LONG-TERM UNDERGROUND TEMPERATURE MEASUREMENTS BY QUARTZ THERMOMETERS AT SYOWA STATION, EAST ANTARCTICA

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Abstract: Underground temperature measurements in two shallow boreholes were carried out by Japanese Antarctic Research Expedition at Syowa Station, East Antarctica from April 1981 to January 1984. Two quartz thermometers were installed in the first borehole at the depths of 2 and 5 m and three were in the second one at the depths of 1, 4 and 7 m. Measurements of digital recording were made at one hour interval. From observed data, mean underground temperatures at each depth and thermal diffusivity for the observation area were calculated. Mean underground temperatures in the first borehole were -8.002 and -8.681°C at the depths of 2 and 5 m, and in the second one were -8.060 and -8.009°C at the depths of 4 and 7 m. Whereas the mean air temperature at Syowa Station was -10.3°C. The underground temperature is about two degrees higher than the air temperature. The difference might be related to the thermal balance at the earth's surface. The thermal diffusivities for the borehole area are determined by two independent methods. The first method uses decay of the maximum amplitude and the second the phase lag of the temperature wave propagating down the hole. The obtained thermal diffusivities of $2.58\pm0.69\times10^{-2}\,\mathrm{cm^2/s}$ and $2.20\pm0.19\times10^{-2}\,\mathrm{cm^2/s}$ are about two times larger than those of ordinary igneous and metamorphic rocks measured in the laboratory.

1. Introduction

The first heat flow measurements in Antarctica were carried out during the Dry Valley Drilling Project (DVDP; DECKER, 1978; DECKER and BUCHER, 1977). They measured vertical temperature distributions in six holes located in McMurdo Station and in the Dry Valley area. The heat flow values calculated from these measurements ranged from 63 to 143 $\mathrm{mW/m^2}$.

The first underground temperature measurements at Syowa Station in Lützow-Holm Bay, East Antarctica were carried out during the 1980 wintering season by the 21st Japanese Antarctic Research Expedition (JARE-21) using a 20 m-deep borehole. Temperature records at every one hour interval at three different depths (5, 10 and 20 m) were obtained by observation for nine months during the Antarctic winter, from April 1980 to January 1981 (SHIBUYA *et al.*, 1982). The amplitudes of seasonal temperature variation at the depths of 5, 10 and 20 m were 5.47, 1.58 and 0.20°C, respectively, and the temperature variation seems to decay below 0.01°C at the depth of 33.8 m.

JARE-22 made heat flow measurements in Lützow-Holm Bay near Syowa Station using a conventional deep sea heat flow probe in 1981 (KAMINUMA and NAGAO, 1983; NAGAO and KAMINUMA, 1983). They measured temperature gradients in the sea floor sediments beneath the shore fast sea ice, and obtained very high apparent heat flow values (>170 mW/m^2) off the coast of Hönnor Glacier even after removing the effects of annual sea floor temperature variation and thermal refraction deduced from the unevenness of the submarine topography.

Underground temperature measurements at Syowa Station using two close shallow boreholes were started by JARE-22 in April 1981. Measurements have been conducted continually through JARE-23, -24, -25 and -26. In case of measurements at shallow depth, the measured underground temperatures are disturbed by shallow surface events such as air temperature variation and solar radiation. One way of correcting for these effects is to identify the nature of underground temperature wave at various times and depths. In this paper, the mean underground temperature and the thermal diffusivity were obtained from the records of long-term observation of underground temperatures for three years.

2. Measuring System

Underground temperatures were measured by a quartz thermometer developed by SHIMAMURA (1980). This quartz thermometer is essentially a frequency counter and has a resolution of 0.1×10^{-3}°C. One of the most significant advantages of the system is that the signals from sensors can be telemetered by twisted field wires of 1–2 km length instead of coaxial cables of limited length (approximately 30–50 m) which are usually attached to commercial quartz thermometers. The system can be installed and maintained easily. Details of the temperature recording system at Syowa Station used in the present work were reported by SHIBUYA *et al.* (1982).

