HEAT FLOW MEASUREMENTS IN LÜTZOW-HOLM BAY, ANTARCTICA

Toshiyasu NAGAO

Department of Earth Science, Faculty of Science, Chiba University, 33, Yayoicho 1-chome, Chiba 260

and

Katsutada KAMINUMA

National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173

Abstract: Five heat flow measurements were made during the winter season of the 22nd Japanese Antarctic Research Expedition in the Lützow-Holm Bay, Antarctica. The apparatus used for the temperature measurements was a 1.2 m long Bullard type probe with three thermistors. Temperature gradients were determined at five different sites in shallow waters on the shore fast sea ice in November 1981. The temperature data were corrected following Bullard's method. The temperature gradients ranged from -0.028 to 0.197 °C/m. The thermal conductivities were determined on sediment samples recovered by coring before the temperature measurements were made. The thermal conductivities ranged 2.25 to 2.63×10^{-3} cal/cm·s°C. Corrected heat flow values were -0.74, 0.21, 4.39, 4.53 and 1.19 HFU. Since these measurements were made in shallow water, the effects of the sea floor topography and the water temperature variation were considered. The topographic effect computed by a two-dimensional relaxation method resulted in corrections ranging from 7 to 41%. Annual sinusoidal temperature variation with an assumed amplitude of 0.31°C at the sea floor gave a correction of up to ± 4.2 HFU. Because of the sea floor temperature in November is increasing, the temperature gradient of sediments has a tendency to decrease. Therefore, the high heat flows valued 4.39 and 4.53 HFU can not be denied.

1. Introduction

There are few data on heat flow reported in Antarctica. The first direct measurements of temperature gradients in Antarctica were carried out by DECKER and BUCHER during the Dry Valley Drilling Project (DECKER, 1974; DECKER *et al.*, 1975; BUCHER and DECKER, 1976; DECKER and BUCHER, 1977). Vertical temperature gradients were measured in six holes; two located in McMurdo Station, the other four in Dry Valley. Heat flow values calculated from these measurements ranged from 1.5 to 3.4 HFU (1 HFU$=1 \times 10^{-6}$ cal/cm^2·s$=41.9 \times 10^{-3}$ W/m^2). The radiogenic heat production from core and surface samples ranged from 2.2 to 3.7 HGU (1 HGU$=1 \times 10^{-13}$ cal/cm^3·s) (DECKER, 1978).

Heat flow measurements in Lützow-Holm Bay near Syowa Station were carried out during the 1981 winter season by the 22nd Japanese Antarctic Research Expedition

(JARE-22). Lützow-Holm Bay is a part of the Antarctic continental shelf in the marginal area of the East Antarctic shield. A new technique was developed to measure thermal gradients in the sea floor sediments beneath the shore fast sea ice (KAMINUMA and NAGAO, 1982).

2. Temperature Gradients

The location of the five heat flow stations are given in Fig. 1 and Table 1. The duration of temperature observation in the sediment was approximately 20 minutes. This was not long enough for the temperature disturbance caused by frictional heating due to probe penetration to subside to an acceptable level. Therefore, the measured temperatures were corrected using BULLARD's method (1954). BULLARD considered the frictional heating effect associated with the penetration of a probe into soft sedi-

