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Climatic Temperature Anomaly in Bottom Sediments of Lake Biwa

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Abstract

Bottom sediments in deep and old lakes afford a substantial clue to climatic records of past cold events because pore water in clayey sediments is so influid that it is treatable with regard to a question of heat conduction, the bottom temperature being stable.

In this connection, Lake Biwa (35°15′N, 136°05′E), the largest and oldest lake in Japan, which originates from a tectonic movement and whose clayey lacustrine sediments amount to more than 1,000 meters thick, was selected for a deep drilling to the depth of 200 meters below the lake floor.

After the drilling, measurements were made by UYEDA and YASUI of ground temperature in the hole drilled by HORIE and of thermal conductivity of core samples.

The vertical temperature profile obtained shows a straight line in horizons deeper than 75 meters under the lake bottom but the profile in shallower horizons deviates from an extrapolated straight line, indicating a climatic temperature anomaly in an unsteady state affected by a climatic change.

A terrestrial heat flow was calculated to be 1.31×10^{-6} cal/cm^2 s, using the thermal conductivity of 2.30×10^{-3} cal/cm s °C and the thermal gradient of 5.7×10^{-4}°C/cm in horizons deeper than 75 meters in a steady state.

Estimation of an ancient air temperature from geothermal data in the lake sediment was attempted with a view to examining the thermal regime in lake water because the temperature of the lake water lies between the estimated bottom surface temperature and the air temperature.

In Lake Biwa, the following relation was found:

$$T_{70} = 0.75T_{aw}+3.83\ ,$$

where T_{70} is the annual mean temperature in °C in the water depth of 70 meters and T_{aw} is the mean air temperature in °C in winter from December to March.

On the calculation to evaluate the climatic temperature anomaly in the sediments above the 75-meter horizon, the suitable value of 2.43×10^{-3} cm^2/s was chosen as thermal diffusivity. From the results of investigating, it is concluded clearly that in Little Ice Age the annual mean bottom temperature was lower by about 1.5°C than in the present time and the mean air temperature in winter was also lower by about 2°C than in the present time in the central Japan.

1. Introduction

Selection of a suitable field, where movement of ground water does not disturb vertical profiles of ground temperature and allows treatment thereof as a question of heat conduction, is necessary in examination of climatic records of past cold events preserved underground.

Formerly, Lachenbruch[1] studied the climatic temperature anomaly measured in permafrost at Barrow, Alaska, where the confining permafrost in which the movement of fluid is impossible reaches to the depth of about 400 meters.

In addition to the permafrost, the lake bottom sediments also offer a suitable field for pursuing this examination, because it has two advantages, namely, in large and deep lakes that are clayey, consequently, pore water in the sediments is influid, and the thermal diffusivity is about 0.002 cm^2/s, smaller than that of permafrost (about 0.01 cm^2/s); therefore, a climatic anomaly on profiles of ground temperature is likely to be found in shallower depths than in the permafrost.

Meanwhile, Lake Biwa retains a thick clayey lacustrine sediments more than 1,000 meters in thickness. A 200-meter long hole was drilled by HORIE so that a sediments core was obtained from the lake bottom at the water depth of 65 meters downward in the center of Lake Biwa in the coures of 1971.

After the hole was drilled, measurements were made by UYEDA and YASUI[2] of ground temperature in the hole, resulting in vertical profiles of it and of heat conductivity of core samples.

As we attempt to estimate an ancient air temperature from the data, the thermal regime in lake water should be firstly examined because the temperature of lake water lies between the estimated bottom temperature and air temperature.

2. General characteristics and thermal properties of Lake Biwa

Lake Biwa originating from a tectonic movement is the largest and the oldest lake in Japan, 674.4 km^2 in area and 104 m in maximum depth. Its location being northernmost among tropical lakes in the Japanese islands, the lake is classified as a warm monomictic lake on a thermal regime.

Measurements have been made of water temperature monthly by Shiga Prefecture Fishery Experiment Station at the center of the traversed line from Hikone to Funaki-zaki since 1917.

