is linear in ρ with $\beta_s = 10 \ m^{-1}$ if $\rho = 400$ kg m^{-3} and $\beta_s = 4 \ m^{-1}$ if $\rho = 910$ kg m^{-3}. In the underlying ice: $\beta_s = 1.3 \ m^{-1}$. Radiation penetration will be discussed in some more detail in Section 5.2.

The processes affecting the evolution of the temperature profile were already mentioned in Section 2. In the present investigation some of these processes were not taken into account, namely:

- horizontal advection and deformation since there is hardly any movement in the top 25 m (the thickness of the model) at the summit of the ice cap.
- the flux at the bed.
- cooling and freezing of rain since rain fall events were rare in the summer season of 1975 (5.3 mm according to our calculations).

Thus, the change of temperature is determined by conduction, the energy flux from the atmosphere, and the formation, refreezing and run off of melt water.

A few words should be said about how the model deals with the latter. The melt water formed in the top layer moves downwards. Melt water formed in one or more of the other layers is added "en route". If it reaches a model layer with a temperature below the melting point, this layer is warmed up by refreezing the melt water. If the resulting temperature exceeds 0°C, the temperature is put equal to 0°C and the remaining amount of melt water is computed. This melt water penetrates downwards into the next model layer, etc. After penetration through the lowest model layer above the interannual surface the remaining melt water runs off. In the model the density increases by this refreezing process only. Processes like compaction and metamorphosis are not considered. The initial density of snow layers accumulating during the summer season is assumed to be 400 kg m^{-3}.

Conductivity is obtained from a formula given by Paterson (1981):

$$K = 2.1 \times 10^{-2} + 4.2 \times 10^{-4} \rho + 2.2 \times 10^{-9} \rho 3 \qquad (4)$$

Thus, K = 2.1 W m^{-1} K^{-1} for ice.

The sub-model simulating the evolution of the englacial temperature and density distribution consists of 42 layers with increasing thickness from top (6 cm) to bottom (about 3 m at a depth of 25 m).
Equation 1 is solved numerically by an implicit scheme. The temperature in the lowest grid point is constant. The effect on the temperature profile calculations of this assumption was proved to be negligible. The time step for the calculations is 30 minutes and the initial conditions are the temperature and density profile obtained from the first measurements. At that time the ice was covered by 1.5 m of snow with a mean density of 400 kg m^{-3}. This value was used for the whole layer. Initial temperature conditions below 10 m were specified by values obtained from a linear interpolation between the 9.5 m-value of April 16 and the 16- and 23 m-values of September 5, when temperatures were measured in a deeper hole nearby. Once a day the grid and the englacial profiles were adjusted to the new surface level as it is determined by accumulation, melting and evaporation.

5. EXPERIMENTS

Two kinds of experiments were carried out. In the first an attempt was made to calculate the right amount of ablation for the summer season 1975 (37 cm w.e.). After tuning in such a way that this value was indeed obtained, the resulting error in the temperature profile calculations and the effect of the melt water penetration and refreezing on the temperature profile were studied. The second kind of experiments solely dealt with the evolution of the temperature profile below the interannual surface. Here the boundary condition at the top of the model was given by the measured temperature at the interannnual surface.

