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Temperature distribution of Collins Ice Cap, King George Island, Antarctica

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Abstract Temperature measurements in boreholes show that ice is of temperate state in accumulation area and of cold state in ablation area in Collins Ice Cap. Ice temperature of active layer is significantly influenced by seasonal variations of air temperature. The warming of ice by the melt water infiltration is remarkable. Snow cover also noticeably affects thermal regimes of the Collins Ice Cap. The measurements also reveal that temperature below the active layer is approximate to the melting point in the majority of the glacier except in the vicinity of the Little Dome , where ice temperature varies sharply within a surface distance of more than 10 metres. Significant water oozing from ice cores was observed at a depth of 30 m during the drilling near the Little Dome, which is probably caused by the combined effects such as internal runoffs, differential movement and high salinity of the glacier.

Key words Collins Ice Cap, temperature, warm infiltration.

1 Introduction

Temperature distribution results from the interactions of many internal and external processes of glaciers and casts important influences on many glacial processes in the meantime. It is very important for inclusive and thorough study of glacier to understand the distribution of temperature field.

Many measurements and observations on glacier temperatures have been carried out by Chinese glaciologists in King George Island and adjacent areas in Antarctica (Ren, 1988, 1990). Although temperature measurement sites were fixed in both accumulation and ablation areas, the previous temperature data were obtained only in limited elevations and depths and only in summer. Based on these works, many inferences have been made, e. g., the ice temperature is -5.13 ± 0.86 C at a depth of 10 m in the Great

Dome of Collins Ice Cap; the temperature at the ice-rock interface is below 0℃ and the glacier at bed is frozen together with the bedrock (Ren, 1990).

Ice core drilling were carried out in a quite large scale in Collins Ice Cap in 1991/1992, which provided an opportunity to study temperature distribution of the glaciers in King George Island. Boreholes installed with thermistors are distributed mainly from the terminal of glacier to the Great Dome along the principal ridge which bestrides both ablation area and accumulation area (Fig. 1). The elevation difference between two adjecent boreholes is about 100 m. The temperature fields in boreholes recovered quickly because the thermistors were fixed at given depths in boreholes drilled by an electronically powered mechanic driller. Most boreholes with thermistors are more than 25 m in depth; some of them stretch to the underlying water layers. Hence, a full understanding of temperature variation from active layer to water layers (close to melting points) is acquired in the expedition in 1991/1992. In addition, continuous measurements of temperature had been undertaken for nearly half a year at several boreholes with lower elevations(Table. 1). The paper only sums up and primarily analyses the obtained data. Comprehensive mathematical simulation of temperature distribution and its changes in the glacier will be undertaken in another paper.

Table 1. Borehole distribution and relevant data in Collins Ice Cap

Boreholes	Elevation (m a. s. l.)	Max. depth of measurement (m)	Data duration	notes
BDT	702	32.5	Dec. 13～Dec. 18,1991	
BDA	610	15	Oct. 12,1992	
BDB	510	12.5	Oct. 12,1992	
BDC	380	12.5	Oct. 20,1992	
SD6	252	30.0	May 15～Nov. 3,1992	*
SD8	180	25.0	May 23～Nov. 7,1992	
SD9	110	25.0	June 3～Nov. 8,1992	

* Temperature −0.65℃ was observed at the depth of about 50 m on the same elevation in another boreholes.

2 Installation of thermistors and measurements

The instrument for glacier temperature measurements in the Collins Ice Cap is the SBJ-3 resistance thermometer with multi-thermistors made in the Lanzhou Institute of Glaciology and Geocryology, Academia Sinica. The thermometer has a precision of 0.1℃. Before the installation, the thermometers were rectified with water-snow mixed liquid (0℃) to preclude instrumental error made by using thermistors with the lapse of time.

