ANALYSIS OF THERMOSOLUTAL PHENOMENA OBSERVED IN McMURDO SALINE LAKES (EXTENDED ABSTRACT)*

Yuki YUSA

Geophysical Research Station, Kyoto University, Noguchi-baru, Beppu 874

Through heat balance and macroscopic thermal model studies of McMurdo saline lakes, it has been shown that lakes are balanced thermally with the solar radiation (WILSON and WELLMAN, 1964; HOARE *et al.*, 1964, 1965; SHIRTCLIFFE and BENSEMAN, 1964; BELL, 1967; YUSA, 1972, 1975). Constructing a macroscopic thermal model for each lake, it has been considered that heat transfer in Lakes Bonney and Fryxell (Taylor Valley), in Lake Miers (Miers Valley) and in the lower part of Lake Vanda (Wright Valley) is subject to the molecular diffusion process. On the other hand, development of convective motion must be assumed in the upper part of Lake Vanda. The relation between the heat flow and the temperature gradient in the upper part of Lake Vanda supports the validity of the assumption (YUSA, 1972).

The existing theory of thermosolutal (or thermohaline) convection has dealt with a layer of fluid extending boundless horizontally with constant temperatures and salinities on the upper and the lower surfaces, which are dynamically free (VERONIS, 1965; BAINES and GILL, 1969). Thermosolutal convection is described by the equation of motion, the equation of heat conservation, the equation of salt conservation, the equation of continuity and the equation of state. When both temperature and salinity are higher on the lower surface, that is, the temperature field destabilizes the stratification while the salinity field stabilizes (diffusive regime), the marginal condition for the onset of convective instability is given by the following relation approximately,

$$\alpha \Delta T/\beta \Delta S=(P+\tau)/(1+P)\fallingdotseq 0.9. \qquad (1)$$

Thermosolutal stratification in diffusive regime is observed in Lake Vanda, in the upper part of Lake Bonney's east lobe and in the lower part of Lake Miers. Applying the foregoing criterion to these systems, it is concluded that stratification in each lake is stable except for the uppermost part of Lake Vanda as shown in Figs. 1, 2 and 3.

The experimental study of thermosolutal convection has shown the develop-

* The full paper was published under the title "A Study on Thermosolutal Convection in Saline Lakes" in the Memoirs of Faculty of Science, Kyoto University, Series A, **35** (1), 149–183, 1977.

Table 1. Main symbols used in the paper.

ρ	:	Density of fluid
c	:	Specific heat of fluid
κ	:	Molecular diffusivity for heat
g	:	Acceleration of gravity
α	:	Coefficient of volume expansion by unit temperature change
β	:	Proportional density change by unit salinity change
h	:	Depth of fluid
ΔT	:	Temperature difference between the upper and the lower surfaces
ΔS	:	Salinity difference between the upper and the lower surfaces
F_H	:	Heating rate from below
P	:	Prandtl number
τ	:	κ_s/κ (κ_s: Molecular diffusivity for salt)
T	:	Period of oscillation

ment of a multi-layered stratification (TURNER and STOMMEL, 1964), which quite resembles the step-like structures of temperature and salinity profiles observed in Lake Vanda (HOARE, 1966; SHIRTCLIFFE and CALHAEM, 1968; YOSHIDA *et al.*, 1971; TORII *et al.*, 1972) and in Lake Miers (BELL, 1967). This suggests that thermosolutal convection develops in Lake Vanda and also in Lake Miers.

Thus, it seems that the existing thermosolutal criterion represented by eq. (1) involves some limits in interpreting the actual thermosolutal system.

Cutting each lake into thin slices in order to examine the local thermosolutal situation, we can approximately replace the effect of heat generation due to the solar radiation with the heating of each thin slice from below, because the McMurdo saline lakes are in the thermal equilibrium state with the solar heating. Consequently, it may be reasonable that the thermal condition in the existing thermosolutal convection model (that is, the constant temperature on the lower surface) is replaced by the condition of the constant heating from below.

