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SHORT NOTES

CRYOCONITE HOLES ON SERMIKAVSAK, WEST GREENLAND

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Abstract. The depths and diameters of 158 cryoconite holes were measured at ten positions in the ablation zone of Sermikavsak, West Greenland. It was found that the depths increased on going up the glacier in agreement with other measurements made earlier on polar glaciers. There was no significant correlation of depth with diameter. The relative importance of the combined short- and long-wavelength radiation balances and the transfer of heat by convectional mixing in water-filled holes is discussed. The variations in depth are attributed to changes in the albedo and the bulk extinction coefficient of the surface ice layers on the glacier.

Résumé. *Trous à cryoconites au Sermikavsak, Groenland Occidental.* Les profondeurs et les diamètres de 158 trous à cryoconites ont été mesurés en dix emplacements de la zone d'ablation du Sermikavsak au Groënland Occidental. On a trouvé que ces profondeurs augmentent quand on remonte vers le haut du glacier, conformément avec d'autres mesures antérieures dans des glaciers polaires. Il n'y avait pas de corrélation significative entre profondeur et diamètre. On discute de l'importance relative du bilan de rayonnement, de courtes et de grandes longueurs d'ondes, et des transferts thermiques par convection dans l'eau de remplissage des trous. Les variations en profondeur sont attribuées au changement de l'albedo et du coefficient d'extinction dans la masse des couches de glace à la surface du glacier.

Zusammenfassung. *Kryokonit-Löcher am Sermikavsak, West-Grönland.* An 10 Stellen in der Ablationszone des Sermikavsak in West-Grönland wurde Tiefe und Durchmesser von 158 Kryokonit-Löchern gemessen. In Übereinstimmung mit früheren Messungen an polaren Gletschern zeigte sich, dass die Tiefe gletscheraufwärts zunahm. Zwischen Tiefe und Durchmesser ergab sich keine signifikante Korrelation. Die relative Bedeutung der kombinierten kurz- und langwelligen Strahlungsbilanz und der Wärmefluss durch Konvektionsmischung in wassergefüllten Löchern wird diskutiert. Die Tiefenschwankungen werden durch Änderungen der Albedo und den Gesamt-Extinktionskoeffizienten der oberflächennahen Eisschichten erklärt.

It is well known that small water-filled dust wells or cryoconite holes are common in the weathering crust of superimposed ice in the ablation zone of the Greenland ice sheet and other Greenland glaciers. Their formation is due to the heat energy that first is absorbed by fine, flocculated, dark, silty sediment that has accumulated in the hole and then is used to melt the underlying ice. In a stable state a hole will attain an equilibrium depth when its downward growth rate is equal to the ablation rate at the surface. The heat energy has been attributed to a variety of physical processes: they have been discussed briefly by Sharp (1949). They range from the flow of warm water into a hole (Drygalski, 1897), the absorption of direct solar radiation transmitted obliquely through the walls (Philipp, 1912), and a combination of both direct and diffuse solar radiation reaching the bottom of the hole (Brandt, 1931). It was pointed out by Wagner (1938) that the diffuse radiation coming down the hole was more important than the transmitted direct radiation, but he was unable quantitatively to account for the heat input needed to achieve the observed equilibrium hole depths. Biothermal energy emitted at infrared wavelengths by algae undergoing photosynthesis has also been considered to provide a localized radiation source inside a hole, and its subsequent absorption by ice close to the dust layer helps to contribute to the hole depths found in firn at high latitudes (Gerdel and Drouet, 1958). If an assessment of the relative importance of the processes could be made, a cryoconite hole would act as a rough natural indicator of the contribution that radiation makes to surface ablation.

Measurements were made on 158 cryoconite holes at ten positions on the ice of Sermikavsak, Upernivik, West Greenland, at lat. 71° 11′ N., long. 53° 03′ W. on 18–21 July 1977. Sermikavsak is a typical valley glacier of Ahlmann type II and shows sub-polar characteristics within its ablation zone (Fristrup, 1960): at present Sermikavsak has started to advance with its southern flank close to its 1969 position (Gribbon, 1970) and its northern flank at its 1973 position.*

* Private communication from D. T. Meldrum in 1973.

Our aim was (i) to study how the dimensions of the cryoconite holes depended on their location on the glacier, (ii) to compare our measurements with those obtained elsewhere in the Arctic (Drygalski, 1897; Gadja, 1958; Brochu, 1975), and (iii) to assess the relative importance of the different physical processes.

