THE RISE OF SNOW TEMPERATURES CAUSED BY THE SEWAGE DISPOSAL, MIZUHO STATION, ANTARCTICA

Masayoshi NAKAWO

Department of Applied Physics, Faculty of Engineering, Hokkaido University, Kita-13, Nishi-8, Kita-ku, Sapporo 060

Abstract: Measurements of snow temperature distribution indicated that the temperature was considerably higher in the vicinity of the station than in the natural snow layers far from it. It was considered that the temperature rise was caused by the human activities at the station, in particular by the sewage discharge into the surface snow layer. A simple calculation of the temperature rise was compatible with the field data on the temperature distribution around the station. Vertical profiles of the snow temperature, obtained through shallow/medium depth boreholes, were discussed in terms of the artificial temperature rise.

1. Introduction

For studying the dynamics of an ice sheet, the three-dimensional distribution of temperature is the information of great importance, since the mechanical properties of ice are much dependent on temperature (*e.g.* PATERSON, 1980). The past variation of surface temperature can be derived also from the present variation of ice temperature with depth (*e.g.* RITZ *et al.*, 1982). At various sites on ice sheets, therefore, vertical profiles of temperature have been measured intensively, utilizing drill-holes (*e.g.* GOW *et al.*, 1968; GUNDESTRUP and HANSEN, 1984).

At Mizuho Station, East Antarctica, three shallow holes were bored, in a depth range of 75 to 147.5 m, by the Japanese Antarctic Research Expedition (JARE) in 1971, 1972 and 1975 (SUZUKI and TAKIZAWA, 1978). YAMADA (1975), FUJII (1978) and WATANABE (personal communication) made measurements of temperature profiles, using the respective drill-holes. In 1982, a five-year glaciological research program in East Queen Maud Land was started, in which drillings at Mizuho Station were again performed: JARE-23 made a hole of 90 m deep in 1982 by a mechanical drill, and JARE-24 achieved a depth of 413.5 m in 1983 by a thermal drill. Vertical profiles of temperature were obtained with those boreholes.

The drill sites, however, were not far from the housing facilities of the station, where various human activities were centralized such as cooking, bathing, generating electricity, etc. A question arose, hence, whether the measured temperature profiles along the boreholes were not affected by those activities, since they produced significant amount of heat. It is important to assess the influence of the artificial perturbation for analyzing the temperature data.

2. Snow Temperature Distribution

2.1. *Mizuho Station*

The station, opened in 1970, is located at 70°42′S, 44°20′E, and 2230 m in elevation. Various facilities are aligned from north to south, extending approximately orthogonal to the direction of the prevailing wind (E). The facilities can be divided into two: the northern and southern halves were established and in major use before and after 1975 respectively.

At the very beginning, a few facilities were above the snow surface at that time. A corrugated pipe house set up in 1970, and a residential hut built in 1971 were the examples. Because of a large amount of drifted snow, however, they were buried with snow in a few years and became underground facilities, although the annual net accumulation was only about 70 kg m^{-2} at the station (NARITA and MAENO, 1979). After 1975, all facilities have been prepared underground. In 1983 existed a total of five huts connected by many passages. More than 20 rooms had been excavated from the passages for various use: many storages for foods, equipments, mechanical and electrical parts, core samples, etc., laboratory space, generator rooms and so on. Their floor levels, including those of the housing, was at depths from 3.5 to 5.5 m below the snow surface in 1983.

2.2. *Temperature distribution*

The snow temperature varies with time depending upon the time variation of the ambient temperature, such as cyclic daily or seasonal variations. With increasing depth, however, the amplitude of those cyclic variations decreases rapidly, and becomes about ± 0.1°C around depths of 0.5 and 10 m for daily and seasonal variations respectively.

Utilizing the passages and the rooms excavated in the surface snow layer, the horizontal distribution of snow temperature was measured by inserting a thermister sensor into a 1 m deep drill-holes at about 30 sites in the station. Snow temperatures were thus obtained at a depth of 1 m below the floors of the passages or the rooms so that the daily variation of the ambient temperature, which can be caused partly by human activities, would essentially be attenuated. Since the floor levels were in a range of 3.5 to 5.5 m from the top snow surface, the measured temperatures represented those at depths from 4.5 to 6.5 m below the surface.