3. Observation

After the system calibration using a 0°C cryostat at Syowa Station, the sensors were installed in the two shallow boreholes to the depths of 5 and 7 m at five different locations; 2 and 5 m in borehole 1 and 1, 4 and 6.8 m (expressed by 7 m) depth in borehole 2 as shown in Fig. 1. Two boreholes, 40.8 m apart, were drilled near the Earth Science Laboratory (ESL) at Syowa Station and output signals from the sensors are recorded on digital printers in the ESL.

The local geology of Syowa Station is generally composed of granitic gneisses. Drilling sites are in the outcrop of these rocks. Core drillings were made using air (JARE-21) and water (JARE-22) as drilling fluid. The coring operations were described by KAMINUMA (1984). YUKUTAKE and ITO (1984) measured *P*- and *S*-wave velocities for eight cores of these drilling samples. They reported that the velocity of *P*-wave ranged from 6.00 to 6.64 km/s and that of *S*-wave from 3.51 to 3.63 km/s under the pressure of 0.5 GPa.

Figure 2 shows the daily (at 1200 LT) temperature records of the five sensors for the entire observation period. Solid lines show the records of 1, 4 and 7 m depths

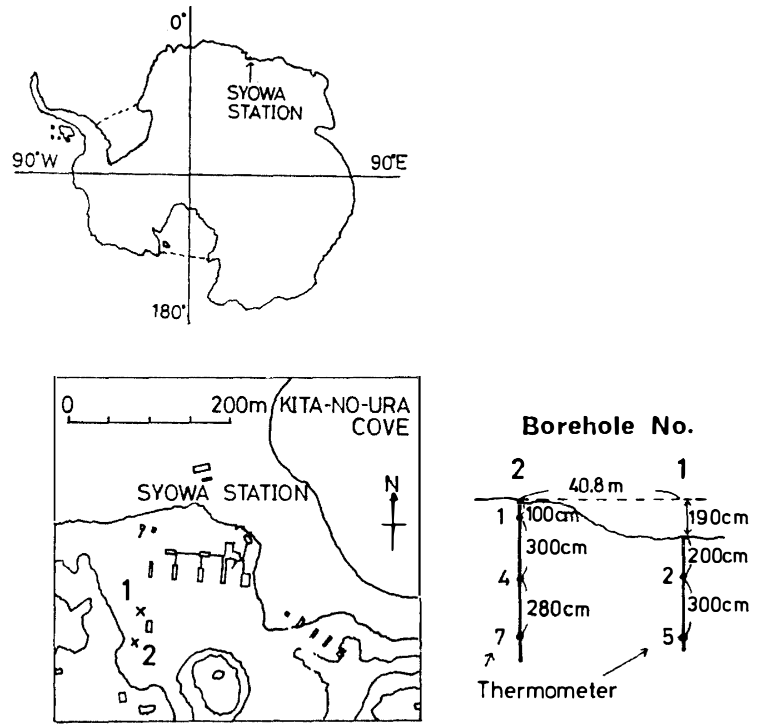


Fig. 1. Locations of the boreholes and sensor installation.

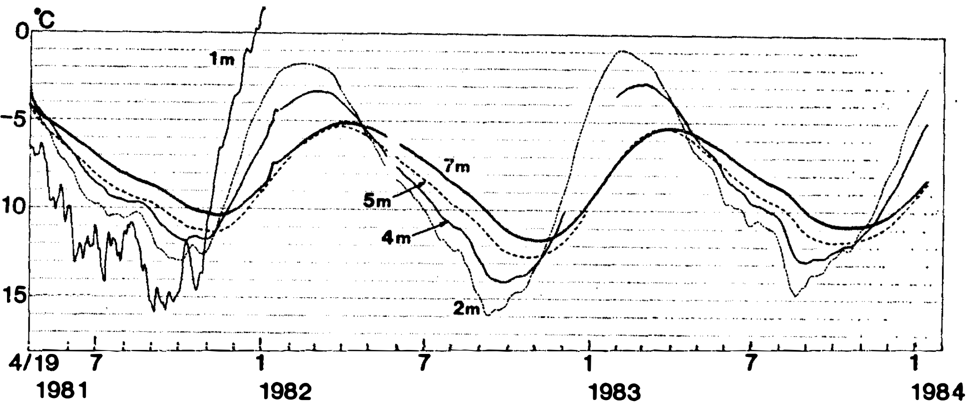


Fig. 2. Observed data for the period from April 1981 to January 1984. Underground temperatures at 1, 4 and 7 m depths in borehole 2 are shown by solid lines. Those at 2 and 5 m depths in borehole 1 are showed by dotted lines.