The dependence of the depth of the holes on their position on Sermikavsak is indicated by the smooth curve in Figure 1. The mean depths of holes with surface diameters in the range 1–2 cm, 2–3 cm, etc., were determined at different positions; the holes with diameters less than 1 cm were not readily measurable. The positions have been marked in Figure 1 on a profile of Sermikavsak, derived from the Geodetisk Institut map 1 : 50 000 : 71V1; their altitudes and distances along the glacier are given on the vertical and horizontal scales: the front lies at about 50 m and the firn line at about 1 200 m. At any position, the extreme mean depth values are indicated by the length of a vertical line, while the diameters are marked by horizontal bars. The average depth for all the holes and their location on the glacier have been shown with the same symbol. Measurements denoted by the same symbol were taken on the same day. The standard deviation of the average depth, which is less than the length of the vertical line, was found to increase on going up the glacier.

Measurements of the depths on the ice sheet at lat. 76° 34′ N., long. 68° 15′ W. near Thule by Gajda (1958) and on the Gillman Glacier, Ellesmere Island, at lat. 82° 08′ N., long. 71° 00′ W. by Brochu (1975) are included in Figure 1 for comparison, and the positions have been plotted on suitable distance scales. Gajda made his measurements close to the boundary of the ice sheet at about 400 m,

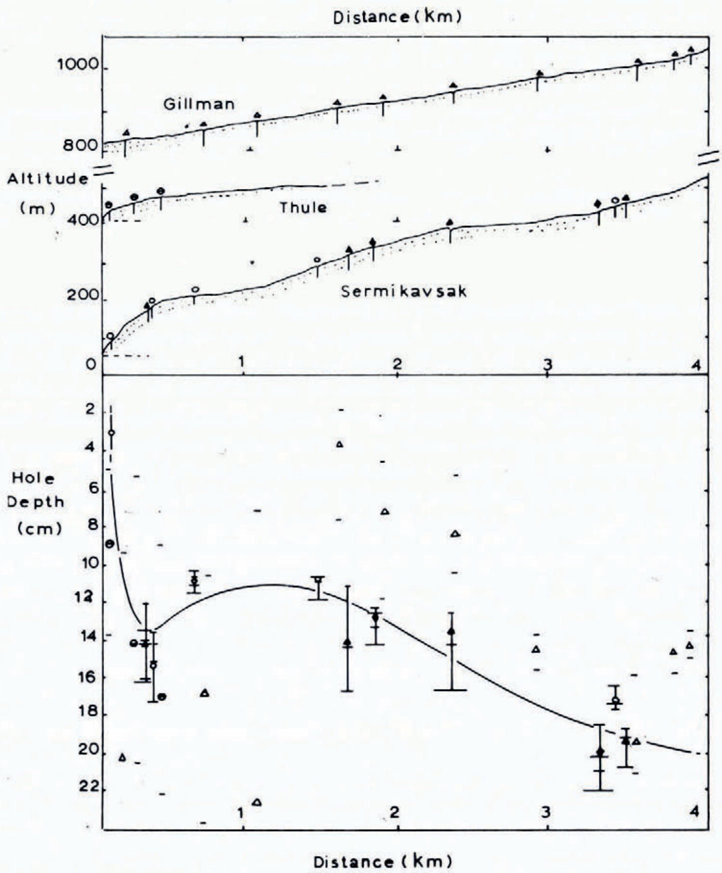

Fig. 1. The dependence of depths of cryoconite holes on their position on Sermikavsak. The symbols and error lines are explained in the text; measurements on Gillman Glacier and near Thule Glacier are included for comparison. The profiles and the positions of the holes on the three glaciers are shown in the upper part of the figure.

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and Brochu worked close to the longitudinal axis of the Gillman Glacier at positions lower than the firn line at 1 200 m and at a distance of about 12 km from the front at 440 m. For each of their positions, the mean depth is indicated by the appropriate symbol and the extreme values for the minimum and maximum depths by the depth-limit bars.

The depth of the holes showed an increase in depth with the distance up the glacier. On all three glaciers the variation in depth was greater than could be accounted for by differences in surface ablation: for example, in the Thule measurements there were marked variations of depth within a distance of less than 0.5 km under conditions where ablation must have been nearly constant, while, on Sermikavsak at 180 m, a large increase in surface ablation was found to result in only a slight deepening of a selected set of holes. It was found on Sermikavsak that although the depth tended to increase with the hole diameter, there was no significant influence on depth of changes in the hole diameter. It was found also that there were (i) greater variations in the depth of the individual holes, (ii) an increase in the proportion of holes with larger rather than smaller diameter, and (iii) a decrease in the total number of holes per unit area in going up the glacier.