The temperatures at these depths, however, are still affected by the seasonal variation of the ambient temperature, *i.e.* the snow temperature at a certain depth varies with an annual cycle and is dependent on the season of the measurements in a year. The measurements were made in the winter season, on 9th and 11th of August 1983, when the temperature profile with depth in the surface snow layer was rather stable. Figure 1 shows the profiles on the dates of the measurements, which were obtained at a distance of about 70 m from the station so as not to be affected by the human activities at the station. The temperature profiles on the two dates were very similar and considered to represent the natural state, and regarded as the standard temperatures at the respective depths.

The snow temperatures measured at various sites in the station were compared

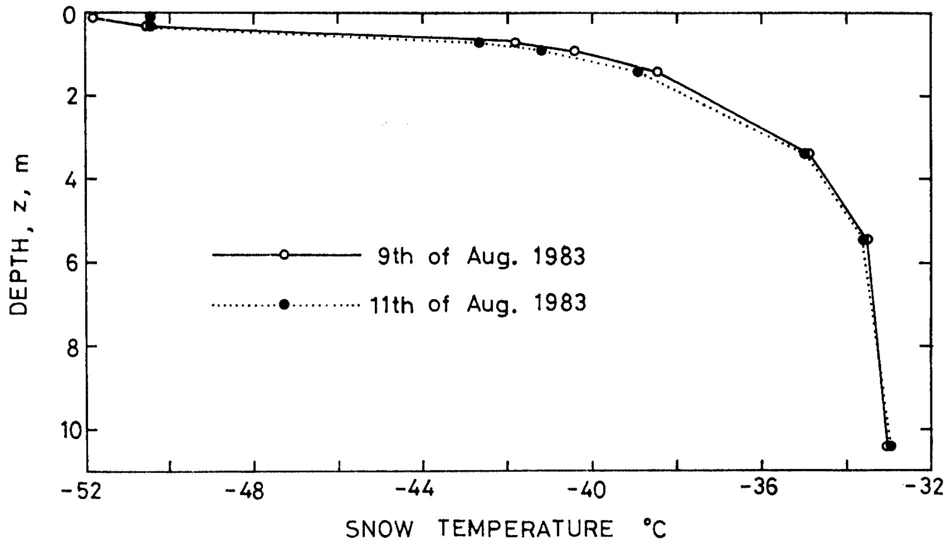

Fig. 1. Vertical profiles of snow temperature in the natural state, at a distance of about 70 m from the main facilities of Mizuho Station. The measurements were made on 9th and 11th of August 1983, when the artificial temperature rise was investigated around the station.

with the standard temperatures at corresponding depths. The differences were considered to be the temperature rise from the natural state, caused by the human activities at the station. The presence of cavities in the snow layer, such as passages or rooms of the station, could also cause the temperature difference from the natural state which, however, is considered less than a degree. The horizontal variation of the amount of the temperature rise is shown by contours in Fig. 2.

Three peaks are noticeable in the horizontal distribution of the temperature rise in the figure. One is at the site of **w4**, where the snow temperature is higher than at the natural place by more than 5°C. The others can be seen at **w6** and between **w2** and **w3**. The temperature rise at the two peaks are as large as about 10°C. The locations of the peaks are apparently identical with those where the sewage water was discharged into the snow layer, rather than with the sites of the electric generators. The rise of the snow temperature, therefore, would perhaps be caused mainly by the sewage disposal at the station.

2.3. Sewage disposal

During an early stage of Mizuho Station, the quantity of the water consumption per capita was as small as 5 kg in a day. The sewage water was frozen mainly outside of the station, and hence the thermal disturbance by the sewage disposal was considered essentially zero. An electric generator of 12 kVA placed at **e1** in Fig. 2 could be the only heat source with the human activities. A bathing facility was set up at **w1**, in 1972, but the sewage water had still been brought outside for freezing. The discharge of the waste water from the bath into the snow layer was initiated by JARE-15 in 1974. Baths were taken, however, only a few times a year (K. SATOW, private communication), and the thermal disturbance would have been perhaps insignificant.