5.1 Experiments with surface energy flux calculations

The initial run was done with the meteorological data as described in Section 3. The ablation thus calculated exceeded the measured value significantly. The calculated net balance for 1974-1975 even became negative. Thus, for matching the measured and the calculated amount of ablation one or more of the meteorological variables, glaciological parameters or properties of the model had to be adjusted. The effects of the following were investigated: reduction of the global and the incoming long wave radiation, higher albedo, lower temperatures, higher conductivity and a smaller aerodynamic roughness length. As long as the adjustment remained within reasonable limits, with none of them the desired result could be obtained with the exception of the incoming long wave radiation. This flux had to be multiplied by a factor 0.88. Such a reduction of 12% appears to be a large amount. It seems improbable that a 12% error in the mean incoming long wave radiation is due to the calculations. While the calculation of the incoming long wave radiation from temperature, vapour pressure and sunshine duration certainly causes large errors in individual dayly means, the mean value for the whole period must have an error much smaller than 12% as the formula used was established by regression analysis of the previous year's data. The regression analysis was done with data from Base Camp station. Then, the formula was applied on the ice cap. An order of magnitude estimate shows that the error possibly caused by this displacement will certainly be much smaller than 12%. Some support for a systematic error in the measurements comes from long wave radiation measurements on another ice cap in the Canadian Arctic (Bradley, 1985) made under comparable conditions. These data have a mean value 14% lower than the mean of the measured values on Coburg Island. Indeed, the accuracy of long wave radiation measurements is generally low. So the 12%-reduction was maintained, although no direct evidence for an error in the measurements on Coburg Island could be obtained. For the simulation of the 1974-ablation season exactly the same multiplication factor was needed to match the calculated and the measured amount of ablation (18 cm w.e.).

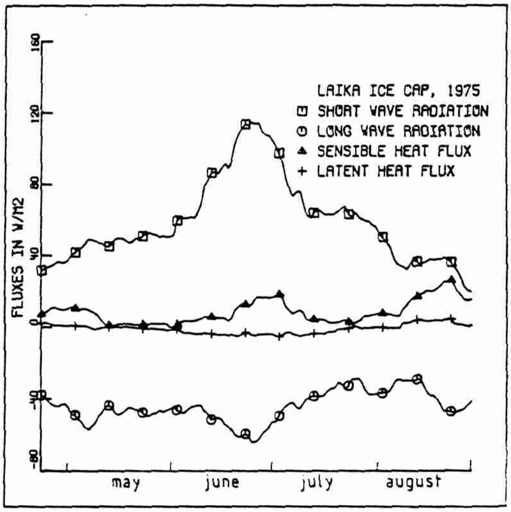

Figure 2. Running means (15 days) of the calculated energy fluxes.

Figure 2 shows the course of the energy fluxes at the surface during this summer (15 days running means). The radiation fluxes are of opposite sign and they dominate the turbulent fluxes. There are rather abrupt changes in the net short wave radiation. This is caused by a positive feedback mechanism. A melting surface has a lower albedo so that the total energy flux towards the glacier is enhanced and that melting conditions can be sustained more easily.

A similar run was made without radiation penetration. The calculated amount of ablation hardly changed (41 cm w.e. against 37 cm w.e. for the original run). Primarily one would expect that penetrating radiation enlarges the amount of ablation, because of the increased total energy flux from the atmosphere during non-melting conditions at the surface. In fact, this effect would enlarge ablation by 9 cm w.e. However, melt water formation at the surface is suppressed, so that the albedo will be high during longer periods and ablation is reduced.

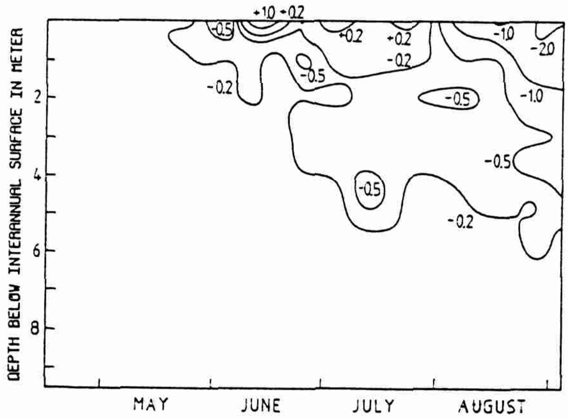

Figure 3. Error in the temperature calculation after run without interface temperature control. Calculations are based on the energy balance calculations at the surface. Contour labels give degrees centigrade. Positive values correspond to calculated temperatures being too high.