The first thermistor was fixed on the snow (or ice) surface, indicating zero in depth, the second thermistor at a profile is fixed at a depth of 1 m from the surface. In order to avoid the depth error due to the crooking of wires, all wires in one borehole were girded indoors and a proper heavy object was tied under the bundle of thermistors when it

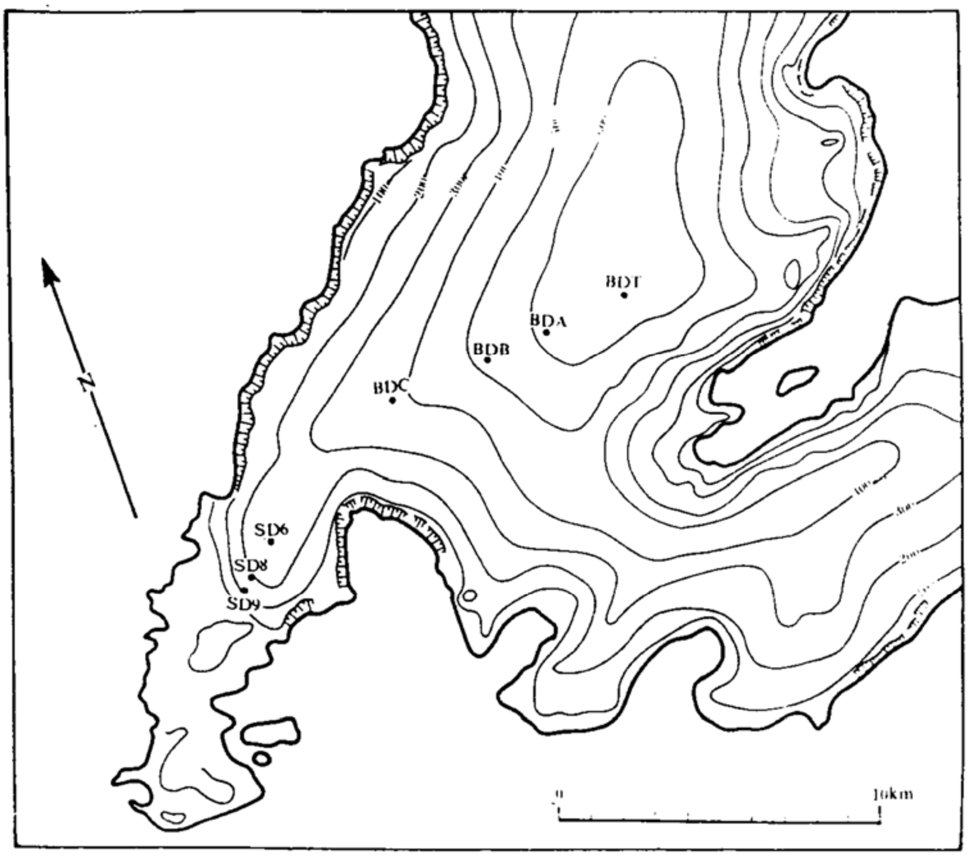

Fig. 1. Distribution of boreholes for temperature measurements in Collins Ice Cap.

was lowered into a borehole. The mouths of the boreholes were covered with plastic bags filled with snow to prevent air convection in boreholes. The reading of the thermometer can be made 2 to 3 hours after fixation. However, the temperature is generally read 24 hours after to ensure that the reading represents the real condition in boreholes. The temperature at a given depth was read 3 times. The average of the three figure (approximating to 0.1°C) is considered to be reliable temperature of ice or snow.

Quartz crystal thermometer made in the Lanzhou Institute of Glaciology and Geocryology, Academia Sinica was used to measure the temperatures at a depth deeper than 30 m below the glacier surface on supplementary sites. The thermometer can be used in a stable state 40 minutes after installation. Its precision is 0.01°C.

3 Ice temperature of active layers

Ice temperature in the upper layer about 15 m in thickness is affected by seasonal variations of surface air temperature. The layer is called the active layer of glacier. In comparatively low latitudes, ablation is severe on glacier surface in summer. Thermal regimes of active layer and even deep layer change greatly in the mass-heat transfer processes caused by melt water permeation downward. Our result of glacier temperature measurements in Collins Ice Cap, King George Island reveals the same phenomenon as that in low latitude.