Several major facilities were added in 1976 for a succeeding continuous occupation of the station. Two electric generators were set up at **e2** and **e3**, replacing the generator

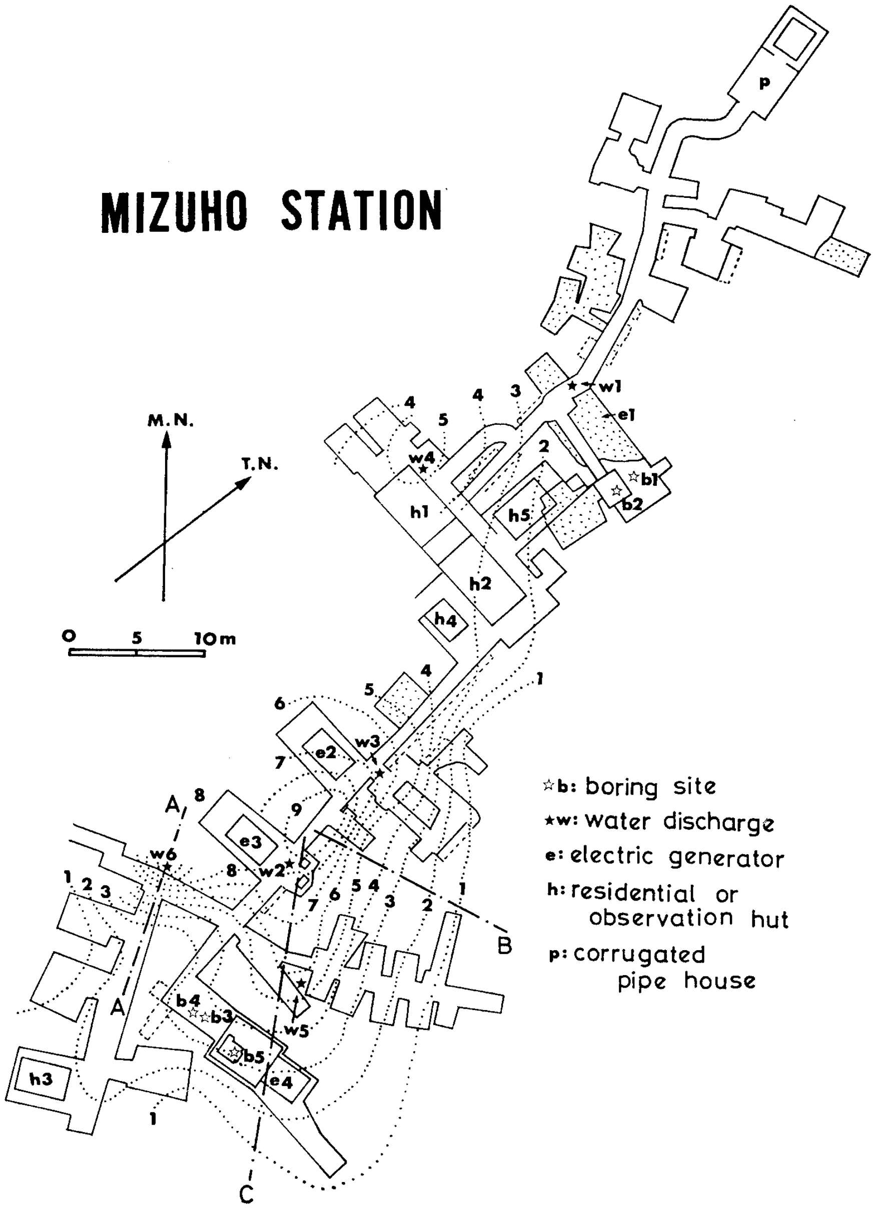

Fig. 2. Horizontal distribution of snow temperature, at a depth in a range of 4.5 to 6.5 m from the surface, around Mizuho Station. Numerical figures with dotted lines indicate the amount of the temperature rise in °C. All the rooms, passages and facilities were underground of the station. Dotted areas show the quarters which were once excavated but buried with snow after certain periods.

at **e**1 which was lost because of a fire in 1975. A system for producing water from ice/snow, which utilized the heat from the generators, was installed at a site between **e**2 and **e**3. A new bath tub was prepared close to the system of the water supply (near **w**2). Owing to those convenient new utilities, the water consumption increased rapidly up to 43 kg per capita for a day in 1976 (KOKURITSU KYOKUCHI KENKYŪJO, 1977). All the waste water was discharged into natural cracks at **w**2/**w**3. It is considered, hence, the significant heat generation in the surface snow layer by the sewage disposal would have taken place since 1976.