for borehole 2 and dotted lines show the records of 2 and 5 m depths for borehole 1. The signal from the 1 m-deep sensor was terminated due to break-down in January 1982 after nine months observation. The record of 1 m-deep sensor was not used in the following analyses because its observation period was too short. Due to power supply troubles, the records from all sensors were absent in June 1982 and from the 4 m-deep sensor from December 1982 to January 1983. The missing record for these periods were supplemented from the data by interpolation as shown in Fig. 3 for the analyses described in the following sections.

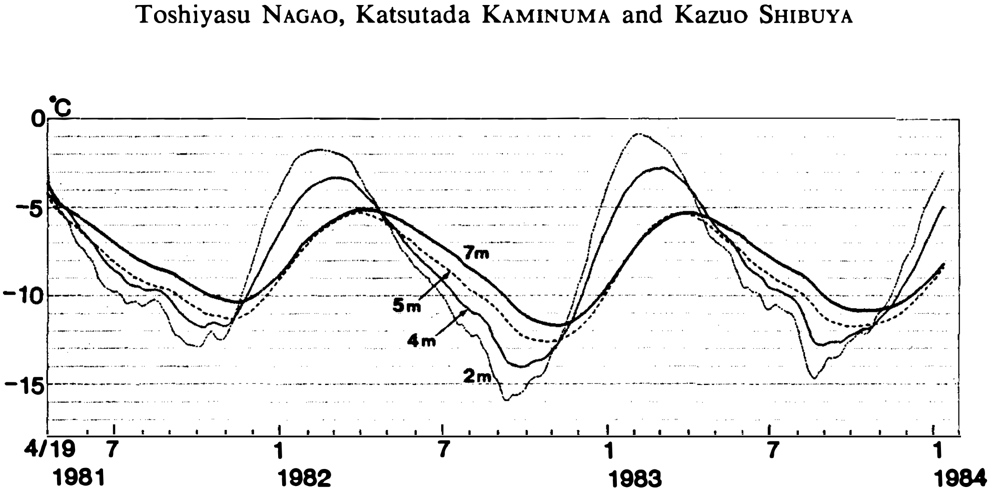


Fig. 3. Temperature data after the gaps in measurements have been interpolated. Data from 1 m-deep sensor are excluded.

4. Mean Temperature

The annual mean temperatures at each depth are calculated by the arithmetic mean of the data shown in Fig. 3 for the period from 1 July 1981 to 30 June 1983. The average temperature values at the depths of 2 and 5 m for borehole 1 are -8.002 and -8.681°C, and those at 4 and 7 m for borehole 2 are -8.060 and -8.009°C. The values at 2, 4 and 7 m depths are consistent within 0.06°C, but the value at 5 m depth is about 0.6°C lower than the other three values. The reason for this discrepancy is not well understood yet. The geothermal gradient in borehole 2 is tentatively given as 17×10^{-3}°C/m from mean underground temperatures of 4 and 7 m depths. This appears to be a reasonable value for an area of Pre-Cambrian continental shield such as East Antarctica.

5. Thermal Diffusivity

5.1. Method

Thermal diffusivity k is defined by

$$k=K/\rho c\,, \qquad (1)$$

where K is the thermal conductivity of the medium, ρ the density, c the specific heat. It is not always easy to make measurements of the three quantities in the eq. (1). In order to estimate the thermal diffusivity of small samples in the laboratory, the Ångström method is one of the most convenient way (CARSLAW and JAEGER, 1959; FUJISAWA *et al.*, 1968), in which a harmonic variation of temperature wave is added to one side of a measuring sample, and we can estimate the thermal diffusivity of the sample by measuring the amplitude decay and phase lag of the temperature wave along the direction of propagation. Observed temperature records reported in this paper enable us to determine the thermal diffusivity by applying directly the same principle as the Ångström's. KESSELS (1983) determined the thermal diffusivity by inserting 13 discrete sets of the temperature-depth data to the solution of thermal diffusion equation by the trial and error method. We believe that the measurement of the thermal diffusivity in this paper is the first attempt to use continuous long-term temperature records.