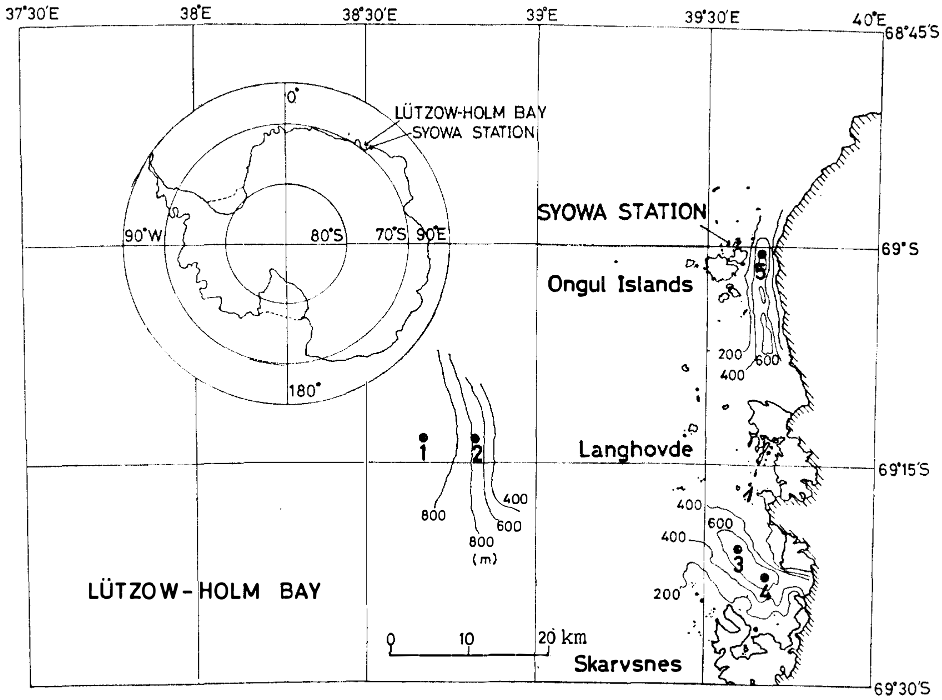

Fig. 1. Locations of the stations where temperature measurements of sea water and sea floor sediment were carried out beneath the sea ice.

Table 1. Temperature measurement stations in the sea floor.

Date	Location	Station No.	Latitude	Longitude	Depth	Sea ice thickness
Nov. 3	Off the coast of Langhovde	1	69°13.4′S	38°40.5′E	666 m	140 cm
Nov. 4	Off the coast of Langhovde	2	69°13.4′S	38°49.2′E	778 m	140 cm
Nov. 8	Honnör Glacier	3	69°20.6′S	39°36.4′E	668 m	120 cm
Nov. 8	Honnör Glacier	4	69°22.5′S	39°40.9′E	683 m	120 cm
Nov. 17	Ongul Starit	5	69°00.4′S	39°39.8′E	537 m	120 cm

ments. The probe was idealized as an infinitely long, perfectly conducting cylinder of radius a, and water equivalent m per unit length, initially at temperature θ_0 and immersed in an infinite medium of conductivity K, specific heat c and density ρ. The solution to this problem is of the form $\theta/\theta_0=F(\alpha,\tau)$, where $\alpha=2\pi a^2\rho c/m$, $\tau=kt/a^2$ and $F(\alpha,\tau)$ is a function defining the decay of the disturbance. k and t are the thermal diffusivity of the sediment and the time after penetration, respectively.

The probe used in this study is made of stainless steel and m can be computed from its thermal properties as 6.42 cal/cm°C. Likewise $\rho c=0.8$ cal/cm^3°C and $k=K/\rho c$. The thermal diffusivity of the sediments was estimated from an empirical formula developed by VON HERZEN and MAXWELL (1959). A value of $k=1.53K-0.70\times 10^{-3}$ was chosen.

Table 2. Corrected temperatures and temperature differences after Bullard's method.

Station No.	Thermistor	T(Bullard) (°C)	ΔT(Bullard) (°C)	Sea floor temperature (°C)
	A	−0.387	—	
1	B	−0.369	−0.018	−0.292∼−0.253
	C	−0.359	−0.028	
	A	−0.056	—	
2	B	−0.085	+0.029	−0.083∼−0.050
	C	−0.064	+0.008	
	A	−0.654	—	
3	B	−0.748	+0.094	−0.919∼−0.855
	C	−0.840	+0.186	
	A	−0.673	—	
4	B	−0.786	+0.113	−0.919∼−0.878
	C	−0.870	+0.197	
	A	−1.235	—	
5	B	−1.275	+0.040	−1.298∼−1.285
	C	−1.288	+0.053	