A drainage hole was drilled in 1981 at **w4** for discharging the waste water from a kitchen located in **h1**. A continuous use of a crack at **w5** was started also in 1981 as part of the sewage disposal. The utilization of the crack, however, was ended in 1983, because **w5** was so close to a medium depth hole (**b5**), drilled as one of the major activities of JARE-24 in 1983 at the station, that the discharged water could happen to enter into the borehole. Instead, a crack at **w6** was employed for discharging the water from the bath near **w2**.

The quantity of the discharged water into the snow layer was estimated 10 to 50 kg per day at each site, by examining, in 1983, the water consumption for various purposes by the personnel of the station. Taking into account the variation of the number of the personnel from 1976 to 1983, it is considered that about 30 kg day^{-1} of water was discharged at a site into the surface snow layer as a mean for the last 8 years.

The shape of the frozen waste water, which was poured into the snow layer through natural cracks or boreholes, would perhaps be conical (SCHMITT and RODRIGUEZ, 1963). Observations by JARE-22 indicated that the solidification of the water took place at depths of 4 to 5 m and 12 to 13 m below the floor of the station (K. SATOW, private communication). It is considered, therefore, that the water discharged into the snow layer was re-frozen and generated the latent heat at depths of 10 to 20 m below the top snow surface.

3. Calculation

Let us consider a semi-infinite snow, in which the thermal properties are independent of position and temperature. It is assumed, for simplification, that ambient temperature is constant, and equivalent with the temperature at the snow surface, T_0. The cylindrical coordinates (r, θ, z) are employed here, and z is zero at the snow surface, being positive downward. Suppose a point heat source is at $r=0$ and $z=h$, where the heat is generated at a rate of w through the freezing of the discharged water. Namely, the water being assumed at the melting point,

$$w=Ld, \tag{1}$$

where L is the latent heat of freezing (3.3 MJ kg^{-1}) and d is the rate of discharge.

The equation of heat conduction is given by

$$\frac{\partial T}{\partial t}=\frac{\kappa}{r}\left[\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial \theta}\left(\frac{1}{r}\frac{\partial T}{\partial \theta}\right)+\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right)\right], \tag{2}$$

where T, t and κ are the temperature, time, and the thermal diffusivity of snow, respectively. Since the temperature distribution should be symmetric with respect to z-axis, eq. (2) becomes

$$\frac{\partial T}{\partial t}=\kappa\left[\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right]. \tag{3}$$

For the steady state, the heat generated at a rate of w through the freezing of the discharged water has to be released toward the atmosphere at the same rate, and hence

$$w=\int_0^{\infty}\int_0^{2\pi} K\left[\frac{\partial T}{\partial z}\right]_{z=0} r\, d\theta\, dr\,,$$

where K is the thermal conductivity of snow and a value of 0.4 W m^{-1} °C^{-1} is used (*e.g.* MELLOR, 1977) for the subsequent calculations. Equations (1), (3) and (4), and the boundary condition of $T=T_0$ at $z=0$ give the following solution for the steady state condition.

$$T-T_0=\frac{Ld}{4\pi K}\left[\frac{1}{\sqrt{r^2+(h-z)^2}}-\frac{1}{\sqrt{r^2+(h+z)^2}}\right]. \tag{5}$$

Equation (5) is shown in Fig. 3 by isothermal contours on a vertical cross section. It is noted that the snow temperature rises, at depths of 10 to 20 m, by more than 5°C at a horizontal distance from the heat source, r is about 20 m. The rise of about 1°C is expected at such a far distance as more than 40 m from the source.