We consider one dimensional thermal diffusion equation is:

$$dT/dt = k(d^2T/dZ^2)\,, \qquad (2)$$

with the boundary conditions

$$T = T_0 + \sum_{i=1}^{\infty} A_i \cos[(2\pi/\tau_i)t + \alpha_i] \qquad \text{at } Z=0\,,$$

$$dT/dZ = g, \qquad \text{at } Z=\infty\,,$$

where A_i, τ_i and α_i are the amplitude, the period and the initial phase of the ground surface temperature. g is the underground temperature gradient at the observation area and T_0 is the mean ground temperature at $Z=0$. The solution of eq. (2) is expressed by CARSLAW and JAEGER (1959) as

$$T(Z,\,t) = T_0 + gZ + \sum_{i=1}^{\infty} A_i \exp(-H_iZ)\cos(-H_iZ + P_i)\,, \qquad (3)$$

with $\quad H_i = \sqrt{\pi/k\tau_i}\,, \qquad P_i = (2\pi/\tau_i)t + \alpha_i\,.$

The thermal diffusivity can be calculated independently by the third term of the right-hand side of the solution (3) using either the amplitude decay or the phase lag of the temperature wave. But data shown in Fig. 3 seem to contain higher modes of fluctuations. Therefore, it is hard to determine precisely the amplitude decay and

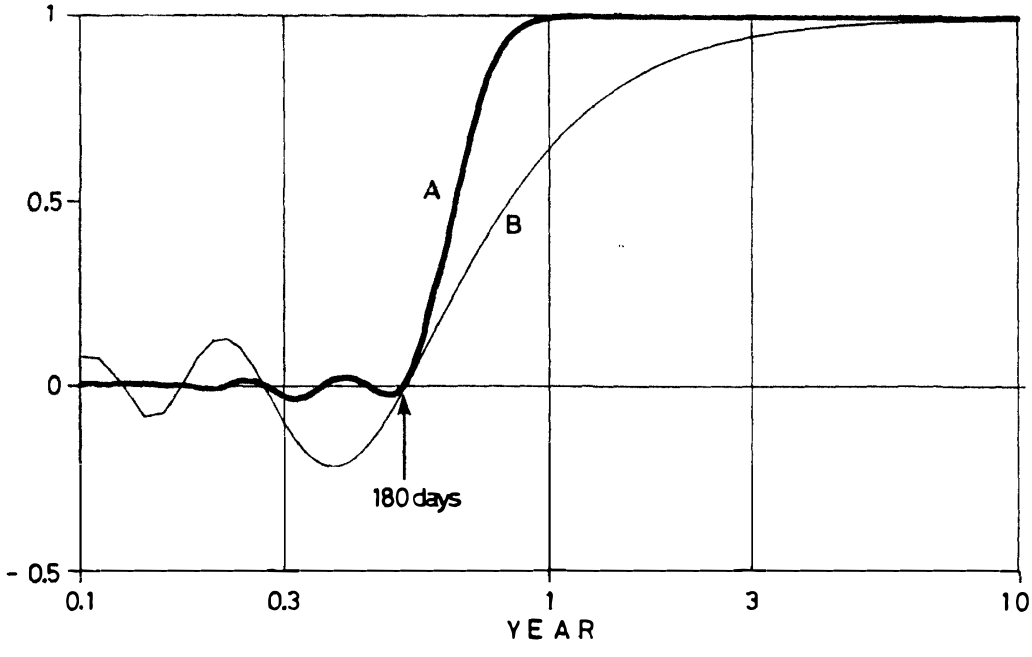
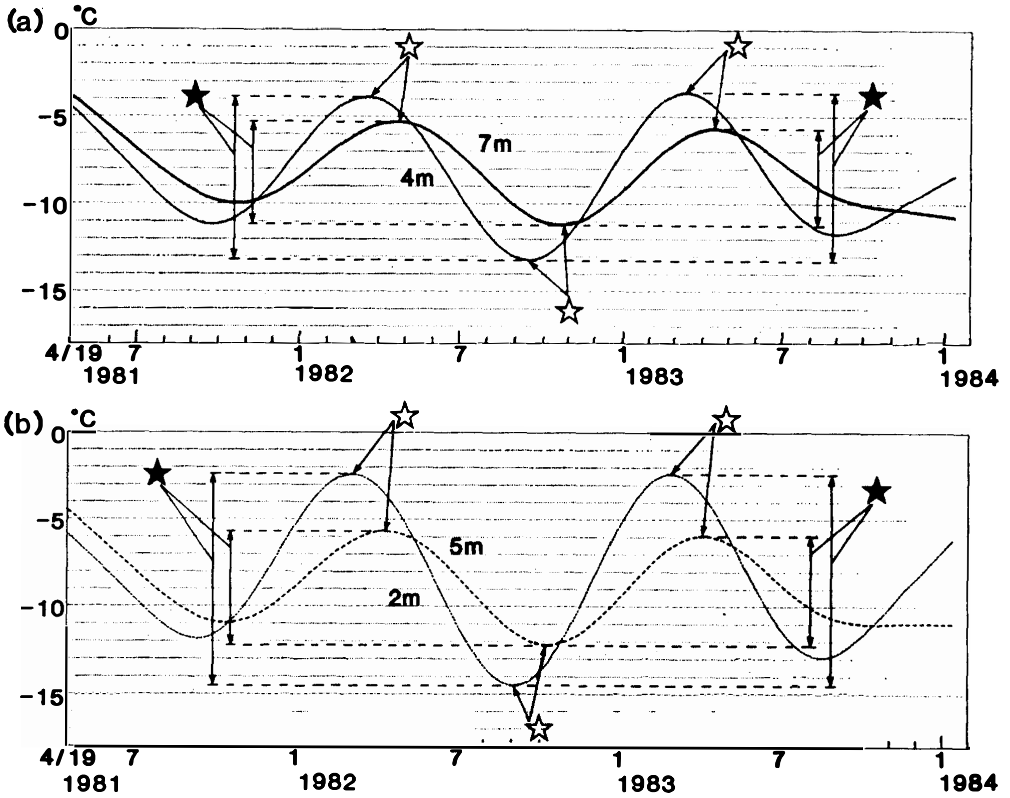