An evaluation of the evolution of the calculated temperature profile can be obtained from Figure 3. It gives the difference with the measured temperature profiles. The layer above the interannual surface is omitted from these comparisons as the fluctuations in this layer are dominated by surface energy fluxes with high frequencies, which are not represented in the input data (only daily means of the meteorological variables were used). The model calculations generally give too low temperatures. The error grows during the summer and larger discrepancies occur near the surface. Apparently the downward energy flux through the interannual surface is too small. In Section 5.2 ways of eliminating the discrepancy will be discussed.

In order to assess the effect of the penetrating melt water on the englacial temperature an experiment in which all of the melt water immediately runs off was carried out. Melt water keeps the temperature of the layer above the interannual surface close to the melting point during the ablation season. If conduction would be the only energy transport mechanism, temperatures would be substantially lower (see Figure 4). It is evident that the simulation of melt water penetration and refreezing thereof is essential at the site of these measurements.

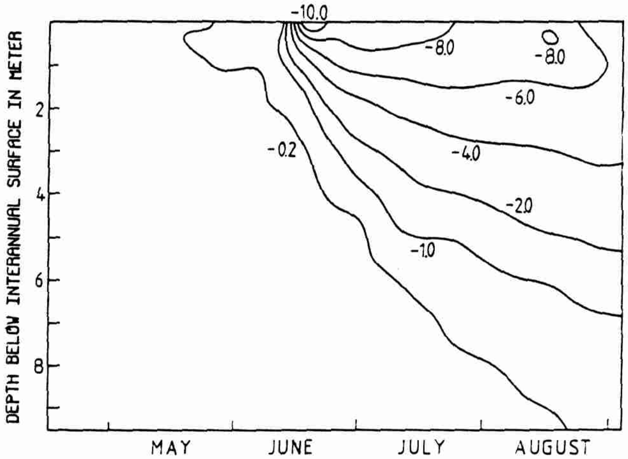

Figure 4. See Figure 3. However, in this case melt water penetration was inhibited.

5.2 Experiments with interface temperature control

The second kind of experiments solely dealt with the temperature distribution below the interannual surface. The temperature at this surface was taken from the measurements and in a first experiment radiation penetration was neglected. The calculated temperature distribution then is a solution of Equation 1 with $W = 0$ and $k = K/\rho c$ independent of time and depth and equal to $1.15 \times 10^{-6}\ m^2\ s^{-1}$. The error made under these conditions can be evaluated from Figure 5. Three periods can be distinguished.

Until the first decade of June the error is within the accuracy of the observations. During this period no melt water penetrates to the interannual surface and the thick snow cover will almost completely inhibit radiation penetration into the ice. So, energy will only be redistributed by conduction. These circumstances were used to test the value of the diffusivity of ice as used in this study. By varying k in a systematic way we found that the optimal value is within 10% equal to $1.15 \times 10^{-6}\ m^2\ s^{-1}$.

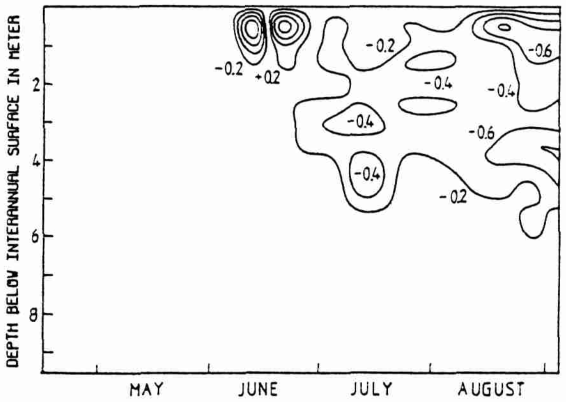

Figure 5. Error after run with temperature at the interannual surface prescribed by the measured data. Radiation penetration was neglected. Values give degrees centrigrade and positive values correspond to calculated temperatures being too high.

In June the calculation close to the interannual surface becomes more inaccurate. Both positive and negative deviations are obtained, with maxima about plus and minus 0.8°C. Two possible explanations may be given:

a. The interface temperature at this time of the year rises rapidly from about -11°C on June 14 to close to the melting point on June 18, caused by the refreezing of penetrating melt water. As the boundary condition was determined by an interpolation of the measured values (only 4 observations in June), the error in the interface temperature on some days during this time of the year will be large.
b. Melt water penetrates and refreezes below the interannual surface, possibly only along the thermistor string. However, this should only provoke positive deviations.