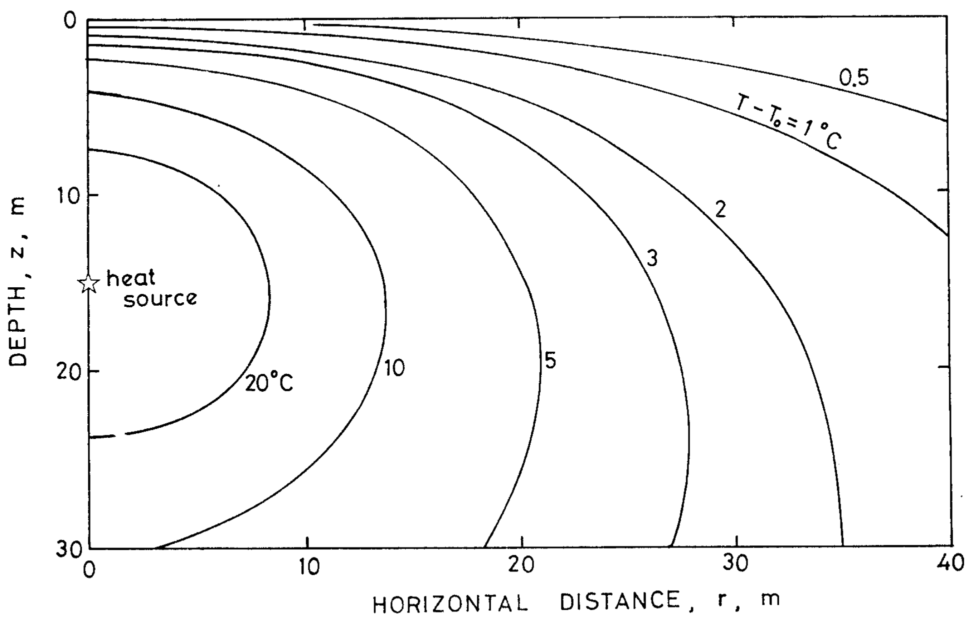

Fig. 3. Distribution of temperature rise $T-T_0$, caused by a point heat source calculated by a steady state model. The calculation was made with the conditions that the heat source is located at a depth of 15 m, and the heat produced by the freezing of discharged water at a rate of 30 kg day^{-1}.

4. Discussion

The calculations by the steady state model are compared with the observations in Fig. 4, where the temperature rise is shown with the horizontal distance from a heat source. The calculations were made using eq. (5) with the conditions that the rate of discharge $d=30$ kg day^{-1}, and the depth of heat source $h=10$, 15 or 20 m. The results are shown by three dotted lines corresponding to the three different values of h. They are the horizontal variation of the temperature rise, $T-T_0$, at a depth of 5 m, approximately the same depth at which the snow temperature distribution was measured around Mizuho Station. The observational results, on the other hand, are shown

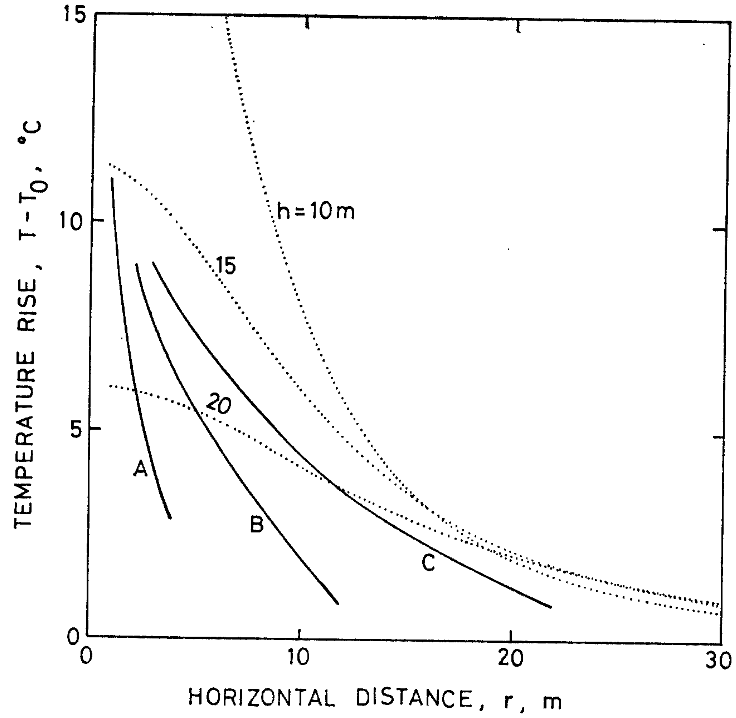

Fig. 4. Temperature rise at a depth of about 5 m against horizontal distance from the heat source. Dotted lines show calculations in which the depth of heat source was assumed 10, 15 and 20 m. Solid lines show the observed decreasing trends of temperature rise as the distance from the heat source increases, which were obtained along lines of corresponding notations shown in Fig. 2.

with solid lines denoted by A, B or C. Line A represents the variation in temperature rise along a line noted by A in Fig. 2, which intersects a peak of w6. Lines B and C are those crossing a peak in between w2 and w3.