Based on the model, the marginal condition for the onset of convective instability is deduced as follows;

$$(\alpha F_H h/\rho c\kappa\beta\Delta S)A=(P+\tau)/(1+P)\fallingdotseq 0.9, \qquad (2)$$

where A is a time-dependent function, and $A\rightarrow 1$ when $t\rightarrow\infty$.

Putting $A=1$, the following relation (3) gives a criterion for judging the development of thermosolutal convection.

$$\alpha F_H h/\rho c\kappa\beta\Delta S\geqq 0.9. \qquad (3)$$

Distributions of $\alpha F_H h/\rho c\kappa\beta\Delta S$ in Lakes Vanda, Bonney and Miers are shown in Figs. 1, 2 and 3 respectively. From these figures, it is concluded that thermosolutal convection develops in the upper part of Lake Vanda and in the deeper part of Lake Miers, though the convective motion in the latter may be very weak; while stratifications in the deeper part of Lake Vanda and in Lake Bonney are quite stable

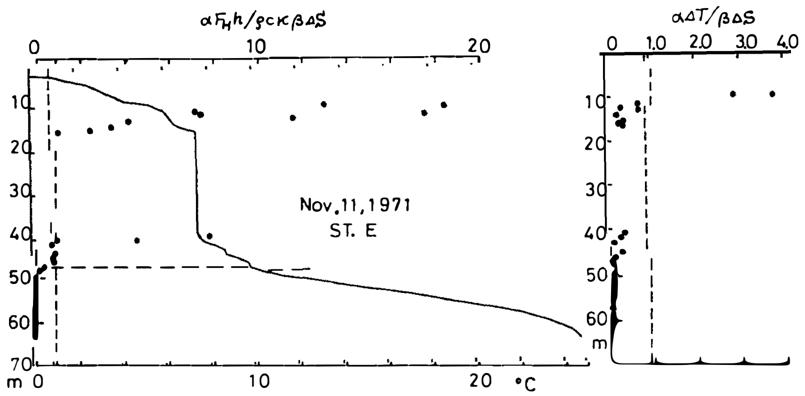

Fig. 1. Distributions of $\alpha\Delta T/\beta\Delta S$ *(right) and* $\alpha F_H h/\rho c\kappa\beta\Delta S$ *(left) in Lake Vanda.*

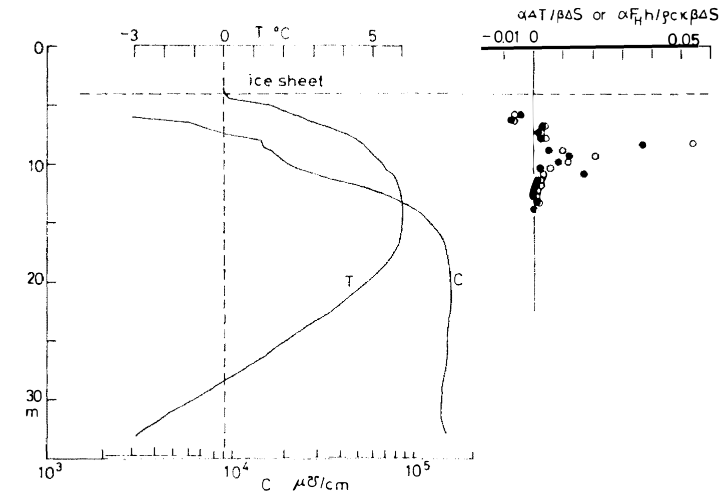

Fig. 2. Profiles of temperature and salinity (left, after TORII et al., 1972) and distributions of $\alpha\Delta T/\beta\Delta S$ *(solid circles) and* $\alpha F_H h/\rho c\kappa\beta\Delta S$ *(hollow circles) in Lake Bonney's east lobe.*

where heat and salt are transported by the molecular process. This result is in accord with what has been indicated by observations and thermal model studies.