Like in the run without interface temperature control (Figure 3), it seems that the downward energy flux through the interface is underestimated in the period thereafter. This may be caused by:

a. Melt water penetration and refreezing. However, in that case the deviation in the uppermost measurement point at 0.5 m depth should be large at the onset of the ablation season and decrease afterwards, because the available space in the veins would be occupied by the refreezing melt water later in the season. This seasonal trend is not found. The source of the error seems to persist during the whole period. In order to match the calculated and the measured temperature distribution at the end of the measurements about 14 mm w.e. of melt water would have to penetrate and refreeze.

b. Radiation penetration. Again about 4.6 MJ m^{-2}, that is the energy released when a layer of 14 mm water freezes, would be needed to match the calculated and the measured temperature profiles at the end of the measurements. It is difficult to estimate whether this amount of radiation penetration is feasible. The bulk extinction coefficient for pure ice at some depth is known within reasonable limits of accuracy, $\beta = 1.1 - 1.5\ m^{-1}$ (Grenfell and Maykut, 1977). However, things become complicated in snow, because the extinction coefficient is very dependent on structure and density. Moreover, it varies with wave length, so that even in a homogeneous snow or ice cover the bulk extinction coefficient changes with depth. As the spectral composition of the incoming radiation depends on the state of the atmosphere in general, and especially on cloud conditions, the problem is even more complicated. In view of all these difficulties, and in view of the limited suitability of the present model to simulate the detailed structure of the snow cover, only a rough estimate of the effects of radiation penetration could be obtained. It appeared that with the parameterization as proposed in Section 4 the mismatch could not be eliminated. More radiation had to penetrate and therefore another parameterization was adopted. Again radiation with wavelengths greater than 0.8 μm (36%) was completely absorbed in or reflected from the uppermost model layer. The rest of the radiation was extinguished according to Equation 2, with in the layer above the interannual surface $\beta = 20\ m^{-1}$ for a mean density less than 500 kg m^{-3} and $\beta = \beta_c$ for a greater mean density. This "critical" density was reached on June 24. In the underlying ice $\beta = 1.3\ m^{-1}$. Then, by trial and error β_c was found, so that the calculated and the measured profile for September 5 matched. A value of 1.8 m^{-1} was found. This is a very low value relative to the values given by Holmgren (1985) for fine grained snow during the early melt periods ($\beta = 10\ m^{-1}$) and for loose weathered superimposed ice ($\beta = 4\ m^{-1}$). It should be mentioned that the artificial difference between the extinction coefficients of the ice on both sides of the interannual surface might not be justified. The ice on both sides seems to be about the same (Blatter, pers. comm.). However, the total absorption below the interannual surface is not affected by putting the extinction coefficient below the interannual surface equal to its value above this surface, since it is only determined by the extinction coefficient above the interannual surface and the albedo. The albedo below the interannual surface might be higher than assumed in the calculations. Blatter (pers. comm.) reported dirt layers in the ice due to blowing sand. Figure 6 shows the error after the run with $\beta_c = 1.8\ m^{-1}$.

c. Interface temperatures are too low. A run was made with the interface temperature 0.5°C higher from June 24 on. This interface temperature increase cannot completely eliminate the discrepancy.

Hooke (1983) simulated the evolution of the temperature profile during a summer season on Storglaciären (Swedish Lappland). To match calculations and measurements, he also had to introduce an additional energy flux at the interannual surface. Since his measurement site became snow free rather early in summer, he could estimate the amount of radiation penetration more accurately than it could be done in this study. He concluded that the "energy deficiency" in his calculations could completely be eliminated by radiation penetration.