The agreement between the calculations and the observations is by no means excellent, but the temperature rise predicted by eq. (5) is approximately of the same order of magnitude as those measured around the station. Also, the decreasing trend of $T-T_0$ with r, predicted by the steady state model, is roughly compatible with the observed one, in case of B or C. They are the observations made along slopes from a peak in temperature rise (Fig. 2) found between w2 and w3, at which the waste water had been discharged since 1976. It would be reasonable to consider that the steady state had been achieved for the 8 years, 1976–1983.

A very sharp drop of $T-T_0$ with r represented by line A in Fig. 3, on the other hand, is not in good accordance with the predictions by eq. (5). Line A shows the temperature rise along a slope from a peak at w6, where the water discharge was started just 3 months before the temperature distribution was measured. It is considered, therefore, that the stationary state had not been achieved yet around the peak at w6. Its slope, hence, could be very sharp, while eq. (5) predicts a gentle slope in the steady state.

General agreement of the prediction with the observation suggests that the horizontal distribution of the temperature rise around the station would be mainly explained in terms of the latent heat generation caused by the sewage disposal in the surface snow layer. On the vertical distribution of temperature also, therefore, eq. (5) would perhaps provide reasonable estimates of the thermal perturbation caused by the sewage disposal.

The steady state model given in the previous section assumed the thermal conductivity K of a constant value, being independent of position. Near the surface of an ice sheet, however, the thermal conductivity increases with depth as the density of snow/ice increases. An assumption of constant thermal conductivity, therefore, would lead to an overestimation in the temperature rise $T-T_0$, in particular at deep depths where K is much larger than the value used in the calculation. None the less, eq. (5) was used for estimating the vertical profiles of $T-T_0$, since it would provide an idea of the order of the magnitude for $T-T_0$, in particular at shallow depths, say above 70 m where the transformation from snow to ice would be completed.

Figure 5 shows the predictions by eq. (5), the vertical profiles of temperature rise, $T-T_0$, at various horizontal distances from a heat source. The temperature rise is large near the heat source, and decreases, at a given depth, as the horizontal distance r increases. At a given distance from the heat source, on the other hand, the temperature rise increases with depth, showing a maximum value at a certain depth, below which the temperature rise decreases with increasing depth. The position of the maximum temperature rise becomes deeper and deeper as r increases, although the amount of the temperature rise decreases at the maximum position. The amount of the temperature rise is surprisingly large. The rise of about 1°C is found at the site where the distance is as large as 50 m. When the thermal conductivity of pure ice is used,