When the value of the criterion ($\alpha F_H h/\rho c\kappa\beta\Delta S$) is equal to or slightly larger than the marginal value (*i.e.* 0.9), the theory predicts the development of an oscillating convection whose period is given by the following relation;

$$T=2\pi\sqrt{3(1+P)/\beta g\Delta S/h}. \tag{4}$$

Accompanying oscillation of heat flow may be the just half period of the convective motion itself.

The value of the criterion in the zone about 25 cm below the lake ice in Lake Vanda was from 0.80 to 1.27 on December 1971, which is a possible value for the development of the oscillating convection. The oscillating period is calculated to

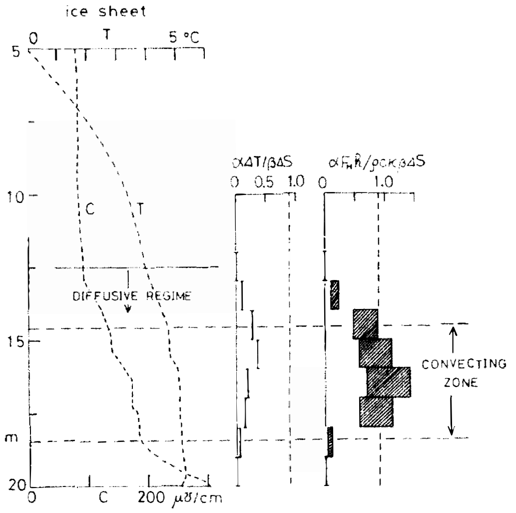

Fig. 3. Profiles of temperature and salinity (left, after BELL, *1967) and distributions of* $\alpha \Delta T/\beta \Delta S$ *(middle) and* $\alpha F_H h/\rho c \kappa \beta \Delta S$ *(right) Lake Miers.*

be from 19.8 to 26.2 minutes, and therefore the period of heat flow oscillation is from 9.9 to 13.1 minutes. Fig. 4 is an example of heat flux chart obtained at the lower surface of the lake ice in Lake Vanda on December 31, 1971. The pattern of the heat flux chart is similar to the solar radiation chart obtained at the ground surface. However, it is noticeable that a small oscillation with short period is always superposed on the record, though a severe disturbance took place around 14 to 15 o'clock due to floating clouds in the sky. Those periods are distributed in the range from 9 to 15 minutes, and the most predominant period is 12 minutes, which agrees well with the theoretical prediction.

It is considered that Lake Vanda was formed by the inflow of glacial melting water on top of a highly concentrated solution or a dried-up salt sediment, and that the salinity profile has been formed by the diffusion process from below (WILSON, 1964). A simple diffusion model shows that the inflow took place about 900 years ago. Since that time, the lake has been continuously heated by the solar radiation. If no convection occurred, Lake Vanda with the present depth would have an ex-

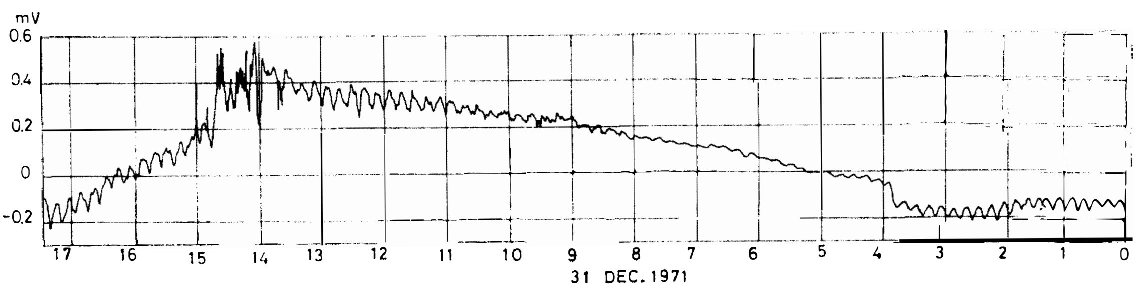

Fig. 4. Heat flux chart obtained at the lower surface of the lake ice in Lake Vanda, December 31, 1971.

