ON THE WATER TEMPERATURE IN LAKE VANDA, VICTORIA LAND, ANTARCTICA

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***Abstract*:** A simple and quasi-steady thermal model of Lake Vanda is presented based on reasonable thermal properties. The model leads to a possible conclusion that water temperatures up to 25°C can be attributed to solar heating. The model also suggests that the rise in the lake level and the increase in the thickness of the isothermal convecting layer may have caused the decrease in temperatures over the past ten years.

1. Introduction

Since ANGINO *et al.* (1963) observed unusually high water temperatures and chemical concentrations in the saline lakes in the Dry Valley area of Victoria Land during the 1960–1961 austral summer season, numerous other physical and chemical investigations have been carried out. They concentrated on tracing the origin and history of these lakes, including the cause of the high water temperatures as well as the origin of chemical constituents. For the thermal problems of saline lakes such as Lake Bonney and Lake Fryxell in the Taylor Valley and Lake Miers in the Miers Valley, sun-heated models have been developed and have been generally accepted (SHIRTCLIFFE and BENSEMAN, 1964; SHIRTCLIFFE, 1964; HOARE *et al.*, 1964, 1965; BELL, 1967). On the other hand, there is no thermal model for Lake Vanda in the Wright Valley, which is the largest saline lake in this area and which has the highest temperatures reaching about 25°C near the bottom,

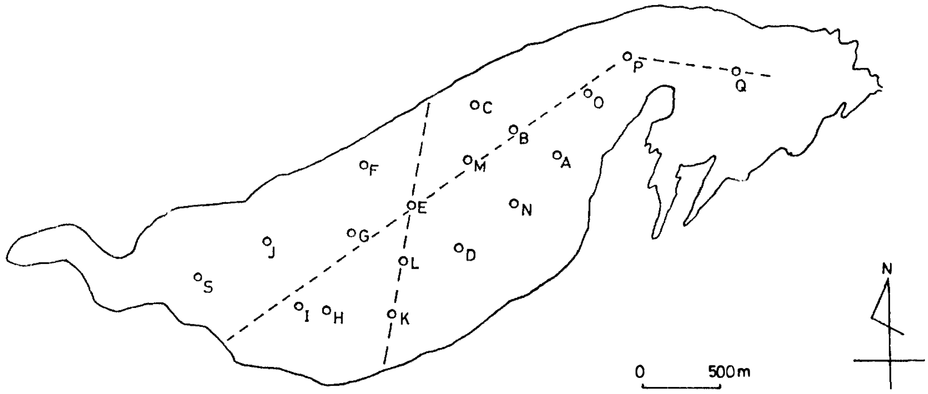

Fig. 1. Location of observation station.

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although some suggestions for its heat origin have been made (ANGINO *et al.*, 1965; WILSON and WELLMAN, 1962; RAGOTZKIE and LIKENS, 1964). However, these authors have given incompatible interpretations of the heat origin.

YOSHIDA *et al.* (1971) and TORII *et al.* (1972) carefully observed and analysed the thermal properties of the lake during the 1970-1971 and the 1971-1972 summer seasons, and YUSA (1972) evaluated each term composing the heat balance equation of the lake on the basis of their observations. The result is shown in Table 1. According to the table, heat gain terms are composed of the net flux radiation and the sensible heat exchange with the atmosphere, while heat loss terms

Table 1. Heat balance in Lake Vanda (cal/cm² · day).

Period	Heat gain			Heat loss+storage+advection		
	Q_i	Q_a	Q_i+Q_a	Q_e	Q_v+Q_f	$Q_e+Q_v+Q_f$
November 13-December 3	197	47	244	184	81	265
December 3-January 3	190	28	218	171	28	209
Total	193	36	229	176	55	231

Q_i: Net flux radiation, Q_a: Sensible heat exchange with the atmosphere, Q_e: Heat loss by evaporation, Q_v: Change of heat storage, Q_f: Heat exchange by advection.

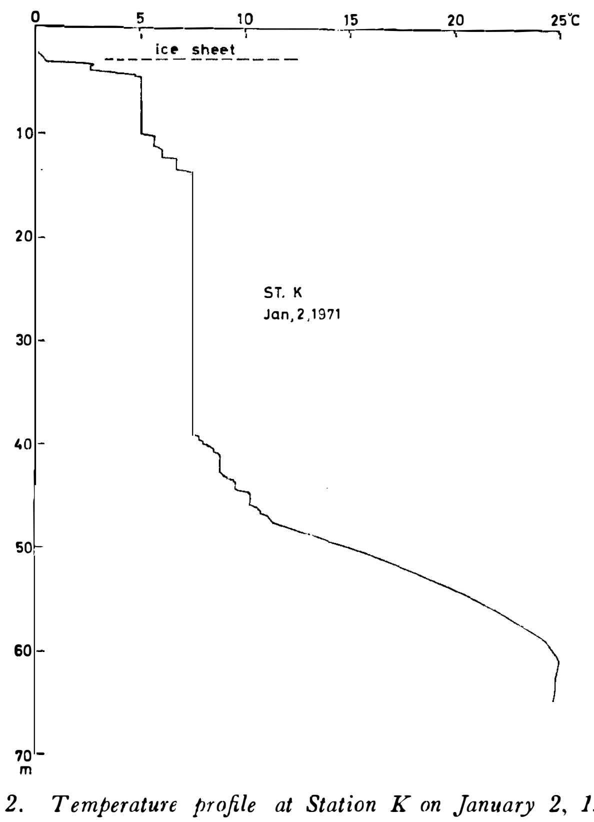

Fig. 2. Temperature profile at Station K on January 2, 1971.