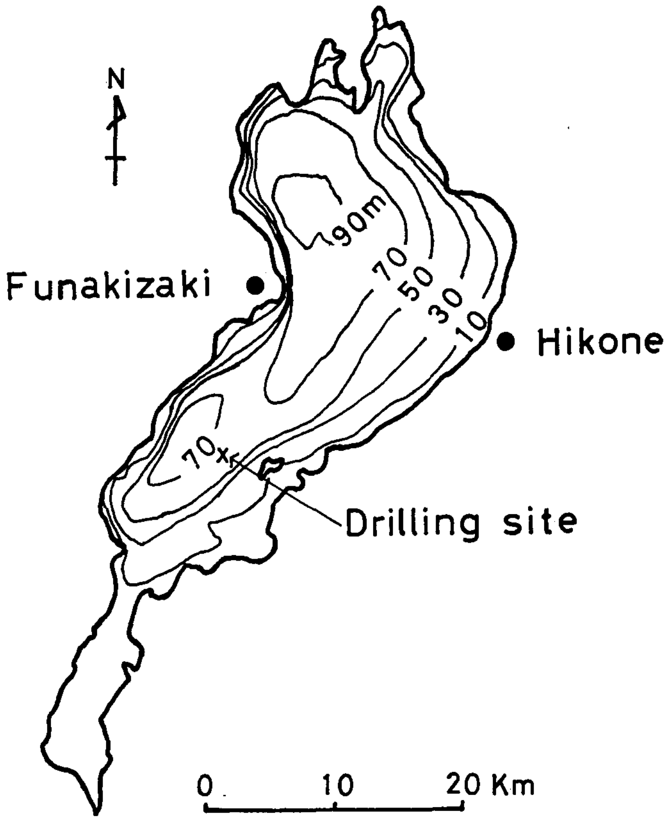

Fig. 1 Bathymetric map of Lake Biwa, locations of drilling and temperature measuring site.

Such data accumulated for a long period of time are useful in examination of thermal properties in the lake. They disclose that lake water is continuously heated from March to August in the epilimnion above the depth of 5 meters, the period being called summer stagnation period, and that this heating period extends longer with increasing water depth; namely the water mass in the hypolimnion deeper than the depth of 50 meters is gradually heated during ten months from March to January and is rapidly cooled subsequently until March, as shown in Fig. 2.

Also, downward heat fluxes averaged from 1948 to 1973 were calculated by using changes in heat storage in each water stratum (Fig. 3). The heat