The cryoconite holes tended to occur in highly weathered ice which had developed into a permeable honeycomb structure and was riddled with small narrow vertical holes and interlinking channels. This form of weathered ice was common above the steep slopes at the snout and it enabled these low-altitude holes to have greater depths than those further up the glacier. An accurate comparison of the heat input needed to produce a hole of a certain depth at a given position should allow for the variations in the surface-structure density along the glacier. At positions close to the snout in the region of high ablation, the development of the cryoconite holes was either prevented by the existence of bare ice surfaces without the permeable layer suprastructure or restricted by a continuous flow of melt water within the thin surface layer so that the silt was carried downhill. The larger depths at lower altitudes on both Thule and Gillman ice must have been due to similarly structured surface layers. Because there are always variations of surface structure from one place to another on a glacier, our measurements were taken on visually similar, dirty, white ice patches, each of area several square metres and situated on slight hummocks or ridges. The ice was more compact in the upper section of Sermikavsak and the maximum hole depths of *c.* 20 cm were similar to those measured by Brochu. They were less than the depths of *c.* 40–50 cm measured both at lat. 70° N. by Drygalski and at lat. 76° N. by Gerdel and Drouet. However the hole depths at lat. 76° N. were measured in the soaked zone close to the firn line, where the firn structure was very different from that of the superimposed ice of Sermikavsak: this may account for the differences in the depths at the two glaciers.

The initial formation of a hole needs a supply of poorly sorted, fine-grained, black dust with median size about 0.18 mm (Thurman, unpublished) that has been transported by melt-water percolation and flow and has accumulated within the interstices in coarse-grained superimposed ice. Our measurements on the local fluctuating water table showed that holes were linked and could extend to bare ice at the base of the surface water table. This facilitates the passage and flow of melt-water within small-scale topographical ridge-like features of the glacier surface. There does not appear to be any physical significance in either the magnitude of the diameters or the number of the holes per unit area other than the availability of an adequate silt supply.

The relative importance of the different physical processes may be estimated by considering the heat balance first at the surface and then at the bottom of a cryoconite hole. There is a heat balance at the surface when the energy flux gained at the surface from the absorption of the visible or short-wavelength solar radiation balance $(RB)_S$ and from the transfer of sensible heat Q from the air is equal to the energy flux lost at the surface due to the infrared or long-wavelength radiation balance $(RB)_L$ into the atmosphere, the ablational melting M of ice, the latent heat loss L due to surface evaporation, and the heat conduction B into the underlying ice.

On 18–21 July 1977, in stable weather conditions with a clear sunny sky and with occasional gravitational winds coming down the glacier, about 80% of the heat input came from energy flux of the solar radiation $(RB)_S$ balance (Kuhlman, 1959), and 20% came from the sensible heat Q transferred by turbulence from the warm air close to the surface. We will consider some approximate daily surface-energy input values in order to discuss the magnitude of the different processes in the cryoconite holes on Sermikavsak. Our values were either measured or estimated by considering the values for some other comparable glaciers that have been comprehensively listed by Lliboutry (1964–65) and Paterson (1969). Our measured average daily energy input for surface-ice melting M and evaporation L was 360 ± 40 cal cm^{-2} d^{-1} (15 ± 2 MJ m^{-2} d^{-1}), with the minimum and maximum values being 240 cal cm^{-2} d^{-1}

(10 MJ m^{-2} d^{-1}) and 460 cal cm^{-2} d^{-1} (19 MJ m^{-2} d^{-1}) (Thurman, unpublished). This average value represents about 70% of the total energy utilized at the surface. It was obtained from the lowering of the surface at fixed stakes placed at 212 m. The estimated long-wavelength radiation balance due to the exchange of the infrared radiation between the ice and the atmosphere was $(RB)_L \approx 100$ cal cm^{-2} d^{-1} (4 MJ m^{-2} d^{-1}); the estimated latent heat loss $L \approx 50$ cal cm^{-2} d^{-1} (2 MJ cm^{-2} d^{-1}), an energy loss being assumed because during the summer melt period evaporation was much greater than condensation; the thermal-conduction energy loss B was negligible. It was assumed that the dirty surface ice at its melting point had an emissivity $\epsilon \approx 0.9$ and that it radiated $G_0 \approx 590$ cal cm^{-2} d^{-1} (25 MJ m^{-2} d^{-1}), so that the downward diffuse infrared radiation reaching the surface $G_a = G_0 - (RB)_L \approx 490$ cal cm^{-2} d^{-1} (20 MJ m^{-2} d^{-1}). The short-wavelength radiation penetrated into the ice; the long-wavelength radiation G_a was absorbed close to the surface.