are composed of evaporation (sublimation) and heat storage plus advection, but no effects of geothermal and/or hydrothermal activities were detected. Therefore, it is possible to conclude that Lake Vanda is also a sun-heated lake similar to the others.

Nevertheless, this heat balance analysis cannot verify whether or not the temperature of the bottom water can rise all the way up to 25°C solely by solar heating. In order to answer the above question a thermal model of Lake Vanda is presented in this paper and other general problems related to water temperatures are discussed.

2. Temperature, Salinity and Density Distribution of the Lake

2.1. *Temperature*

The water temperature increases from 0°C just below the lake ice to about 25°C near the bottom. The vertical profile of the upper part reveales a typical step-like structure, in which layers of homogeneous temperature and sheets with sharp gradients of temperature occur alternately. In the middle part, a large convecting layer develops, which is more than about 20 meters thick. Below this layer, the step-like structure appears again and then the temperature profile shows a steady curve below about 50 meters.

Figure 2 is an example of a temperature profile on January 2, 1971 observed at Station K (Fig. 1), which is located at the deepest part of the lake. This profile resembles others obtained at different times by other investigators, but it is especially significant because the highest temperature (25.0°C) appeared at the level of several meters above the bottom, and the bottom temperature lowered to 24.8°C. In the 1970–1971 summer season, this feature appeared at other stations such as L, H, I, G, E and D located around the deepest part of the lake. During the following summer, this feature was seen again, although not so clear, even though it had not been observed in other years. However, it has been repeatedly observed that the temperature gradient gradually decreases as the depth increases, and in the deepest part nearly reaches zero.

Figure 3 (a) is a cross-sectional distribution of water temperature along the longitudinal axis of the lake (see Fig. 1) taken in the 1970–1971 summer season, and Fig. 3 (b) is a magnified picture of the upper part. From Fig. 3 (b), we can see that each step-like structure, which may indicate the existence of some motion of the lake water, is spaced horizontally over the entire lake, though the thickness of each homogeneous temperature layer varies in places. On the other hand, as seen in Fig. 3 (a), equi-temperature lines in the deepest parts are completely flat, which seems to indicate a stagnant state in the lake water.

In order to understand the thermal state of the lake, more information about the ground temperatures around the lake and below the bottom is needed, for it is generally lacking. WILSON *et al.* (1962), based on their observations in December of 1961, reported that the temperature in the soft mud at the lake bottom near the center of the lake was decreasing downward with a gradient of 0.04°C per foot, while RAGOTZKIE *et al.* (1964) obtained reverse results during the 1962-1963 summer season. Results of observations by YOSHIDA *et al.* (1971) in an attempt to verify the situation showed that the temperatures of the sediment at L, K, D,

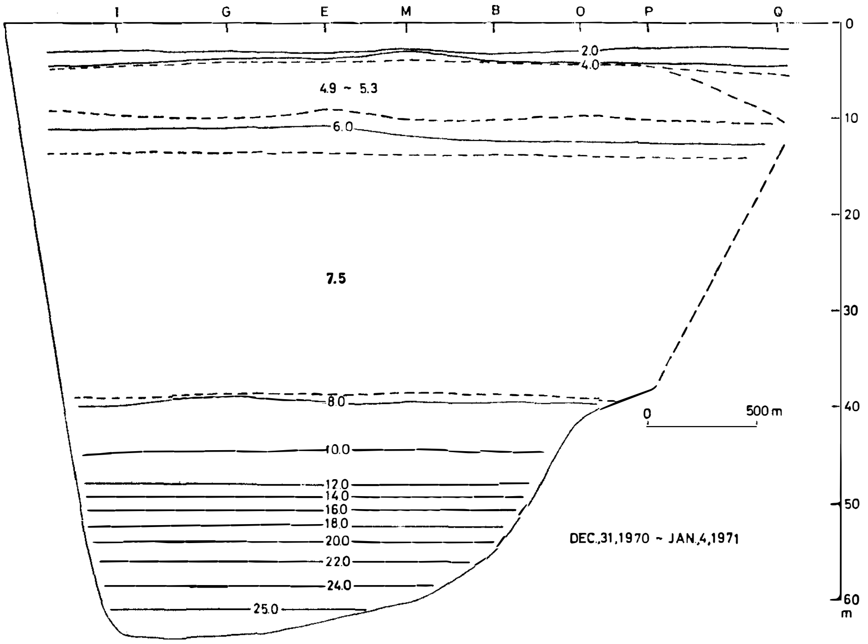

Fig. 3 (a). Cross-sectional distribution of temperature along the longitudinal axis drawn in Fig. 1 during a period from December 31, 1970 to January 4, 1971.