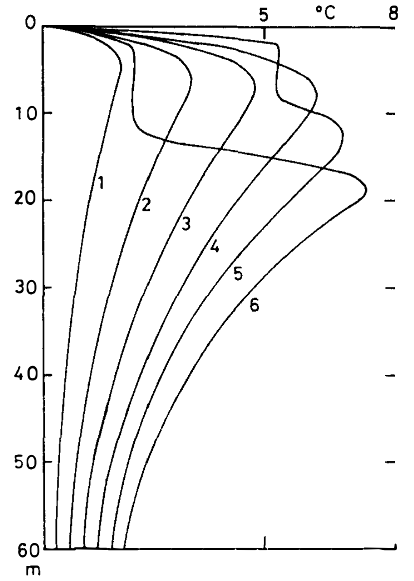

Fig. 5. An example of numerical experiment of thermosolutal convection in Lake Vanda. Numerals are the years lapsed since the beginning of solar heating.

traordinarily high temperature beyond 100°C, and it would take around a thousand years until a thermal steady state could be attained.

Fig. 5 shows an example of numerical experiment of thermosolutal convection in Lake Vanda. Numerals are the years lapsed since the beginning of solar heating. This experiment suggests that convective motion could occur already within several years after the inflow of glacial melting water. This means that the mean diffusivity over the whole lake had shifted from the molecular level to the higher level. Owing to this, the water temperature could not rise so high. Assuming that the present lake level and the present convecting zone have been maintained, it is expected that the maximum temperature of about 23°C must appear near the lake bottom in the steady state, which agrees well with the observation (YUSA, 1975). In this case, such a steady state may have been attained sufficiently after five hundreds years or so.

The onset or the development of thermosolutal convection is determined by the combined effect of the salinity gradient and the intensity of heating. In the deeper part of Lake Vanda as well as in Lake Bonney, no convection can occur at the present time, because of the small amount of heating in comparison with the strong salinity gradient. Since the salinity and its gradient at a certain depth are due essentially to the diffusion from the bottom, they will change in the future with the progress of the diffusion. Depending on this, the value of the criterion at each depth will also change, and consequently the possible zone for the onset of convection may change. Fig. 6 shows a rough prediction of changes in the salinity profile and the criterion in the deeper part of Lake Vanda, supposing the unchangeable lake level and solar radiation. The result shows that it would take more than

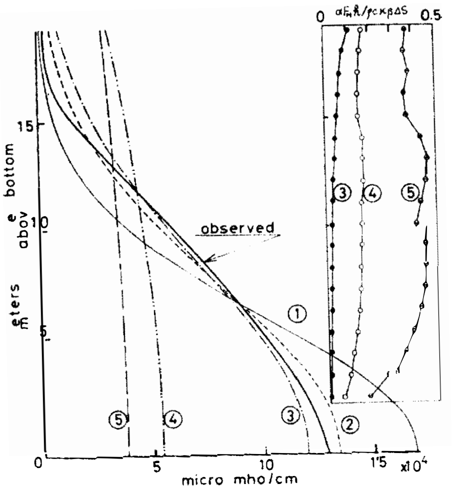

Fig. 6. Calculated profiles of salinity with the observation data and the predicted change of $\alpha F_H h/\rho c\kappa\beta\Delta S$ in Lake Vanda. ①: 500 years, ②: 800 years, ③: 1,000 years, ④: 5,000 years, ⑤: 10,000 years.

10 thousands years for the attainment of a gentle salinity gradient to raise convective instability even in the deeper part. Accordingly, as long as the present lake level is maintained, a general shape of the thermosolutal structure may last extending over a fairly long period for the future.