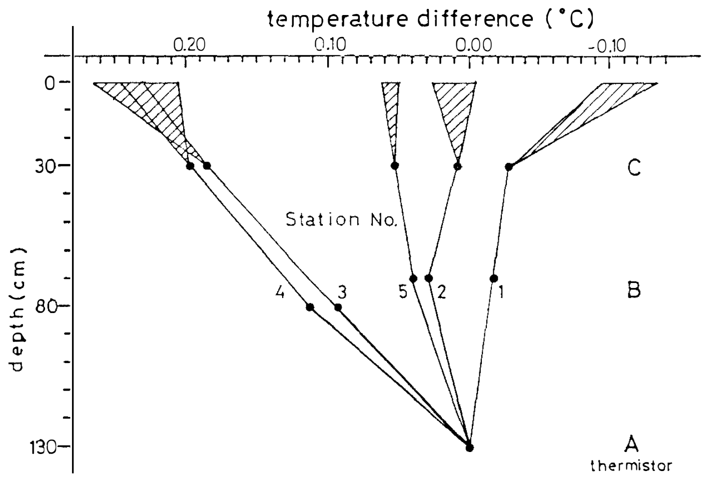

Fig. 2. Temperature gradients after applying the Bullard's correction. A, B and C are the position of thermistors. The temperature of thermistor A is normalized to 0°C.

Temperatures corrected for frictional heating and the temperature differences between fixed thermistors are summarized in Table 2 and Fig. 2. In Table 2, T (Bullard) is the corrected temperature and ΔT (Bullard) is temperature differences of A–B and A–C. In Fig. 2, A, B and C are the fixed positions of the thermistors in the probe. We assumed that the depth of thermistor A was always 130 cm from the surface of the sediment. The sea floor temperatures were estimated from the temperature records taken just before and after penetrations. In Fig. 2, the temperatures at Stations No. 1 and No. 2 show negative gradients. This suggests a fluctuation of sea floor temperature. In this paper, the difference between temperatures measured at thermistor A and C was used to compute the thermal gradient. The values of temperature gradients at Stations No. 1, No. 2, No. 3, No. 4 and No. 5 were −0.028, 0.008, 0.186, 0.197 and 0.053°C/m, respectively.

3. Thermal Conductivity

Before the temperature measurements were made, sediment samples were collected at each site using coring tubes. The core samples consisted light grey clay or silt. They were returned to Japan in a frozen state for later determination of thermal conductivity. Measurements were made for the samples collected at Stations No. 2, No. 3, No. 4 and No. 5. Because no sediment samples were obtained at Station No. 1, the conductivity value for nearby Station No. 2 was used for calculating heat flow at Station No. 1. Both the needle probe (NP) method (VON HERZEN and MAXWELL, 1959) and the quick thermal conductivity meter (QTM) (SUMIKAMA and ARAKAWA, 1976; HORAI, 1982) were used for the measurement. The values of thermal conductivity measured by the QTM were in the range of 2.54 to 3.07×10^{-3} cal/cm•s°C. These values were corrected for the effect of water depth D (m) at the heat flow station and the temperature difference between the sea floor $T_{\mathrm{in\ situ}}$ (°C) and the laboratory T_{lab} (°C) by RATCLIFFE formula (1960).

$$K_{\mathrm{in\ situ}} = K_{\mathrm{lab}}\left(1 - \frac{T_{\mathrm{lab}} - T_{\mathrm{in\ situ}}}{400}\right)\left(1 + \frac{D}{183000}\right),$$

where K_{lab} is the thermal conductivity measured in the laboratory at temperature of T_{lab} (°C) and $K_{\mathrm{in\ situ}}$ is the corrected thermal conductivity.

For the needle probe measurement, the sediment samples were kept at 0°C during the experiment. After correction for depth, most thermal conductivity values were in the range of 2.25 to 2.63×10^{-3} cal/cm•s°C. The thermal conductivities measured by the QTM are larger than those measured by the NP as shown in Table 3. The same trend was also reported by HORAI (1982).