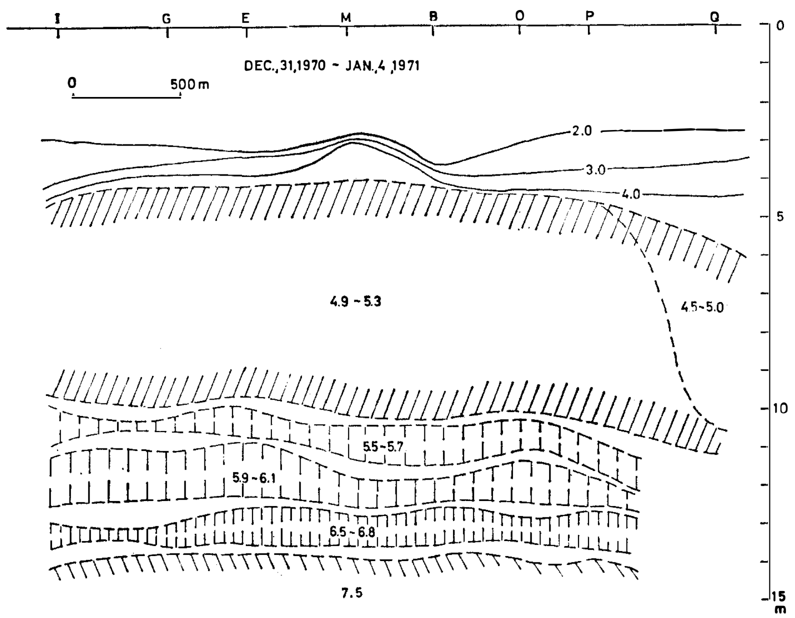

Fig. 3 (b). Cross-sectional distribution of temperature in the upper part.

N and near H were somewhat lower than those of water just above the bottom. Thus, it might be possible to conclude that the heat has a tendency to flow out of the lake through the bottom.

2.2. Salinity (electrical conductivity of lake water)

Figure 4 is an example of the vertical profile of the electrical conductivity of lake water observed at Station K with a 30 cm long cell on January 2, 1971. This figure shows a step-like structure which corresponds to the temperature profile, though not as clear as Fig. 2 because the cell used was too long to detect finer structures. Figure 5 shows a cross-sectional distribution of conductivity along the line K-L-E in Fig. 1. Equi-conductivity lines in the deepest part are completely flat, while in the upper part they are only approximately flat.

2.3. Density

As stated above, both the temperature and the electrical conductivity (salinity) of the lake water increase with depth, and the lake is stratified thermo-solutally.

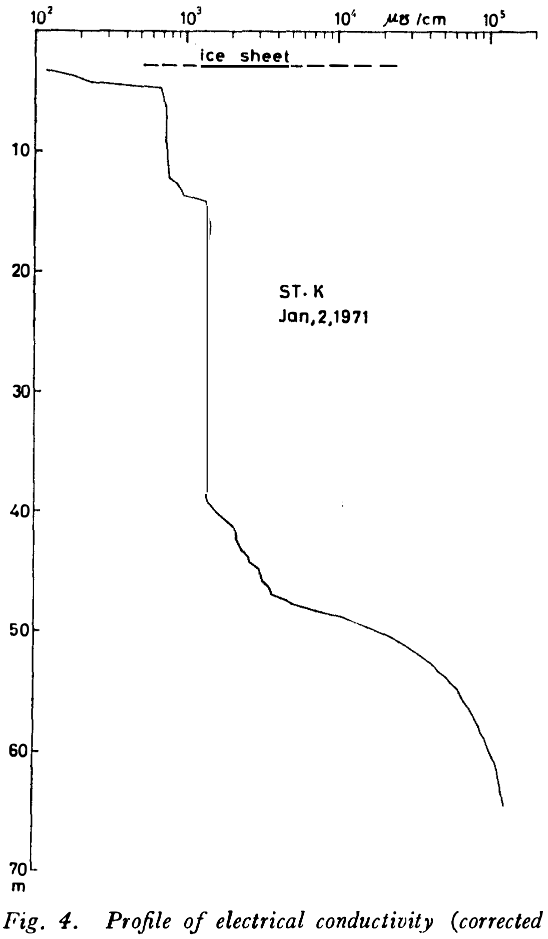

Fig. 4. Profile of electrical conductivity (corrected at 18°C) at Station K on January 2, 1971.