The existence of numerous ancient shorelines around the lake suggests long-term fluctuation in the lake level. Such a fluctuation changes the amount of solar heating at each depth, and the value of F_H. Since the change in the criterion due to the salinity change is extremely slow, the development of thermosolutal structure in the future may be influenced significantly by the lake level fluctuation.

References

Baines, P. G. and Gill, A. E. (1969): On thermohaline convection with linear gradients. J. Fluid Mech., **37** (2), 289–306.

Bell, R. A. I. (1967): Lake Miers, South Victoria Land, Antarctica. N. Z. J. Geol. Geophys., **10**, 540–556.

Hoare, R. A. (1966): Problems of heat transfer in Lake Vanda, a density stratified antarctic lake. Nature, **210**, 787–789.

Hoare, R. A., Popplewell, K. B., House, D. A., Henderson, R. A., Prebble, W. M. and Wilson, A. T. (1964): Lake Bonney, Taylor Valley, Antarctica: A natural solar energy trap. Nature, **202**, 886–888.

Hoare, R. A., Popplewell, K. B., House, D. A., Henderson, R. A., Prebble, W. M. and Wilson, A. T. (1965): Solar heating of Lake Fryxell, a permanently ice-covered antarctic lake. J. Geophys. Res., **70**, 1555–1558.

Shirtcliffe, T. G. L. and Benseman, R. F. (1964): A sun-heated antarctic lake. J. Geophys. Res., **69**, 3355–3359.

Shirtcliffe, T. G. L. and Calhaem, I. M. (1968): Measurements of temperature and electrical conductivity in Lake Vanda, Victoria Land, Antarctica. N. Z. J. Geol. Geophys., **11**, 976–981.

TORII, T., YUSA, Y., NAKAO, K. and HASHIMOTO, T. (1972): Nankyoku Bikutoria Rando no Dorai Barê chôsa hôkoku. X. 1971–1972-nen no Banda-ko o chûshin to shita chikyû butsuri oyobi chikyû kagaku-teki chôsa ni tsuite (yohô) (Report of the Japanese Summer Parties in Dry Valleys, Victoria Land. X. A preliminary report of the geophysical and geochemical studies at Lake Vanda and in the adjacent Dry Valleys in 1971–1972). Nankyoku Shiryô (Antarct. Rec.), **45**, 76–88.

TURNER, J. S. and STOMMEL, H. (1964): A new case of convection in the presence of combined vertical salinity and temperature gradients. Proc. Natl Sci., **52**, 49–53.

VERONIS, G. (1965): On finite amplitude instability in thermohaline convection. J. Marine Res., **23**, 1–17.

WILSON, A. T. (1964): Evidence from chemical diffusion of a climatic change in the McMurdo Dry Valleys 1200 years ago. Nature, **201**, 176–177.

WILSON, A. T. and WELLMAN, H. W. (1962): Lake Vanda: An antarctic lake. Nature, **196**, 1171–1173.

YOSHIDA, Y., YUSA, Y., MORIWAKI, K. and TORII, T. (1971): Nankyoku Bikutoria Rando no Dorai Barê chôsa hôkoku. IX. 1970–1971-nen no Dorai Barê chôsa—chikyû butsurigaku-teki kenkyû o chûshin to shita—ni tsuite (yohô) (Report of the Japanese Summer Parties in Dry Valleys, Victoria Land. IX. A preliminary report of the geophysical study of Dry Valleys in 1970–1971). Nankyoku Shiryô (Antarct. Rec.), **42**, 65–88.

YUSA, Y. (1972): The re-evaluation of heat balance in Lake Vanda, Victoria Land, Antarctica. Contrib. Geophys. Inst. Kyoto Univ., **12**, 87–100.

YUSA, Y. (1975): On the water temperature in Lake Vanda, Victoria Land, Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **4**, 75–89.

(*Received August 31, 1978*)