Table 3. Thermal conductivities.

Method	Station No. 2	Station No. 3	Station No. 4	Station No. 5
QTM	3.07	2.54	2.60	2.54
NP	2.63	2.36	2.30	2.25

(unit: $\times 10^{-3}$ cal/cm·s°C)

4. Discussion and Conclusion

4.1. Heat flow values

Using the values for the temperature gradient and the smaller values for the thermal conductivity measured by the needle probe, heat flow values were calculated as shown in Table 4. The calculated heat flow values were −0.74, 0.21, 4.39, 4.53 and 1.19 HFU, respectively, at Stations No. 1, No. 2, No. 3, No. 4 and No. 5.

Table 4. Calculated heat flow values.

Station No.	Temperature gradient (°C/m)	Thermal conductivity ($\times 10^{-3}$cal/cm·s°C)	Heat flow (HFU)
1	−0.028	2.63	−0.74
2	0.008	2.63	0.21
3	0.186	2.36	4.39
4	0.197	2.30	4.53
5	0.053	2.25	1.19

The amount of heat flow at Station No. 5 seems to be reasonable as a value at the marginal area of the East Antarctic shield. However, those at Stations No. 3 and No. 4, larger than 4 HFU, seem to be too large for a shield's marginal area.

4.2. Correction of heat flow values

The first order correction to be applied to temperature data taken by a thermistor probe is for frictional heating caused by probe insertion (BULLARD, 1954). SCLATER *et al.* (1970) discussed the effects of ocean bottom topography and sedimentation rates. HYNDMAN (1976) indicated seven factors that are necessary for the correction. They are the variation in sea floor water temperature, sedimentation rate, thermal refraction by the sediment prism, submarine topography, Pleistocene thermal history, uplift and erosion rates. Further corrections will be applied to our heat flow result for the effect of topography and the effect of water temperature fluctuation at the sea floor.

4.3. Topographic correction

For the topographic correction, SCLATER *et al.* (1970) made a comparison between a numerical method and a relaxation method. Between the two solutions, there was an excellent agreement.

We adopted a two-dimensional relaxation method. The two-dimensional heat diffusion equation is

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)=\frac{\partial T}{\partial t},$$

which was reduced into a difference equation. X and Y co-ordinate axes express the horizontal direction and the vertical one.

$$T(x,y,t+\Delta t)=T(x,y,t)+\frac{k\Delta t}{h^2}\,[T(x+h,y,t)+T(x-h,y,t)\ \ T(x,y+h,t)+T(x,y-h,t)$$
$$-4T(x,y,t)],$$

where k and h are the thermal diffusivity and the mesh interval respectively t and Δt are time and a fixed step of increasing time.

We consider a model of finite half space, which has a linear thermal gradient from the surface to the bottom. A boundary condition of $\partial T/\partial t=0$ is always satisfied at the surface, both sides and the bottom. At $t=0$, a condition of $\partial T/\partial t=0$ is also satisfied at every mesh point. At $t=1$, a valley is formed on the surface of the finite half space and the valley is covered with sea water with a constant temperature. The valley floor is cooled by sea water, therefore the sediment-water boundary does not satisfy the condition of $\partial T/\partial t=0$. We calculated the above difference equation to satisfy the condition of $\partial T/\partial t=0$ at every mesh point. The simulation, at Stations No. 3, No. 4 and No. 5, was performed using 200×100 meshes with mesh interval $h=100$ m, which corresponds to a vertical plane of 20×10 km. The simulation at Stations No. 1 and No. 2 was performed using 400×50 meshes and $h=200$ m corresponding to a vertical plane of 80×10 km. The bathymetric data were taken from the Sôya Coast observation map issued by National Institute of Polar Research and the echo sounding data by JARE-22 (MORIWAKI; personal communication).