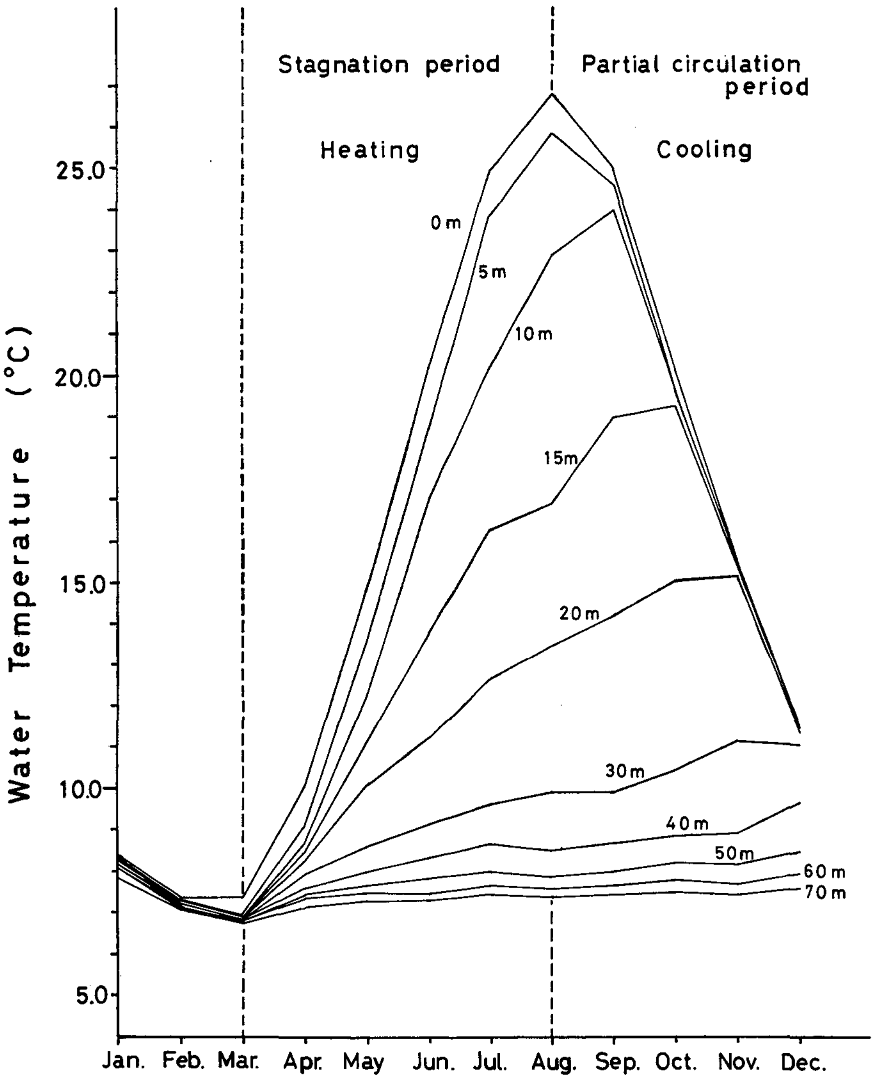

Fig. 2 Annual variations in water temperature in Lake Biwa, averaged monthly from 1948 to 1973.

flux downward from the depth of 50 meters is only one - hundredth of that through the water surface.

Meanwhile, Fig. 4 presents secular variations in annual mean air temperature (T_{air}), mean air temperature in winter from December to