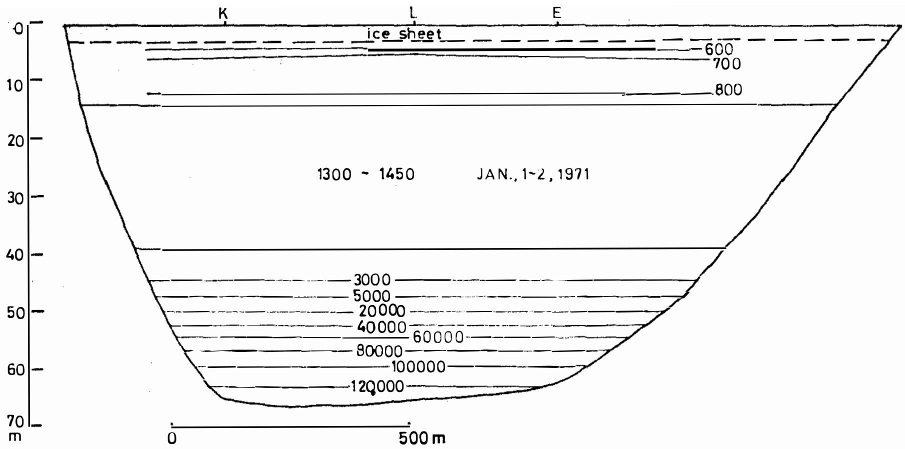

Fig. 5. Cross-sectional distribution of electrical conductivity ($\mu\mho$/cm at 18°C) along K-L-E in Fig. 1 during January 1–2, 1971.

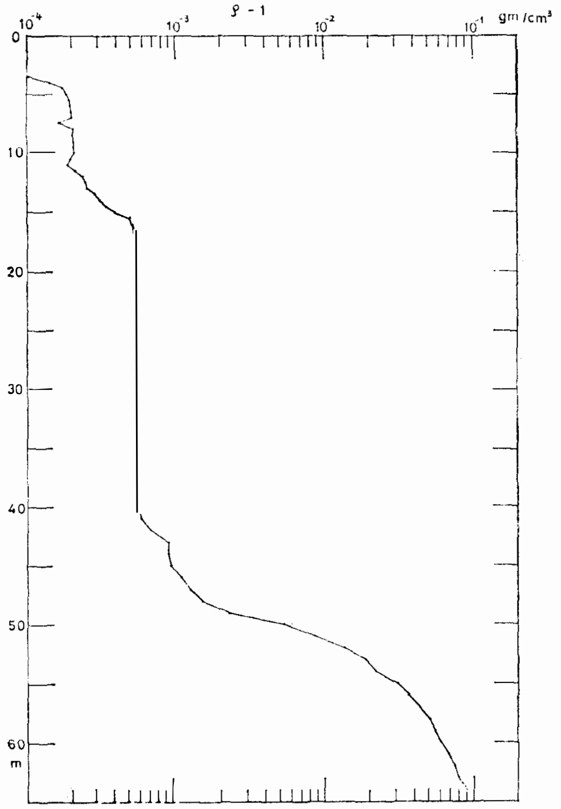

Fig. 6. An example of density profile (Station E, November 11, 1971).

The distribution of the water temperatures has a destabilizing effect on the stratification, while that of the salinity has a stabilizing effect. Figure 6 gives a vertical profile of the density of the lake water, which generally increases with depth as a result of the combined effect of the above two properties despite the inversion in the upper part, and reaches a maximum value of about 1.09 gm/cm^3 at the bottom.

3. Construction of the Lake Model

As shown in Fig. 3, isotherms of the lake water may seem approximately flat, and therefore it is possible to assume the one-dimensional heat flow in the lake as a first approximation. We simplify the lake as a four-layered lake as drawn in Fig. 7, in which the top layer corresponds to the upper step-like structure zone, the second to the thick isothermal zone, the third to the lower step-like structure zone and the bottom to the smooth profile zone, respectively. And understanding their formation mechanism is an important step in investigating the thermal characteristics of the lake, but here we will consider that formation of the zones occured well in the past, and that the annual mean water temperature is in a quasi-steady state. Besides, minimal effects from the freezing or melting of the lake ice, from the Onyx River run-offs or from other streams and from cooling (heating) through the side walls of the lake are ignored.

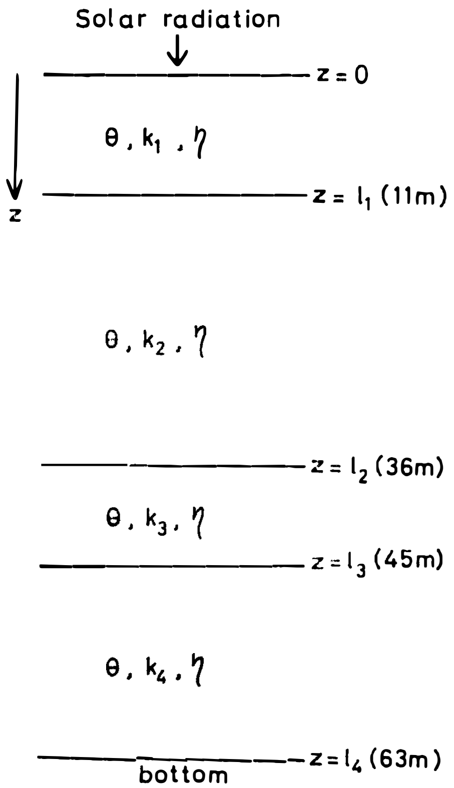

Fig. 7. A four-layered model for Lake Vanda. θ_i, k_i and η are water temperature, thermometric conductivity and extinction coefficient, respectively.