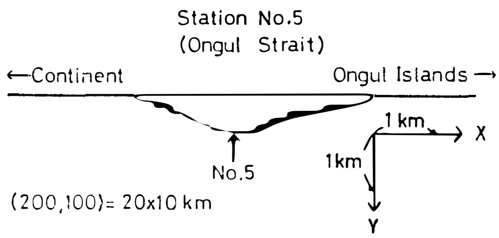

Fig. 3. The cross section of a topographic model for Station No. 5.

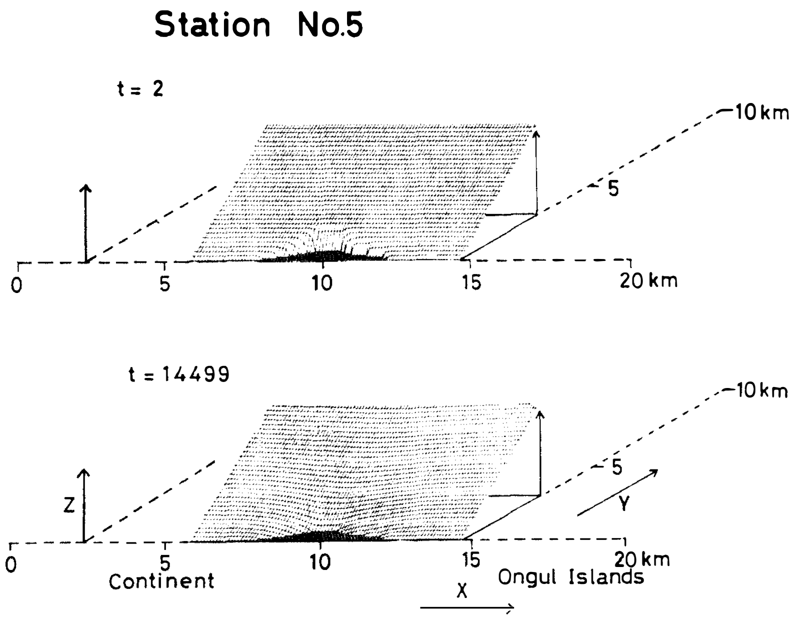

Fig. 4. Three-dimensional simulation of temperature relaxation with time. The top is the state at t=2 and the bottom is the steady state (t=14499). The change of slope inclination expresses the change of temperature gradient at the bottom of the valley.

Table 5. Topographic effects.

Station No.	t for $\partial T/\partial t=0$	Correction factor	Remarks
1	$t=9032$	1.067	400×50 meshes $h=200$ m
2	ditto	1.142	ditto
3 and 4	$t=18559$	1.212	200×100 meshes $h=100$ m
5	$t=14499$	1.412	ditto

Figure 3 shows the topographic cross section used for the simulation at Station No. 5. Figure 4 is three-dimensional displays for the development of the simulation. X axis is taken along the sea surface, Y axis is the depth from the sea surface and Z axis shows temperature. The state at $t=2$ is given in the top in Fig. 4. Cooling of the valley bottom by sea water is already started at this state. The bottom in Fig. 4 displays a steady state ($t=14499$) which is satisfied the initial condition of $\partial T/\partial t=0$ at every mesh point. The correction to the thermal gradient is proportional to the change of inclination of the slope. Table 5 summarizes the simulation data. The topographic effects on the gradient were 6.7, 14.2, 21.2, 21.2 and 41.2%, respectively at Stations No. 1, No. 2, No. 3, No. 4 and No. 5. The simulation shows that the temperature gradient in the bottom of valley was increased by the topographic effect.

Adopting $k\Delta t/h^2=0.1$ and assuming a thermal diffusivity of $k=8.0\times 10^{-3}$ cm^2/s (SCLATER *et al.*, 1980), we obtained for

$$h=100\text{ m};\ \Delta t=37.6\fallingdotseq 40\text{ years},$$
$$h=200\text{ m};\ \Delta t=158.5\fallingdotseq 160\text{ years}.$$

The time necessary to reach steady state conditions was 1.5 million years at Stations No. 1 and No. 2, 0.75 million years at Stations No. 3 and No. 4 and 0.60 million years at Station No. 5.