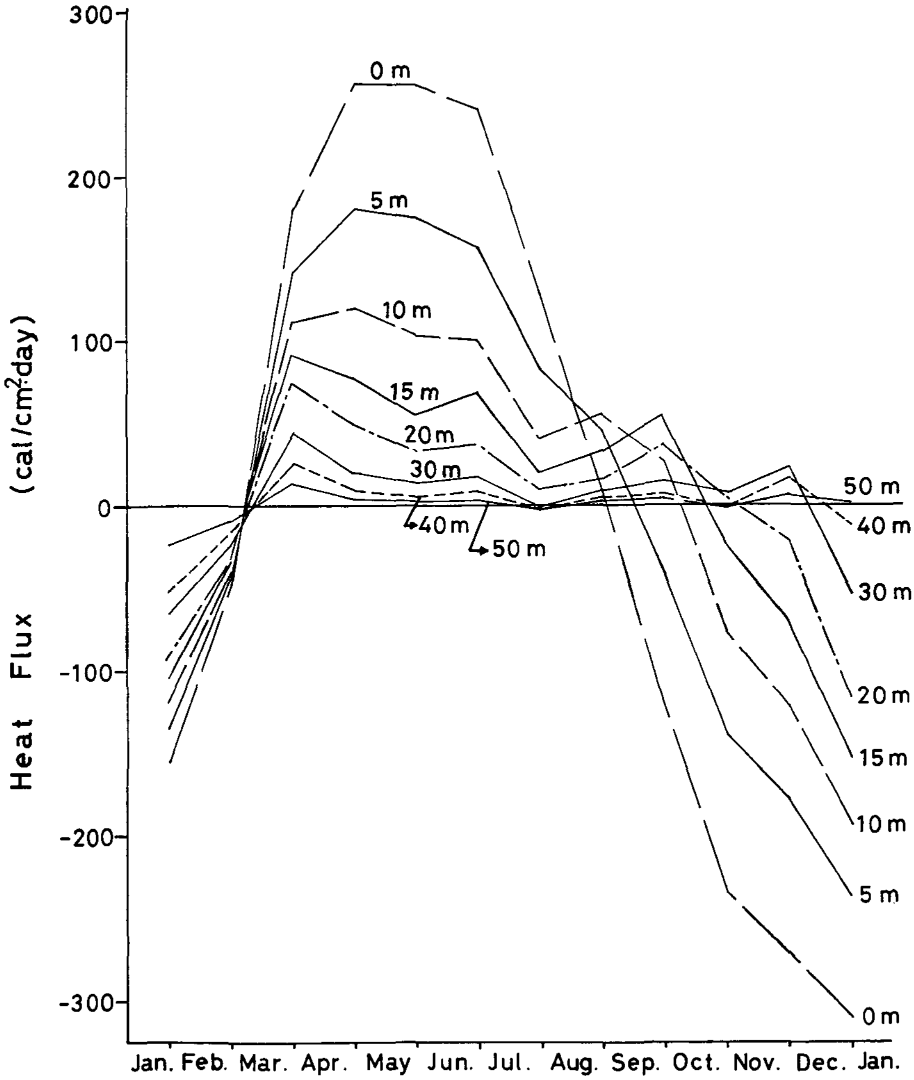

Fig. 3 Annual variations in heat flux through the each depth in Lake Biwa, averaged monthly from 1948 to 1973.

March at Hikone Meteorological Observatory (T_{aw}), annual mean water temperature in each depth (the depth being indicated in figure), and minimum water temperature in the depth of 70 meters (T_{min}). A correlation is found

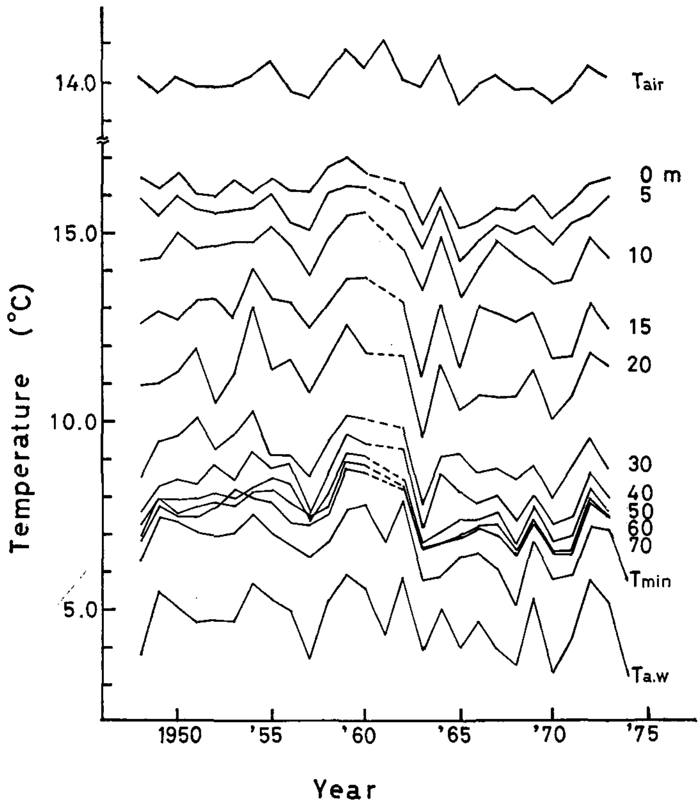

Fig. 4 Secular variations in annual mean air temperature (T_{air}) and annual mean air temperature in winter (T_{aw}) observed respectively at Hikone Meteorological Observatory, minimum water temperature in the depth of 70 meters (T_{min}) and annual mean water temperature in each depth (the depth being indicated in the figure) in Lake Biwa.

between the mean water temperature in the epilimnion and T_{air}; a good correlation is found between T_{min} and T_{air}.

Examinations of the thermal stratification disclose that, though the thermal regime is stable in terms of annual change, the regime in the hypolimnion is unstable or catastrophic in terms of secular change. Relations between T_{min} and T_{70} at the bottom surface 70 meters below the water surface, between T_{min} and T_{aw} and T_{70} vs. T_{aw} are shown in Figs. 5, 6, 7. If a temperature deviation from the present temperature at the bottom surface (or bottom water) is calculated by examining a climatic temperature anomaly