3.1 *Spatial temperature variation of active layer in early summer*

Temperature profile of ice layers in the upper 15 m is shown in Fig. 2 based on the measured data of early austral summer in 1992 (but the data at site BDT were measured in the same season of 1991). Among those sites, SD9 is located in ablation area, and the others in accumulation area. The thermal regimes of glacier surface then remain almost the same as that in winter because: (1) the surface mean air temperature is negative and only slight surface melting occurs; (2) warm waves spread only to as deep as 1 m in ablation area in low elevations, and ice layers under 2.5 m in accumulation area in high elevations have not been influenced by meltwater infiltration. The temperatures of the layers with depths from 8 to 15 m below glacier surface vary slightly with the altitudes, which is close to 0℃ except in ablation area and the Little Dome (SD6, 252 m a.s.l.), where the temperature of about −1℃ is observed. This can be explained by the variation of snow cover with altitudes and infiltration in the previous year. In ablation area and the Little Dome, the bottom of active layer can remain in a cold state because latent heat of melting loses with runoff above the impermeable ice layer where snow (firn) cover is pretty thin. Temperature at 180 m a.s.l. and above 380 m a.s.l. can reach to 0℃ because of the strong meltwater infiltration in thick snow cover there (Wen *et al.*, 1994). The negative temperature observed on the bottom of active layer at the peak of the Great Dome with a firn layer of more than 30 m may be explained by that winter cold waves can freeze up liquid water in firn of active layers, which may be due to limited water infiltration in the previous year.

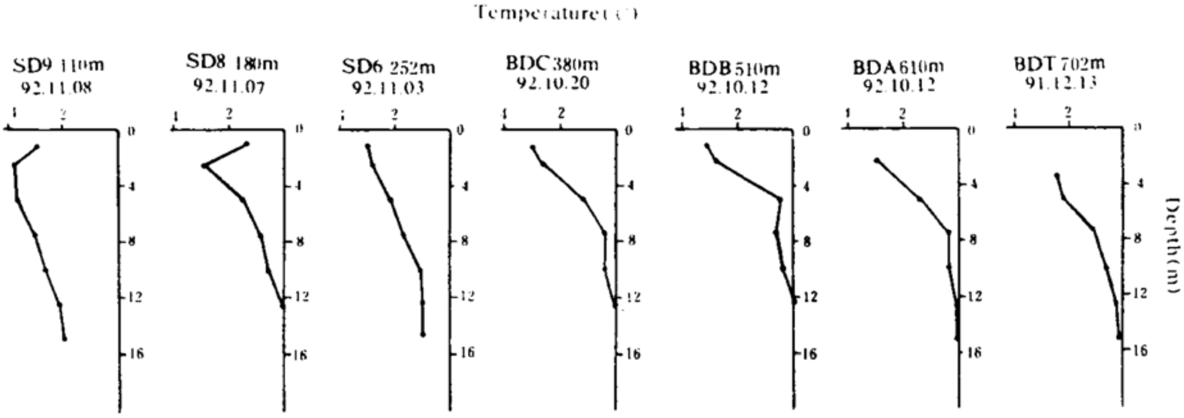

Fig. 2. Temperature-depth profiles of active layer in early summer in Collins Ice Cap.

3.2 *Temporal temperature variation of active layer from winter to early summer*

From temporal variation of active layer in early summer, three types of ice temperature profiles in the Collins Ice Cap can be clarified: that of ablation area, middle and low infiltration zones of accumulation area. The latter two differs from each other mainly in that the firn cover is very thick in the middle infiltration zone, which is no less than a quater of the thickness of active layer; whereas infiltration zone it is comparatively thinner and is underlain by a thick impermeable ice layer. The collected data in the three lowest sites (Fig. 1) represent the three types of ice temperature distribution. The temperature curves at those sites which reflect variations from mid-May to early November of 1992 (Fig. 3) share the following common characteristics:

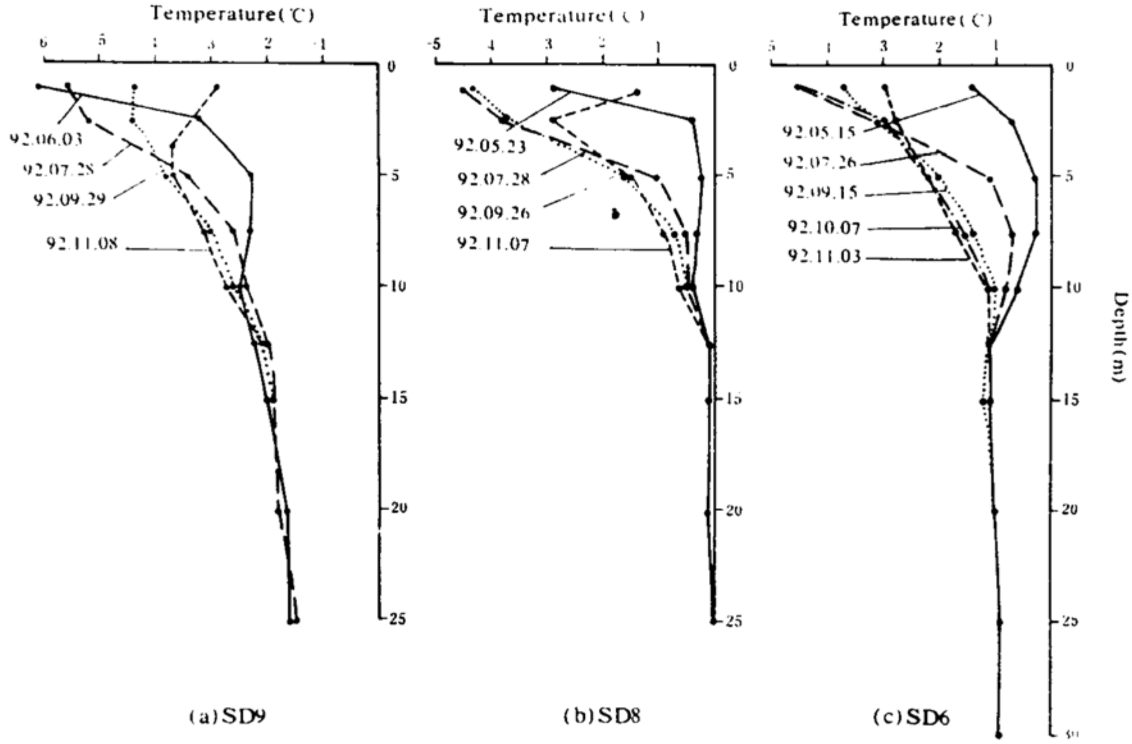

Fig. 3. Measured temperature—depth curves of the site SD9 (a), SD8(b) and SD6(c) from May to November of 1992.

(1) Seasonal fluctuations curves from right to left, then to right again reveal two temperature alternations from early winter to early summer: the temperature decreases first and increases afterwards. It also proves that although summer water seepage can greatly influence temperature distribution of active layer, ice temperature is still predominantly controlled by seasonal variations of air temperature at different altitudes in a whole year.

(2) The amplitude of temperature change dwindles with depth. When the meltwater percolating downward into snow layer is frozen up in winter, heat variations and snow-ice temperatures either in ablation or in accumulation area are foundamentally controlled again by the one dimension Fourier Equation of heat conduction as the surface air temperature varies seasonally. This is in accord with the analytical solution of the equation, which indicates that ice temperature fluctuations dwindle downward. As shown in Fig. 3. the fluctuation range of ice temperature in Collins Ice Cap is about 4 K at the depth of 1 m, and less than 1 K at the depth of 10 m, while the temperature changes at

15 m can be hardly dete[illegible] of 15 m.

Some pecularities in the three temperature curves can also be observed in Fig. 3:

(1)The fluctuations of surface temperature penetrate deeper in ablation area than in accumulation area. The seasonal variations of surface temperature can reach to the bottom of active layer with dwindled amplitudes generally. For example, the maximum surface ice temperature occurring at site SD9 in mid-summer spreads to the bottom of active layer in mid-July, the annual amplitude of ice temperature is about 0.2℃ at the depth of 15 m . However, in the whole active layer the ice temperature reaches to 0℃ in accumulation area at the end of summer. The "warm" condition will remain for a stretch of time after the end of summer or even until all water in snow layer is frozen up. Thus temperature distribution of the snow-ice layers can be described by the equations of one dimension conduction without phase changes. In addition, snow cover delays the downward spreading of "cold waves" after the summer, the fluctuation of winter temperature can not reach to the "real" boundary of active layer before next warmer season. This also raises the lower boundary of active layer in accumulation area, which is comparatively shallower than that in ablation area. As shown in Fig. 3, the lower boundary of all sites in accumulation area is about 12.5 m in depth, whereas that in ablation area is about 15 m.