4.4. *Variation of sea floor water temperature*

The variation of sea floor water temperature in the Lützow-Holm Bay is poorly known. WAKATSUCHI (1982) made ten measurements of sea floor water temperature at the Ongul Strait near Station No. 5, on May to December 1976 and his result is shown in Fig. 5. The change of water temperature at the sea floor during the measurement period reached 0.62°C as shown in Fig. 5.

An annual sinusoidal temperature variation at the sea floor can be described by the following equation

$$T(t)=T(0)+A\cos\frac{2\pi}{P}t,$$

where A and P are the amplitude and the period of the temperature variation and $T(0)$ is a mean temperature at the sea floor.

The corresponding temperature variation in the sediment at depth Z, as a function of time t (MATSUBARA *et al.*, 1982) is

$$T(Z,t)=T(0)+A\exp\left(-\sqrt{\frac{\pi}{kP}}Z\right)\cos\left(\frac{2\pi}{P}t-\sqrt{\frac{\pi}{kP}}Z\right),$$

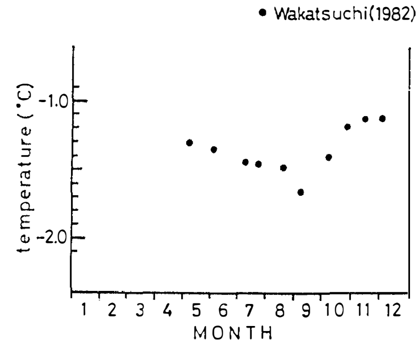

Fig. 5. The water temperature variation at the sea floor near Station No. 5, measured by WAKATSUCHI *(1982).*

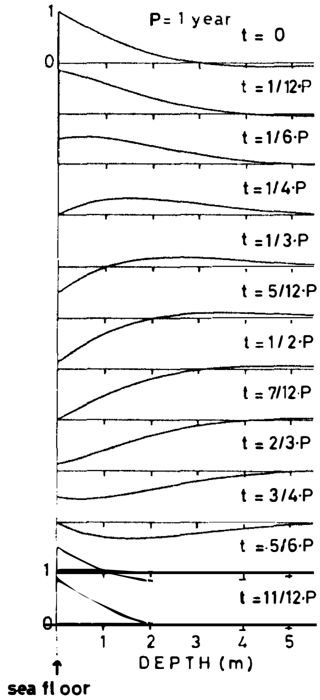

Fig. 6. Effects of sea floor temperature variation. Amplitude was normalized to 1. "t" varies from 0 to 11/12 P in steps of 1/12 P from the top to the bottom.

where k is the thermal diffusivity (3.0×10^{-3} cm^2/s).

Figure 6 shows the temperature distributions in the case of $A=1$, to the depth of 5 m from the surface of the sediment. In the figure, the value of t varies from 0 to 11/12 P in steps of 1/12 P from the top of the figure to the bottom.

In our experiment temperature differences were only determined in the upper 1 meter of sediment. If we assume $A=0.31$°C and $K=2.5\times 10^{-3}$ cal/cm•s°C, it is found that the maximum heat flow correction would be ± 4.2 HFU. As shown in Fig. 5, sea floor water temperature is increasing in November when the present temperature measurements were carried out. The temperature gradient at the upper part of sediment was found to be decreasing. Therefore, the high heat flows at Stations No. 3 and No. 4 can not be denied.

In the measurements reported in this paper, we used a probe only 1.2 m long under the prediction that see floors of the area were covered by a thin layer of sediments. Since the sediment layer in the observation area appears to be thicker than a few meters, future measurements should be made with longer probe. MATSUBARA *et al.* (1982) developed a new technique for heat flow measurements in shallow seas. The measured temperatures in sediments every 10 cm to the depth of 5 m, using one thermistor sliding vertically downword within the probe. We propose to use the MATSUBARA *et al.* type probe. In order to minimize the effects of fluctuating sea floor temperature, deeper temperature profiles in the sediments are needed.

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