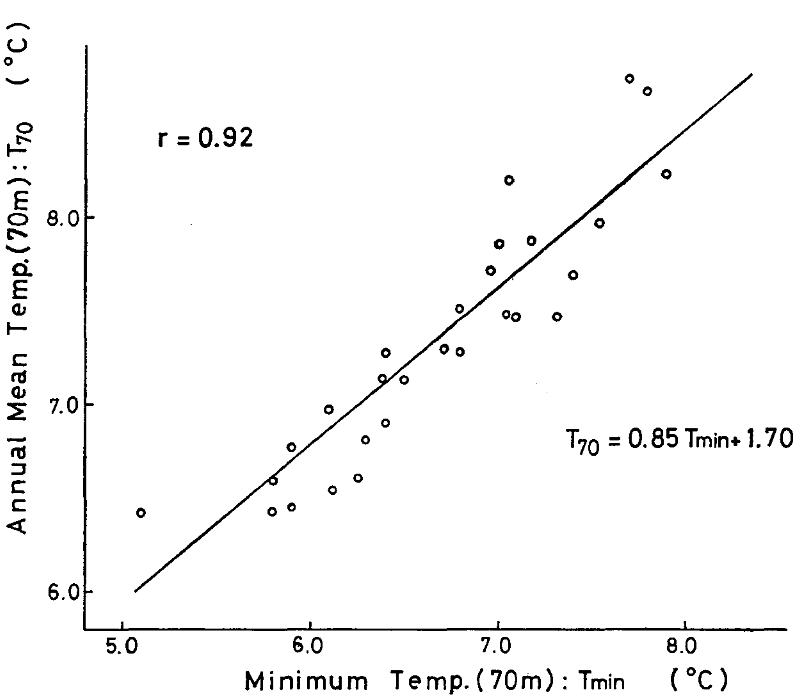

Fig. 5 Relation between annual mean water temperature (T_{70}) and minimum temperature ($T_{\min}$) at water depth of 70 meters. The equation represents the regression line, correlation coefficient being $r=0.92$.

in the drilled hole, then the mean winter air temperature in the past is derived from the following relation:

$$T_{70} = 0.75T_{aw} + 3.83\,, \tag{1}$$

where temperature is expressed in °C.

3. Vertical profiles of ground temperature in the bottom sediments

Generally, in a steady state the vertical profile of ground temperature $T(z)$ is given by:

$$T(z) = qz/k + T_0\,, \tag{2}$$

where q is the terrestrial heat flow and k is the thermal conductivity, T_0 is the annual mean temperature at the bottom surface, and z is the depth under the bottom surface.

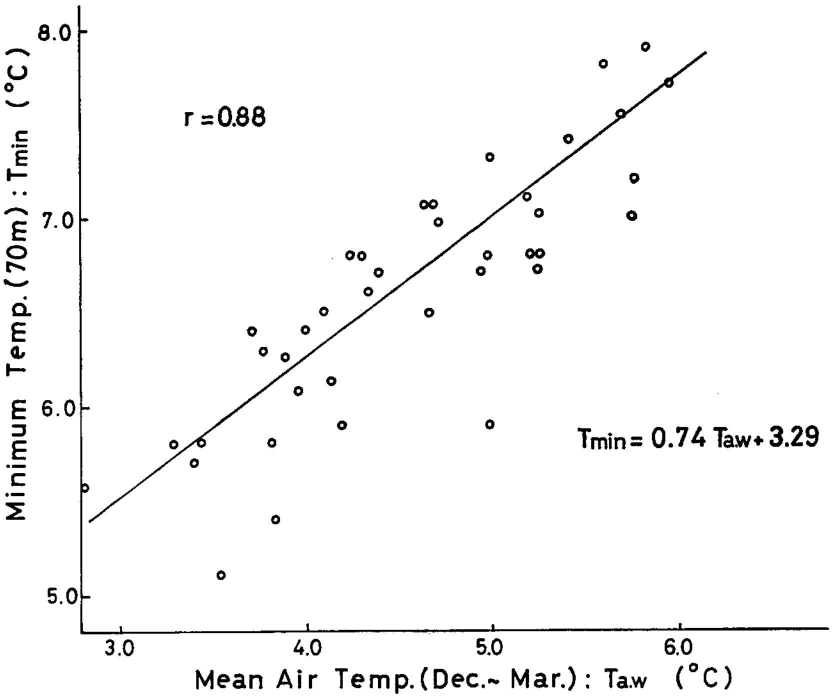

Fig. 6 Relation between minimum temperature at water depth of 70 meters (T_{min}) and mean air temperature in winter (T_{aw}). The equation represents the regression line, correlation coefficient being $r=0.88$.