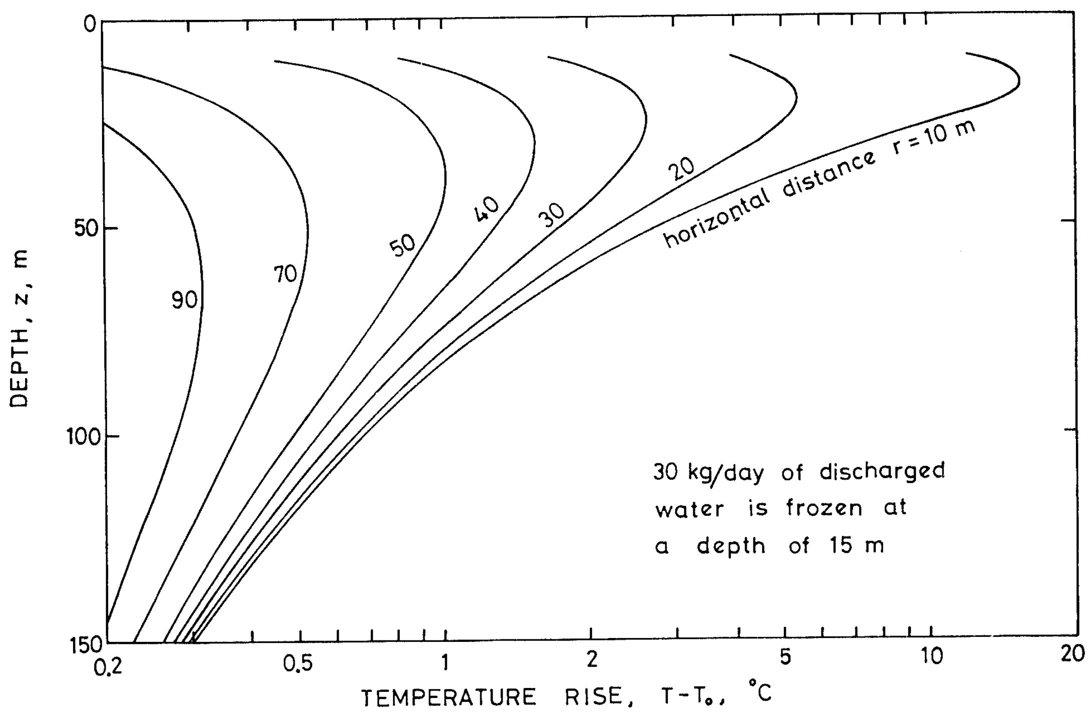

Fig. 5. Vertical plofiles of temperature rise at various distances from the heat source. The calculation was made with an assumption of constant thermal conductivity for 0 to 150 m in depth, which is not realistic. See the text.

which is about ten times larger than the value for snow, the calculation of the temperature rise $T-T_0$ becomes approximately one-tenth of the original calculation shown in Fig. 5. Since K increases with depth from the value for snow near the surface to that for ice at depths below say 100 m, the temperature rise $T-T_0$ would become at least a few tenth of a degree.

NISHIO *et al.* (1981) analyzed the temperature data (FUJII, 1978) taken through a 145 m borehole (**b**2 in Fig. 2) at Mizuho Station. The temperature gradient in the surface snow layer was also calculated theoretically by a model of BUDD *et al.* (1971) with the present data on accumulation rate, flow rate and ice thickness. It was smaller, however, than the gradient of FUJII's data. NISHIO *et al.* explained the difference in terms of the recent climatic warming. FUJII (1978) made the measurements, however, of the snow/ice temperature in 1977, when the significant thermal perturbation had already been taken place at the station after a major renewal of several utilities in 1976, as described in Section 2.3. By the discharge of the waste water at a certain rate for about one year, the temperature distribution in the surface snow layer would have become very close to the stationary state (HIGASHI and MORI, 1984).

The major heat source caused by the sewage discharge was located, in a period of 1976–1977, around **w**2 in Fig. 2 and the horizontal distance between **w**2 and **b**2, where the temperature was measured, was only about 30 m. With this short distance, the temperature rise by the water discharge is 2 to 3°C in the depth range of 10 to 50 m, as can be seen in Fig. 5. Because of the increasing trend of the thermal conductivity of snow with depth, as discussed before, the temperature rise could be smaller than those given in Fig. 2, but not less than several tenth of a degree in the similar depth range. This much of the temperature rise near the surface could also explain the larger temperature gradient observed by FUJII (1978) than the gradient predicted theoretically. It is not certain, at present, whether the gradient was caused only by the artificial perturbation, or by the both: the artificial and the climatic warming. It has to be stressed, in any event, that careful treatments would be necessary for analyzing the temperature data obtained near heat sources in the station.

Other two sets of temperature data are available, measured along boreholes at **b**4 and **b**5 in Fig. 2 (H. OHMAE; H. NARITA, private communication). They were different from one another by about one degree, presumably caused by the difference in drilling technique: the drilling at **b**4 was made by a mechanical drill, while by a thermal drill at **b**5. When the drilling was performed by a thermal drill, the temperature in the drill hole is much higher than the natural state as discussed by NAKAWO (1982). As far as the temperature gradient is concerned, however, the profiles at **b**4 and **b**5 are similar to each other. Their gradients were much larger than that of the profile at **b**2, FUJII's data. The difference can be explained by eq. (5), as shown in Fig. 5, in terms of the difference in horizontal distance r: the drill sites, **b**4 and **b**5 were closer to the position of the water discharge (heat source). For having temperature data of reliance, the drill site has to be far enough from the artificial heat source. Equation (5) would be applicable for rough estimates of the distance, between the drill site and the heat source, which depends on the rate and the depth of the heat generation, and also on the required precision for the temperature determination.