Fig. 4. Characteristic curves of digital filters. Filter A with a very sharp cut-off frequency is used in the calculations. Characteristic curve B is a commonly used successive running mean filter.

the phase lag of the ground tone which correspond to the annual temperature variation. In order to get rid of the effects of the higher modes, successive running mean of the temperature data were taken. In this paper, the improved successive running mean filter, developed by SHICHI (1973), was used. This low pass filter has a very sharp cut-off frequency as shown in Fig. 4. The characteristic curve of commonly used successive running mean is also displayed with a symbol B in Fig. 4. By filtering the data by the 180-day successive running mean, fluctuational modes with period less than 180 days are removed, leaving the mode of annual variation essentially unchanged.

Figures 5a and 5b show the results of the 180-day successive running mean of boreholes 2 and 1, respectively. The data wave showed for the first and the last 180 days, from April to October, 1981 and from July 1983 to January 1984 because of the nature of the successive running mean. We consider that the filtered temperature data shown in Figs. 5a and 5b contain only a ground tone *i.e.* the term $i=1$ in the solution (3).



Figs. 5a and 5b. 180-day successive running mean of the data of boreholes 2 (5a) and 1 (5b). The shorter fluctuations with less than a year period are mostly removed. Solid and open stars are the amplitude decay data and the phase lag data, which data sets were used for calculating the thermal diffusivities.