Considering that the intensity of solar radiation penetrating into the lake water exponentially decreases as a result of absorption in the lake water, the equations for heat conservation in a quasi-steady state are given as follows for individual layers,

$$\frac{d^2\theta_i}{dz^2} = -\frac{\eta}{k_i} Q_0 e^{-\eta z} \quad (i=1,\ 2,\ 3,\ 4). \tag{1}$$

where θ_i is the temperatures of individual layer, Q_0 the intensity of solar radiation just below the lake ice ($z=0$), k_i thermometric conductivity of layer and η the extinction coefficient of lake water, which is assumed as constant throughout the lake. The vertical co-ordinate z is downwardly positive. And the following is given as boundary conditions,

$$\left.\begin{array}{ll} \theta_1 = 0 & \text{at } z=0, \\ \left.\begin{array}{l} \theta_i = \theta_{i+1}, \\ k_i \dfrac{d\theta_i}{dz} = k_{i+1}\dfrac{d\theta_{i+1}}{dz}, \end{array}\right\} & \text{at } z=l_i \ (i=1,\ 2,\ 3), \\ h(\theta_4-\theta_0) = Q_0 e^{-\eta l_4} - k_4 \dfrac{d\theta_4}{dz} & \text{at } z=l_4 \end{array}\right\}. \tag{2}$$

where the last expression describes the assumptions that the solar radiation reaching the lake bottom is absorbed there, and that a part of heat flows out of the lake through the bottom. θ_0 is the temperature of the surrounding and h is a coefficient for the thermal exchange between the lake water and the surrounding.

Here, if we assume that the thermometric conductivity in the second layer, k_2, is sufficiently large compared with others, and put $k_1=ak$, $k_3=bk$ and $k_4=k$, solutions are given as follows,

$$\left.\begin{array}{l} \theta_1 = \left\{\dfrac{Q_0}{k\eta}(1-e^{-\eta z}) + \gamma z\right\} \cdot \dfrac{1}{a}, \\ \theta_2 = \left\{\dfrac{Q_0}{k\eta}(1-e^{-\eta l_1}) + \gamma l_1\right\} \cdot \dfrac{1}{a}, \\ \theta_3 = \dfrac{Q_0}{k\eta}\left(\dfrac{1-e^{-\eta l_1}}{a} + \dfrac{e^{-\eta l_2}-e^{-\eta z}}{b}\right) + \gamma\left(\dfrac{l_1}{a} + \dfrac{z-l_2}{b}\right), \\ \theta_4 = \dfrac{Q_0}{k\eta}\left(\dfrac{1-e^{-\eta l_1}}{a} + \dfrac{e^{-\eta l_2}-e^{-\eta l_3}}{b} + e^{-\eta l_3} - e^{-\eta z}\right) + \gamma\left(\dfrac{l_1}{a} + \dfrac{l_3-l_2}{b} + z - l_3\right), \\ \gamma = \left\{\dfrac{Q_0}{k\eta}\left(\dfrac{e^{-\eta l_1}-1}{a} + \dfrac{e^{-\eta l_3}-e^{-l_2}}{b} + e^{-\eta l_4} - e^{-\eta l_3}\right) + \theta_0\right\} \cdot \\ \qquad \dfrac{h}{h\left(\dfrac{l_1}{a} + \dfrac{l_3-l_2}{b} + l_4 - l_3\right) + k} . \end{array}\right\} \tag{3}$$

4. Calculated Results with Constants Required for Calculation

4.1. *Thermometric conductivities*

The vertical stability analyses of the thermo-solutal stratification (YUSA, 1974) suggest that the stratification in the deepest part is quite stable, while unstable in upper parts. Thus, it is possible to assume that heat and salt diffuse through molecular diffusion processes in the deepest part, and take the value of k as 1.3×10^{-3} in CGS unit, which seems reasonable for such high salinity water. On the other hand, the apparent thermometric conductivity in the top layer was estimated to be about 50 times larger than the molecular conductivity in the 1970–1971 summer season, and about 6 times in the 1971–1972 summer season according to the heat flow measurements. The larger value in the former season might be attributable to the vertical mixing of the lake water caused by the lake ice motion, when a broad area of open water appeared along the shoreline, so that the lake ice was moved easily by the wind. In the latter season, the lake ice did not move so that the lake water was not disturbed. Therefore, the smaller value may be the lowest for this layer. As we have no information about the frequency of such lake ice motion, it is impossible to estimate a long-term average for it correctly. Nevertheless, we will take a figure of 10 to 20, which seems not so unrealistic.