In the cryoconite layer at the bottom of a hole a heat-balance equation no longer contains the sensible Q and latent-heat L terms, and it can be written approximately as

$$(1-\alpha)\, S \exp(-kz) + f\, G_a + M = 0.$$

In this equation, the first term is the $(RB)_S$ balance. It is expressed as the visible-radiation balance transmitted obliquely through the ice. It is absorbed according to a Bouger–Lambert Law. This means that a fraction $(1-\alpha)$ of the incident radiation energy S is transmitted into the ice and is then attenuated exponentially with distance z in the ice; α is the albedo or mean reflectance, and k is the bulk extinction coefficient of the ice. The second term is the fraction f of the absorbed energy G_a transferred to the ice by a process such as convectional mixing in the water in the hole. Direct infrared radiation does not reach the bottom of the hole, because in water only an energy flux of $0.02\, G_a$ is transmitted further than 10 cm in the 0.9–3.0 μm wavelength range and none is transmitted at longer wavelengths (Geiger, 1961). To determine the energy input accurately, it would be necessary to consider how z changes with the position of the sun in the sky, and would also be necessary to know how α and k depend on wavelength (Mellor, 1977) and on how multiple scattering of radiation and its absorption vary with z (Barkstrom, 1972). The energy flux at a depth z is also caused by the diffusely-scattered upward radiation as well as from the dominant downward radiation coming from the surface: their relative proportions can be as high as 40 : 60 in polar firn (Liljequist, 1956). Our estimate of the energy input from all directions to the cryoconite layer has been made (i) by assuming some optimistic average values of $\alpha \leqslant 0.3$ and $k \leqslant 0.05$ cm^{-1}, (ii) by considering the relative proportions of the upward and downward flux, and (iii) by estimating that a direct-radiation fraction $0.7S$ traversed on average an ice thickness $z \geqslant 30$ cm and that a diffusely scattered sunlight fraction $0.3S$ went on average a distance $z \geqslant 10$ cm inside the hole before reaching the bottom. With the total visible solar radiation input $S \approx 550$ cal cm^{-2} d^{-1} (23 MJ m^{-2} d^{-1}) in mid-July at lat. 71° N. (from Lliboutry, 1964–65, fig. 93), our estimate is that the net radiation energy input available for melting the ice was about 200 cal cm^{-2} d^{-1} (8 MJ m^{-2} d^{-1}). This energy input is significantly less than $M+L \approx 360$ cal cm^{-2} d^{-1} (15 MJ m^{-2} d^{-1}) necessary for melting and evaporation. An additional energy input of about 160 cal cm^{-2} d^{-1} (7 MJ m^{-2} d^{-1}) has to come from another heat source, and this, for example, could be the absorption of the G_a flux to give warm, dense surface water that circulates downwards inside the hole. This additional energy input represents about one-third of the G_a surface flux. In partially water-filled or empty holes G_a can penetrate to the water level or the bottom of the hole by diffuse reflection off the side walls. We consider that there was a decreasing G_a flux with distance down a hole from our observations of the steepening wall profiles for holes with circular cross-section above the water level and of the constant hole diameters below the water surface where thermal mixing was complete. We conclude that there was an energy contribution from diffuse infrared radiation transferred by convectional processes in the water. This brief analysis has been made to point out the absence of accurate, relevant data on the equilibrium conditions for the existence of cryoconite holes.

Our measurements depend on the magnitudes of the different energy inputs. We have pointed out that the equilibrium hole depths on Sermikavsak, Thule, and Gillman Glacier all showed an increase in depth on going up the glaciers. If it is assumed that the effect of convectional heating remains constant, then an increase in depth can be attributed to a decrease in the surface albedo α or the bulk extinction coefficient k. These mutually dependent parameters depend on factors such as the ice grain size and shape, the air-bubble number density, the dimensions of intergranular spaces, and the relative proportions of air and water in the veins and channels.

Further systematic studies of the statistical behaviour of cryoconite holes in conjunction with measurements of the radiation balances and the structure of the surface ice layers are needed to clarify the influence of the different physical processes. Their short-term behaviour should show a response to daily variations of the energy input. It would therefore be useful to investigate the growth and the development of the depths and the profiles of the holes over a prolonged time during the ablation season on a glacier.

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