5.2. *Amplitude decay*

From the amplitude decay of the temperature variations at different depths, the thermal diffusivity is obtained using the exponential part of the eq. (3). The T_0 and

gZ in the eq. (3) have no effect on the determination of the thermal diffusivity as the following relation holds

$$A_k = A_j \exp[-H(Z_k - Z_j)]\,, \tag{4}$$

where A_j and A_k are the amplitudes at depths Z_j and Z_k, respectively. Then, the thermal diffusivity is expressed by

$$k = [(Z_k - Z_j)/\log(A_k/A_j)]^2 \pi/\tau\,. \tag{5}$$

In this study, four pairs of the maximum amplitude decay data were taken as shown by solid stars in Figs. 5a and 5b. The maximum and minimum temperature changes at the depth of 4 m for periods from March to September, 1982 and from September 1982 to March 1983 are 4.456 and 4.779°C, and those at 7 m are 2.950 and 2.623°C in Fig. 5a. It means that the temperature amplitude decays between the depths of 4 and 7 m are from 4.456 to 2.950°C, and from 4.779 to 2.623°C in the borehole 2. To use the same argument, the temperature amplitude decays, for the depth interval 2 and 5 m, from 6.043 to 3.258°C, and from 6.061 to 3.123°C in the borehole 1 in Fig. 5b. By inserting the above four sets of values into the eq. (5), the thermal diffusivity was calculated as $2.58 \pm 0.69 \times 10^{-2}$ cm²/s.

5.3. *Phase lag*

The term "phase lag" is defined in this paper as "a time necessary for the maximum or the minimum temperature to appear at two different depths". From the phase lag data, the thermal diffusivity value is obtained using the cosine part of the eq. (3) having the following relation

$$-HZ_j + (2\pi/\tau)t = -HZ_k + (2\pi/\tau)(t + Dt)\,, \tag{6}$$

where Dt is the phase lag between the depths of Z_j and Z_k. The thermal diffusivity can be expressed by

$$k = [\tau(Z_k - Z_j)^2]/(4\pi Dt^2)\,. \tag{7}$$

In this study, six phase lag data as shown with open stars in Figs. 5a and 5b are used. Phase lag data between the depths of 4 and 7 m in the borehole 2 are 34, 35 and 32 days, and those between 2 and 5 m in the borehole 1 are 38, 39 and 38 days, respectively. From these six values, the thermal diffusivity was calculated as $2.20 \pm 0.19 \times 10^{-2}$ cm²/s.

6. Discussion and Conclusion

The mean underground temperatures at four different depths were obtained by the three year long-term observations at Syowa Station. The values are −8.002, −8.060, −8.681 and −8.009°C at 2, 4, 5 and 7 m depths, respectively. It was found that mean underground temperatures at the shallow depths as discussed was about −8°C, whereas the mean air temperature was −10.3°C at Syowa Station from February 1981 to January 1983. The underground temperature is about two degrees higher than the air temperature.

CLAUSER (1984) reported a difference between the mean underground temperatures near the ground surface (shallower than 1 m) and the mean air temperatures in West Germany. In his results, the mean air temperature is about 0.6–2 degrees higher than the mean underground temperature contrary to the result of this study. This conflicting result might be due to the difference in the near-surface thermal balance between the high and the middle latitude areas, and/or an effect of underground water in West Germany and its absence in Antarctica.

The thermal diffusivity of the rocks was obtained using two kinds of methods. Two obtained values are coincident with each other within the range of standard deviation. But these values are about two times larger than the thermal diffusivity of granite (1.1×10^{-2}cm^2/s) at 0°C in the laboratory experiments (HELLWEGE, 1982). HELLWEGE's compilation also shows that the thermal diffusivity of many kinds of rocks dependence upon temperature from 0 to 500°C. Thermal diffusivity of granite decreases steeply near 0°C as the temperature increases in comparison with higher temperatures. Our temperature observations were made a condition of minus temperature ranges. One of the cause of large thermal diffusivities might be a such as low temperature effect.

One of the other interpretation for large thermal diffusivities to be estimated is that the cracks, which are filled by air and the air in the crack is circulating, in the rocks may behave as a high conductive material. The thermal diffusivity we measured concerns with the size much larger than that of usual laboratory experiments. The high values of thermal diffusivity obtained by these *in-situ* methods may express effective thermal diffusivity, which may be influenced by the convective motion of air in the cracks. We want to make sure the measurement of the thermal conductivity and diffusivity of core samples in laboratory for the next step, 'to make a comparison between small scale thermal properties and large scale ones.

SHIBUYA *et al.* (1982) estimated that the underground temperature fluctuation at the depth of 33.8 m is about 0.01°C. By drilling a 100 m-deep borehole, the heat flow may be determined by using the long-term temperature recording and method described in this paper.

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