Since a systematic error in the interface temperature measurements of more than 0.2°C seems unlikely, such an error could only explain a minor part of the mismatch. For warming by the refreezing of melt water open veins in the ice layer from the previous year as a consequence of weathering of the superimposed ice should exist. Such veins were reported by Hooke (1983) on Storglaciären, but according to Blatter (pers. comm.) superimposed ice was not exposed very long in summer 1974 and seemed to be rather compact. Furthermore, as argued before, the effectiveness of this process should decrease with time. Thus, it seems that refreezing of melt water is unimportant so that radiation penetration should play a major role in explaining the extra energy flux.

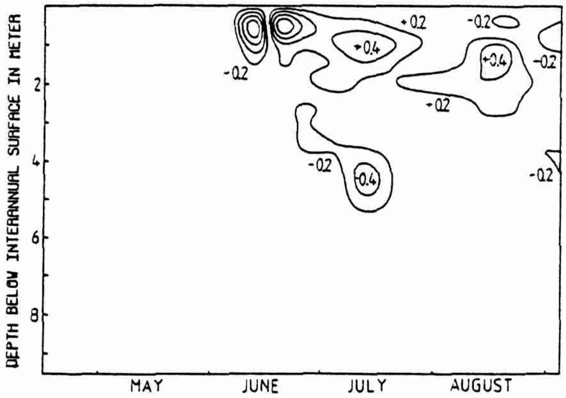

Figure 6. See Figure 5. However, radiation penetration was allowed in such a way as to match the calculated and the measured profile of September 5.

6. CONCLUSIONS

With the present investigation an effort was made to obtain insight into the processes affecting the temperature distribution in the uppermost layers of a non-temperate location on a glacier or ice cap. Besides, the suitability of the model used for this investigation was tested. The simulation of the temperature distribution in the layer above the interannual surface was not considered in the comparison between the measured and the calculated data, since it strongly depends on energy inputs with high frequencies which were not represented in the input data.

It seems that the temperature distribution in a glacier can be calculated very accurately provided the glacier consists of a homogeneous ice body, the temperature at the boundary of the body is known and no other energy fluxes than conduction interfere. If melt water penetration and refreezing thereof is not considered, large errors will occur in the case melt water is formed (see Figure 4). Inclusion of this process in the model leads to much better results (see Figure 3), but a minor discrepancy remains and its source seems to coincide with the ablation season. One of the possible error sources is penetration and refreezing of melt water in the ice below the interannual surface. This will depend on the structure of the ice. Moreover, as soon as the snow cover becomes thin, radiation penetration should be included in the model. The present model can only give rough estimates, but the results indicate that radiation penetration accounts for the major differences between the observations and the calculations. Hooke's (1983) calculations for a site in the ablation zone on Storglaciären lead to a similar conclusion. If accurate estimates of the intensity of the penetrating radiation are desired, a model specially designed for this purpose should be used. Such a model should take account of the spectral dependence of the extinction coefficient, of the spectral distribution of the incoming radiation and of the detailed structure of the snow/ice cover.

In many studies the annual mean air temperature is compared with the temperature at some depth in the glacier. This depth should be great enough for the annual temperature variations to be damped largely. A depth of 20 m seems to be enough, and in order to take the energy flux from below into account Hooke (1983) proposed to extrapolate the 20 m-value to the surface by means of the 20 m-temperature gradient. In the case of Laika Ice Cap the annual mean air temperature (about -14.8°C) is a couple of degrees centigrade lower than the 20 m-value extrapolated to the surface (-11.7°C). This difference will largely be due to warming by refreezing melt water.

The model failed to calculate the thickness of the layer of superimposed ice. The grid used in the model is built up from the glacier surface downwards. Since melting, evaporation and snow fall change the position of the surface, and since numerical problems caused us to stick to the grid point distance, especially at the surface, the grid has to be adjusted regularly. So the grid moves relative to material points and mass diffuses. Only mass transport through the interannual surface could be inhibited. It is recommanded that future models use a grid in which the individual grid points stick to material points. However, special attention should be paid to the grid point distances close to the surface in view of numerical problems.

For more details the reader is referred to an extended version of this paper (Greuell and Oerlemans, 1987)

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