If q and k are constant, the vertical profile should be shown by a straight line. From Fig. 8 it appears that the profile fits a straight line below the horizon 75 meters below the bottom surface, but the solid line extrapolated from a fitting line in the deeper zone deviates from plots of observed temperatures in depths above the horizon. Also a broken line in Fig. 8 shows the temperature profile in a steady state in consideration of a variation in thermal conductivity in each stratum above the horizon.

Undoubtedly, in depths above the horizon the temperature profile indicates a climatic temperature anomaly in an unsteady state affected by a climatic change.

Thermal properties of the sediments of Lake Biwa are shown in Table 1, where thermal conductivity in each stratum is given by the harmonic mean of the measured values. Thermal diffusivities of $\alpha_1=2.43\times10^{-3}$ cal/cm^2,

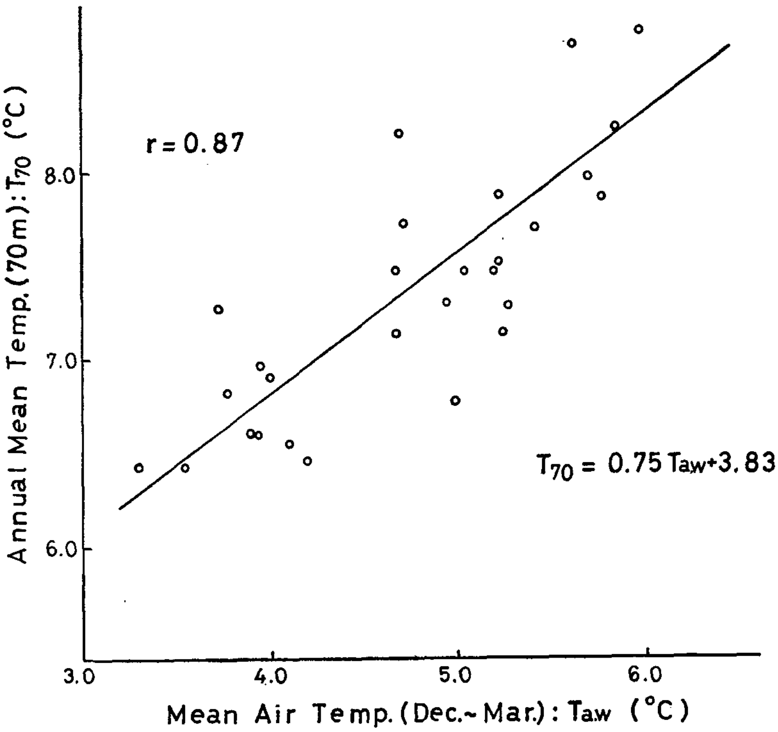

Fig. 7 Relation between annual mean temperature at water depth of 70 meters (T_{70}) and mean air temperature in winter (T_{aw}). The equation represents the regression line, correlation coefficient being r=0.87.

Table 1. Thermal properties of the sediments of Lake Biwa.

depth (m)	conductivity ($\times 10^{-3}$ cal/cm.s.°C)	heat flow ($\times 10^{-6}$cal/cm^2.s)	diffusivity ($\times 10^{-3}$ cal/cm^2)		
			α_1	α_2	α_3
0- 10	1.77				
10- 45	2.02 } 2.04 (mean)		2.43	2.42	2.58
45- 75	2.10 }				
75-200	2.30	1.31			

$\alpha_2=2.42\times 10^{-3}$cal/cm^2, $\alpha_3=2.58\times 10^{-3}$ cal/cm^2 were respectively obtained as follows:

1) The value of α_1 was derived from a general relation between thermal conductivity and thermal diffusivity (α), namely $\alpha=1.53k$-0.70×10^{-3} (in the c.g.s. unit), where $k=2.04\times 10^{-3}$ cal/cm s °C as the harmonic mean above