(2) For the same reason as discussed above, the dissemination of warm waves into deep layers can not be observed in accumulation area, whereas the left-right-left sway of temperature curves at SD9 indicates the fluctuations of ice temperature from cold to warm and then to cold again.

(3) On the whole, the temperature curvic form of active layer is symmetrical in ablation area , but unsymmetrical in accumulation area. Besides, in accumulation area, summer ice temperature of active layer can reach to , but not exceed 0℃; winter ice temperature is much lower than 0 C due to the influence of cold air temperature. Hence the curves at SD8 are noticeably leaning leftward in Fig. 3. In ablation area, however, summer surface ice temperature can reach to 0℃, the straight lines from the point of 0℃ on ice surface to the temperature of the lower boundary of active layer roughly represent the ice tempesature curves at the end of summer. The curves of ice temperature at SD9 in ablation area are almost symmetrical on the two sides of the vertical line from surface to the lower boundary of active layer. The temperature profile at SD6 shows systematical ice temperature curves as a transitional type between the above two types.

In a word, although the seasonal variations of air temperature and altitudes control the spatial and temporal distribution of ice temperature in temperate glaciers, the upper boundary conditions, i.e. the distribution of surface snow cover, cast very important influence on temperature distribution of the glaciers, such as in the Collins Ice Cap. The mass-heat transfer of the downward percolation of meltwater and the insulation of surface snow cover vary noticeably in different ice formation zones in the Collins Ice Cap. Although ice temperature in accumulation area is wholly higher than that in ablation area in the temperate glaciers, the ice temperature at the lower boundary of active layer is quite different from the local mean annual air temperature.

4 Temperature in deep layers

The ice temperature changes from 25 to 30 m in depth in the profile of Fig. 3 prove the relation of ice temperature from deep layers to the lower bundary of active layer. Heedful observation shows that the temperature gradient in the profile at the site SD9 is noticeably bigger than that at the other two sites. Besides ice temperature of active layer, the factors affecting the ice temperature of deep layers include geothermal heat flux, basal frictional heat (if basal sliding exists) and internal differential movement (Paterson, 1981). The former two only affect ice temperature near the interface of glacier base, whereas the last one is the major mechanism that alters ice temperatures within glaciers. The snowline is at about 140 m a. s. l. in the Collins Ice Cap (Wen *et al.*, 1994). The site SD9 is located in the downstream of the ice cap, where the underlying topography varies sharply in a short distance (Zhu *et al.*, 1994), indicating the strong differential movement here which will make the ice temperature increasing downward. And also due to its location, the mass with high ice temperaure in accumulation area, which is transported from the upstream, will reappear under the comparatively cold active layers of the ablation area. So it is reasonable that ice temperature near the bottom of the glacier at SD9 goes much quicker to melting point. The site SD6 on the top of the Little Dome, where the annual ice movement is rather slow (0. 385 m/a, cf. about 5 m/a near the snowlines) and no "warm" ice can reach there, so the temperature gradient is pretty small. As a matter of fact, the measurements in another borehole at the distance of about 20 m from the SD6 reveal that ice temperature is −0. 65 ℃ at the depth of about 50 m in the Little Dome . Based on the gradient at this site, temperature can not reach to melting point until the base. The site SD8 is located lower than the SD6 in elevation. The ice temperature at the lower boundary of active layer is close to 0℃ in the site. Although glacier movement does not contribute much to ice temperature, it quickens the increasing of ice temperature to the melting point. The wet ice core obtained at about 30 m in depth also indicates that the ice almost reach to the melting point at this depth.

The temperature of deep layers in the Great Dome at 702 m a. s. l. can be approximately estimated from Fig. 2. As a matter of fact, ice temperature below lower boundary of active layer rises up with depths, which is measured to be −0. 1 C at 33 m. While drilling downward, wet ice crumbs were observed at 42 m, ice cores with water seeping in the ends appeared at 45 m and water content increased noticeably at about 50 m. The lowest part of the borehole was filled with water in the next day after drilling. Uniform echo wave in the depth of about 50 m under the Great Dome can be observed during radar sounding, indicating an aquifer with a quite large area, i. e. the temperature under the ice layer reaches to melting point. This is significantly different from the estimation of ice temperature under the Great Dome by Ren (1990).