It is interesting to note that for interpretation of the apparent conductivity (k_a) throughout the step-like structure zone, the smaller value stated above is approximately consistent with the value calculated by the following relation (YUSA, 1972).

$$k_a/k=D/\delta, \tag{4}$$

where D is the whole thickness of the zone in question and δ is the total thickness of sheets. This relation is deduced from the assumption that isothermal layers are in a convection state (therefore the diffusivity in them is supporsed to be sufficiently large), while sheets with sharp temperature gradients are in a pure conduction state.

Applying the above relation to the third layer (*i. e.*, the lower step-like structure zone where the motion of lake water may be subject to thermo-solutal convection only, suffering no other disturbances), the value of b is estimated at approximately 3.5.

4.2. *Radiation and extinction coefficient*

According to the heat balance analysis, 6.9% of the incident solar radiation penetrated the lake water through the ice during the 1971–1972 summer season (YUSA, 1972). However, the penetrating fraction varies generally with the change in the ice surface condition. For instance, the fraction was 9.8% for the period of November 13 to December 3, during which the air temperature was relatively low and the ice surface rather smooth, and 4.8% penetrated to the lake water from December 3 to January 3, when the air temperature averaged above 0°C and the ice surface was very rough. Consequently, it is possible to assume that about 10% of incident radiation penetrates through the ice in the cold period and about 7% penetrates in the warm period. Thus, the intensity of Q_0 is calculated as 2.0×10^{-4} cal/cm^2·sec for the annual mean, which corresponds to about 8% of the incident radiation in this area.

The lake water is very transparent to light. According to RAGOTZKIE *et al.*

(1964), the average extinction coefficient was 3.4×10^{-4} 1/cm for visible light. This value will be used for η, though it varies widely with the wavelength of light.

4.3. θ_0 and h

Since there is no adequate data of the ground temperatures around the lake, it is impossible to evaluate correctly the mutual interaction of heat between the lake and the surrounding. But, considering that the heat flowing out from the lake through the bottom is directed only towards the ground surface, a value of θ_0 as $-19°C$ will be used, which is the annual mean for the ground temperture at a depth of 3 meters observed at Vanda Station (THOMPSON *et al.*, 1971).

On the other hand, it is not so easy to estimate the value of *h*. So, the latter will be computed using the temperature profile from Lake Bonney, which is generally regarded as a typical sun-heated lake. Previous authors treated Lake Bonney as a one-layered lake and considered that the heat flow was subjected to the process of molecular conduction (HOARE *et al.*, 1964; SHIRTCLIFFE and BENSEMAN, 1964; SHIRTCLIFFE, 1964). Yet, according to the results of electrical conductivity studies (YOSHIDA *et al.*, 1971; TORII *et al.*, 1972), a low step can be seen between 8 and 11 meters (Fig. 8), which suggests the development of thermo-solutal convection. YOSHIDA *et al.* (personal communication) observed the existence of a weak temperature step at these depths in the 1972-1973 summer season. Therefore, the lake can be divided into two layers. The first layer begins just below the ice (about 4 meters thick) and runs to 14.5 meters depth (*i.e.* 10.5 meters in thickness), and the second layer is the part deeper than the first. Using

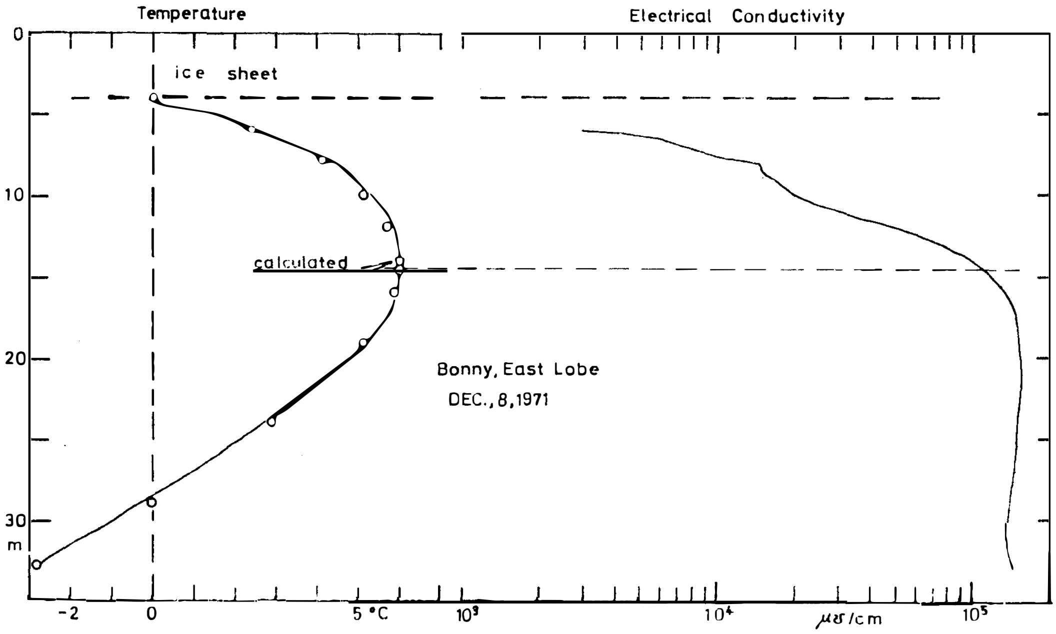

Fig. 8. Profiles of water temperature (left) and electrical conductivity (right) in Lake Bonney on December 8, 1971. Hollow circles are calculated values.

the profile shown in Fig. 8 and the relation (4), the apparent thermometric conductivity in the first layer is calculated as about 1.4 times the molecular conductivity.