Acknowledgments

The author would like to express his gratitude to Mr. H. OHMAE and Dr. H. NARITA of JARE-23 and -24 respectively for providing him with the unpublished temperature data.

References

BUDD, W. F., JENSSEN, D. and RADOK, U. (1971): Derived physical characteristics of the Antarctic ice sheet. ANARE Interim Rep., Ser. A (IV), **120**, 178p.

FUJII, Y. (1978): Temperature profile in the drilled hole. Mem. Natl Inst. Polar Res., Spec. Issue, **10**, 169.

GOW, A. J., UEDA, H. T. and GARFIELD, D. E. (1968): Antarctic ice sheet; Preliminary results of first core hole to bedrock. Science, **161**, 1011–1013.

GUNDESTRUP, N. S. and HANSEN, B. L. (1984): Bore-hole survey at Dye 3, south Greenland. J. Glaciol., **30**, 282–288.

HIGASHI, A. and MORI, Y. (1984): Hyôshô-jô kichi no haisui ni kansuru netsugaku-teki kôsatsu. Dai-1-kai Kyokuchi Setsuei Kôgaku Shinpojiumu Puroguramu·Kôen Yôshi (Program and Abstracts; the First Symposium on Antarctic Logistics, 16–17 March 1984). Tokyo, Natl Inst. Polar Res., 25.

KOKURITSU KYOKUCHI KENKYÛJO (1977): Nihon Nankyoku Chiiki Kansokutai Dai-17-ji-tai Hôkoku (1975–1977) (Report of the 17th Japanese Antarctic Research Expedition, 1975–1977). Tokyo, 198p.

MELLOR, M. (1977): Engineering properties of snow. J. Glaciol., **19**, 15–66.

NAKAWO, M. (1982): Kussakukô o riyô shita hyôon sokutei ni taisuru netsushiki doriru ni yoru shôon no eikyô (Effect of the temperature rise caused by the thermal drill on the exact measurements of ice temperature utilizing the drill hole). Nankyoku Higashi Kuînmôdorando Hyôshô no Seppyôgaku-teki Kenkyû (Glaciological Studies of the Ice Sheet in East Queen Maud Land, Antarctica), ed. by A. HIGASHI. Sapporo, Hokkaido Daigaku Kôgakubu, 10–17.

NARITA, H. and MAENO, N. (1979): Growth rates of crystal grains in snow at Mizuho Station, Antarctica. Nankyoku Shiryô (Antarct. Rec.), **67**, 11–17.

NISHIO, F., FUJII, Y. and KUSUNOKI, K. (1981): Measured and computed temperature profiles at Mizuho Station, East Antarctica. Sea Level Ice and Climatic Changes, ed. by I. ALLISON. Willingford, IAHS, 239–246 (IAHS Publication, No. 131).

PATERSON, W. S. B. (1980): Ice sheets and ice shelves. Dynamics of Snow and Ice Massess, ed. by S. C. COLBECK. New York, Academic Press, 1–78.

RITZ, C., LLIBOUTRY, L. and RADO, C. (1982): Analysis of a 870 m deep temperature profile at Dome C. Ann. Glaciol., **3**, 284–289.

SCHMITT, R. P. and RODRIGUEZ, R. (1963): Glacier water supply and sewage disposal systems. Symposium on Antarctic Logistics, Boulder, 1962, ed. by Natl Academy of Sciences-Natl Res. Council. Washington, D.C., 329–338.

SUZUKI, Y. and TAKIZAWA, T. (1978): Outline of the drilling operation at Mizuho Station. Mem. Natl Inst. Polar Res., Spec. Issue, **10**, 1–24.

YAMADA, T. (1975): Snow temperature at Mizuho Camp in 1971–1972. JARE Data Rep., **27** (Glaciol. 2), 115–144.

(Received May 24, 1985; Revised manuscript received August 30, 1985)