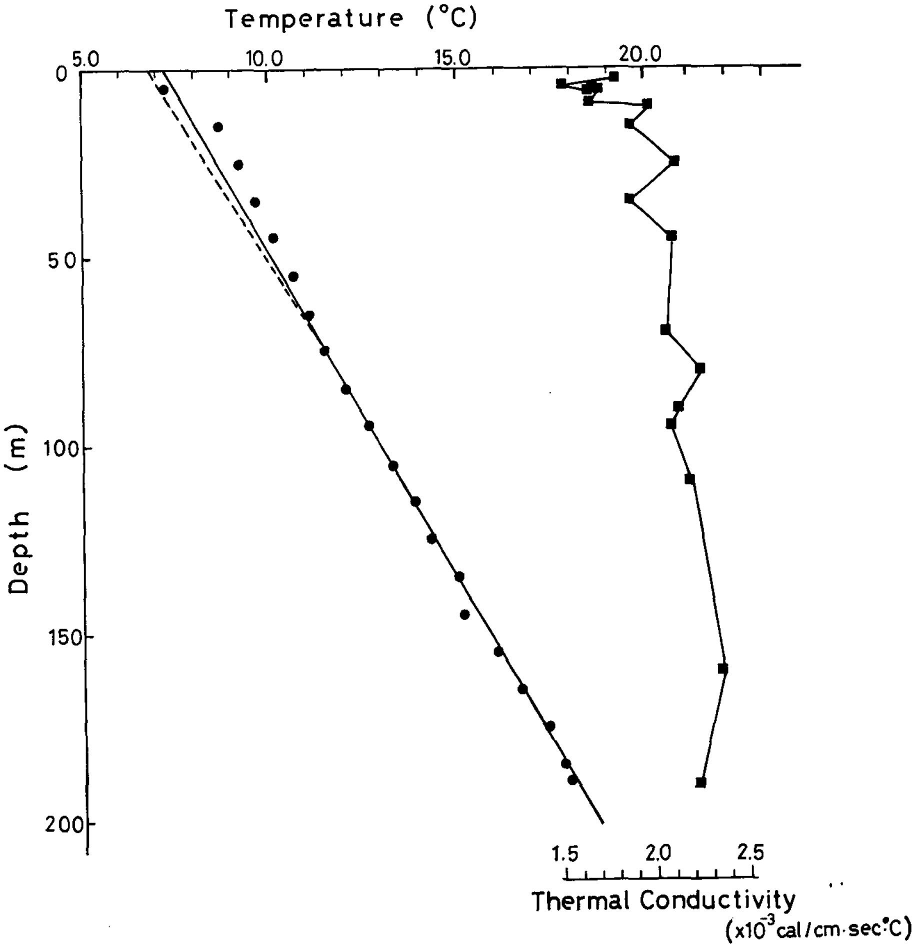

Fig. 8 Vertical profiles of ground temperature (●) and thermal conductivity (■) in bottom sediments of Lake Biwa.

the sediments depth of 75 meters;

2) The value of α_2 was derived from $\alpha=k/\rho c$, where c, the specific heat, is given by Bullard's relation[3], namely $c=0.18+0.82w$ (in the c.g.s. unit) in which $w=\{(\rho_w\rho_s/\rho)-\rho_w\}/(\rho_s-\rho_w)$, w being the water content, ρ_w the pore water density, ρ_s the solid density, and ρ the bulk density, whereas $k=2.04\times10^{-3}$ cal/cm s °C, from values given by YAMAMOTO et al.[4] as $\rho_w=1$ g/cm^3, $\rho_s=2.62$ g/cm^3 and $\rho=1.49$ g/cm^3;

3) Finally the value of α_3 was derived from $k=2.17\times10^{-3}$ cal/cm s °C as the harmonic mean from the bottom surface to the sediments depth of 180 meters, other values being the same as those used in 2) above.

The terrestrial heat flow of 1.31×10^{-6} cal/cm^2 s was calculated from $k=2.30\times10^{-3}$ cal/cm s °C and the thermal gradient of 5.7×10^{-4} °C/cm below the sediments depth of 75 meters.

4. Evaluations of a climatic temperature anomaly in vertical profiles of ground temperature

Generally, if the annual mean temperature at the ground surface or lake bottom surface undergoes the change of ΔT at $z=0$, that is shown by:

$$T(0) = (q/k)z + T_0 + \Delta T\,. \tag{3}$$

And at an arbitrary horizon and a time lapse:

$$T(z, t) = (q/k)z + T_0 + \Delta T(z, t)\,.$$

Lachenbruch gave secular variations in annual mean temperature at the ground surface as follows:

$$T(0, t) = Dt^{(1/2)\,n}, \qquad n = 0, 1, 2, \tag{4}$$

where D is a constant.