Also assuming that the boundary conditions from (2) are similar for this lake, temperatures in the first and the second layers can be given by the following equations, respectively,

$$\left.\begin{aligned} \theta_1 &= \left\{\frac{Q_0}{k\eta}(1-e^{-\eta z})+\gamma z\right\} \cdot \frac{1}{a}, \\ \theta_2 &= \frac{Q_0}{k\eta}\left\{\frac{1-e^{-\eta l_1}}{a}+e^{-\eta l_1}-e^{-\eta z}\right\}+\gamma\left(\frac{l_1}{a}+z-l_1\right), \\ \gamma &= \left\{\frac{Q_0}{k\eta}\left(\frac{e^{-\eta l_1}-1}{a}+e^{-\eta l_2}-e^{-\eta l_1}\right)+\theta_0\right\} \cdot \frac{h}{h\left(\frac{l_1}{a}+l_2-l_1\right)+k}. \end{aligned}\right\} \tag{5}$$

As the temperature gradient vanishes at the level where the maximum temperature appears ($z=z_c$), γ will be expressed as follows,

$$\gamma = -\frac{Q_0}{k}e^{-\eta z_c}. \tag{6}$$

The water temperature at the bottom ($z=l_2$) remained at an almost constant value of -2.8°C over the past ten years, and consequently the following relation is obtained from the second equation in (5),

$$\theta_2\Big|_{z=l_2} = \frac{Q_0}{k\eta}\left(\frac{1-e^{-\eta l_1}}{a}+e^{-\eta l_1}-e^{-\eta l_2}\right)+\gamma\left(\frac{l_1}{a}+l_2-l_1\right) = -2.8. \tag{7}$$

Substituting the following reasonable values into (6), (7) and the third equation in (5); $\eta=1.2\times10^{-3}$ 1/cm, $z_c=l_1=10.5$m, $a=1.4$, $l_2=29.0$m, $k=1.2\times10^{-3}$ cal/cm·sec·deg and $\theta_0=-19$°C; Q_0 and h are obtained as $Q_0=3.35\times10^{-5}$ cal/cm²·sec and $h=5.9\times10^{-7}$ cal/cm²·sec·deg. Hollow circles in Fig. 8 are the theoretical results obtained from the above, which agree with the observation (solid line). The value of Q_0 obtained here corresponds to about 1.3% of the incident radiation and seems reasonable in comparison with the previous results (HOARE *et al.*, 1964; SHIRTCLIFFE and BENSEMAN, 1964).

Although the value of h obtained here may be characteristic to Lake Bonney, we will apply this value to Lake Vanda for trial. The required values for the calculation with (3) are summarized in Table 2, and the calculated profiles for $a=10$, 15 and 20 are drawn in Fig. 9 with solid lines. The calculated temperatures come to increase with decreasing a. Among the three curves in Fig. 9, the curve of $a=15$ is relatively fit to the observed result (broken line), but temperatures near the bottom are fairly lower (23.4°C) than the latter. However, a complete coincidence between calculated and observed results is beyond the present treatment, because the present model is rather rough and has been constructed in order to examine a possibility that unusual temperatures beyond 20°C can be accounted for by solar heating.

Table 2. Values for calculation by (3).

k:	1.3×10^{-3}	cal/cm · sec · deg
η:	3.4×10^{-3}	1/cm
Q_0:	2.0×10^{-4}	cal/cm^2 · sec
l_1:	11	m
l_2:	36	m
l_3:	45	m
l_4:	63	m
a:	10, 15, 20	
b:	3.5	
h:	5.9×10^{-7}	cal/cm^2 · sec · deg
θ_0:	-19	°C