Water oozing in boreholes is a very significant phenomenon in the Collins Ice Cap. Ice cores 82 m in maxiamum length are obtained on the top of the Little Dome in the ice cap. The depth of water oozing varies greatly in the 6 boreholes with the surface distance of less than 30 m . It is 32. 2, 51. 0 and 80. 2 m in three boreholes respectively. However, no water oozing is observed in the other three boreholes. It is worth noticing that temperatures read at the depth of about one meter from water oozing in the former two boreholes are −0.8 C and −0.65 C respectively. It is reasonable to conclude that "supercooled water" or "liquid inclusion" with lower temperature is present in ice layers and that liquid water varies in boreholes not from ice temperature approximating to 0. ℃.

Temperate ice is a complex material consisting of ice, water, air bubbles, salt and carbon dioxide. The glacier temperature in deep layers approximates to melting point due to the heat conduction of "warm" active layer, especially that with thick snow cover. This makes the temperature go far more quickly to melting point under the combined effects of several factors, in particular, pressure exerted on ice and impurities in ice. Preliminary snow-ice chemical analysis of the Collins Ice Cap (Han *et al.*, 1993) indicates a rich content of salt in the snow-ice samples obtained in this region. It is estimated that ice temperature reaches to 0.01 C at the ice equivalent depth of less than 30 m because of the effect of salt. Harrison(1972) pointed out , the effective specific heat of ice is 100 times that of pure water when the temperature of ice with a typical salt content is −0.01℃. When heat is acquired, it will be used to melt ice rather than to raise temperature of ice in this condition (Paterson, 1981). In addition, water with high salinity can exist in form of stable super-cooled water even in quite low temperature. This explains well why aquifers appear in comparatively shallow depth (e.g. at about 45 m in the Great Dome).

It is noticed that most water oozing occurs below 30 m in depth in the Little Dome. At Little Dome, ice crevasses are quite well developed. Theoretically, the depth which crevasses can reach to is generally about 30 m. So, it is of great possibility that some liquid water is formed by the internal glacier runoff along these crevasses. Quite strong ablation is observed on the top of the Little Dome in summer. The stored water will convergently stream into depressions along the cracks after the meltwater percolates downward to the bottom of the firn layers. Hence water will store up in these caves or hollows. When autumn comes and snow cover is formed, unfrozen water will be saved in liquid form, which can not freeze up all the unfrozen water into ice due to the high glacier temperature. The presence of the water will influence the ice temperature nearby, but its influence is quite limited. So the temperature is still negative in the vicinity of the "liquid inclusion" or "pockets of water".

5 Conclusions

The measurements of ice temperature in the Collins Ice Cap shows that glacier ice is of temperate state in most parts of the accumulation area, whereas it is possibly of cold state in entire ablation area. Spatial variations of ice temperature is dramatic on the top of the Little Dome. Although seasonal variations of air temperature control the ice temperature of active layer in the Collins Ice Cap, the heat insulation of surface snow cover and the percolation of summer meltwater affect ice temperature, especially that of active layer. Significantly, due to their influences, the temperature distribution of the Collins Ice Cap shows several different characteristics from that of cold glaciers. Spatially, the temperature and its gradients in the upper part of active layer change little with the elevation in accumulation area in early summer; the depth of the lower boundary of active layer is shallower in accumulation area than that in ablation area; ice temperature curves and temperature in the lower boundary vary with observation sites in different ice formation zones. Temporally, in deep layers of accumulation area only a single of dropping in temperature can be observed in winter; the temperature-depth curves of seasonal variations in accumulation area are unsymmetrical. The temperature distribution of deep layers in the Collins Ice Cap shows that heat produced by the differential movement and downstreaming transportation of "warmer" ice raise ice temperatures in ablation area. However ,the fact that temperature reaches to melting point in a shallow depth in accumulation area as in the Great Dome shows that air bubble and impurities in glacier ice play an important role in temperature distribution of temperate glaciers.

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