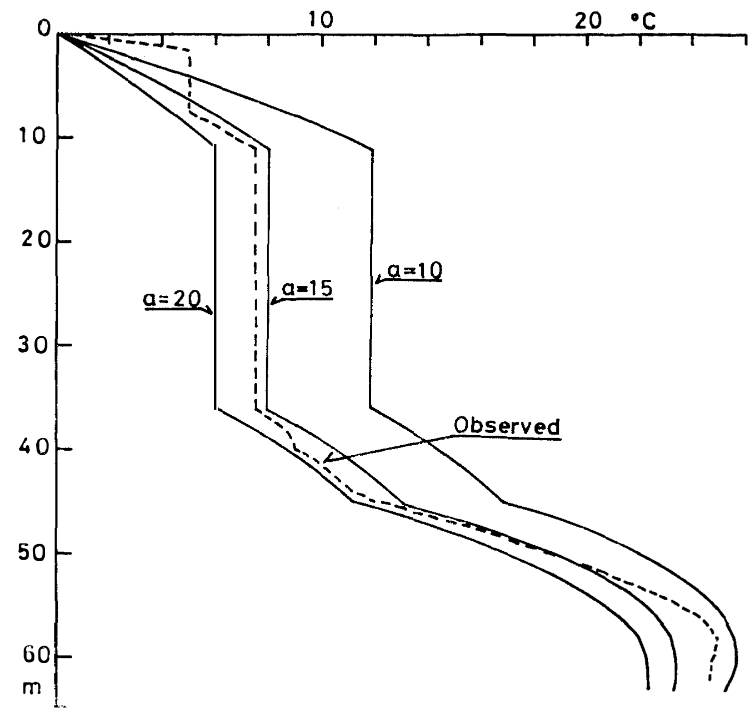

Fig. 9. Calculated temperatures for Lake Vanda by (3).

5. Discussions

The present model can explain the appearance of unusually high temperatures by solar heating, using reasonable thermal properties obtained through this work and others. Especially, the following conditions are to be noted for the appearance of high temperatures in Lake Vanda:

(i) The existence of strong density stratification in the bottom part. This precludes the convective motion, and therefore the heat diffuses slowly by molecular processes.

(ii) The lake is permanently covered by a ice sheet, which protects the lake water from stirring by wind. Thus, the apparent conductivity in the top part is relatively low.

(iii) The lake water is surprisingly transparent, so that radiation reaches the bottom part.

(iv) Cloudiness in this area is relatively small as compared with those in other antarctic areas, so that the amount of incident radiation is large (YOSHIDA and MORIWAKI, 1972).

(v) The lake ice is also very transparent to light. The extinction coefficient of it was 1.28×10^{-3} l/cm in the 1971-72 summer season.

(vi) In addition to the above, the lake is large enough and deep enough to store the heat within it. It also seems that the magnitude of h, which is interpreted as a property representing the cooling rate of the lake, may be related with the scale of the lake, but this will not be discussed further here.

Also, it is worthy to note that the maximum temperature has been decreasing rather slowly for the past ten years as shown in Table 3. In addition, the temperature in the middle isothermal part also has shown a tendency to decrease. The present model, of cource, cannot treat such time-dependent phenomena quantitatively, but gives a somewhat qualitative figure for them. As seen from the equations in (3), water temperature should fluctuate spatially and time-dependently in accordance with the fluctuation of such factors as the incident radiation, the lake level and the distribution of thermometric conductivity.

Table 3. Change of the maximum water temperature in Lake Vanda.

	Dec. 1961	Dec. 1962	Jan. 1965	Dec. 1965	Jan. 1971	Jan. 1972	Jan. 1973
Temp. (C°)	25.7	25.52	25.1	24.9	25.0	24.8	24.5*

* YOSHIDA *et al.* (unpublished).

At Lake Vanda, numerous ancient shorelines are visible around the lake, which suggest long-term fluctuations in the lake level. Recently, a rise of about 3 meters over the last ten years was observed. On the other hand, it is clear that the thickness of the middle isothermal layer (convecting) increased from about 20 meters at the beginning of the 1960's to about 25 meters at present. This suggests the change of the macroscopic diffusivity of the lake.

Based on the temperature measurements and the changes in the lake level, the depth of each boundary can be assumed as follows: $l_1=14$m, $l_2=34$m, $l_3=43$m and $l_4=61$m. Using the same values as shown in Table 2 for other properties, the calculation with $a=15$ leads to higher temperatures than those ($a=15$) in Fig. 9; the maximum temperature in the bottom part is 26.2°C and that in the middle isothermal layer 9.5°C. These are in accord with the decreasing tendency of the water temperature stated above. Thus, it is clear that fluctuations in the lake level and of the internal stratification affect the water temperature of this lake, although it is not possible to refer to the effect of fluctuations in incident radiation on account of a lack of long-term data in this area.

The lake level indicates a sensitivity to climatic change. In this sense, the water temperature is also sensitive to the latter. The internal stratification (in other words, the distribution of thermometric diffusivity) will change mainly as a result of physical processes such as the development of thermo-solutal convection, which is also largely dependent on temperature changes.

The stabilizing profile of salinity will be deformed by diffusion in the future, which will produce a different state of density stratification by the combined effect with temperature distribution. Accordingly, the pattern of convective motion in the lake will change and eventually the convection will commence even in the bottom part. Such a process, again, will bring a different distribution of temperature. In this paper, nevertheless, we have considered that the lake level and the salinity distribution change slowly as compared with thermal phenomena, and assumed a quasi-steady thermal state in order to give a macroscopic explanation of the unusual temperature.

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