Then, the temperature disturbance is given by:

$$\Delta T(z, t) = \Delta T(0, t)\,\frac{i^n \operatorname{erfc} \dfrac{z}{2\sqrt{\alpha t}}}{i^n \operatorname{erfc} 0}\,, \tag{5}$$

where $i^n \operatorname{erfc}(x)$ is the repeated integral of the error function, $\operatorname{erfc}(x)$, and given by:

$$i^n \operatorname{erfc}(x) = \int_x^\infty i^{n-1} \operatorname{erfc} u\, du\,,$$

$$i^0 \operatorname{erfc}(x) = \operatorname{erfc}(x)\,.$$

If the secular variation starts on the bottom surface in t_1 years before present and the thermal regime in the sediments was in a steady state before t_1 years, a temperature disturbance at present is given by:

$$\Delta T(z, t_1) = \Delta T(0, t_1)\,\frac{i^n \operatorname{erfc} \dfrac{z}{2\sqrt{\alpha t}}}{i^n \operatorname{erfc} 0}\,. \tag{6}$$

Determinations to choose the proper values of ΔT_0 of initial temperature deviations at present on the bottom surface and T_1 are performed by fiting between the calculated values of climatic temperature anomaly and the measured values for each of values of n as shown in Fig. 9.

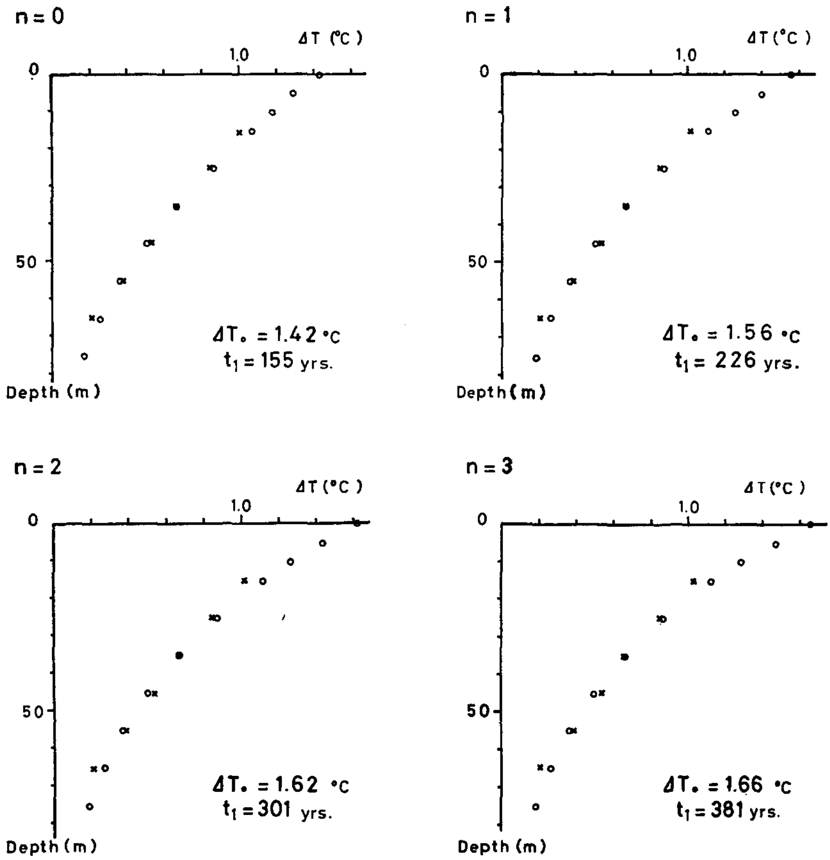

Fig. 9 The fitting between calculated climatic temperature anomaly for measured value in Lake Biwa, o: calculated value, ×: measured value.

The thermal diffusivity uses the suitable value of $\alpha=2.43\times10^{-3}$ cm^2/s on the calculation because a difference between the calculated and the measured value is not recognized over a narrow range of α from $2.43\times10^{-3}\sim2.58\times10^{-3}$ cm^2/s, and a suitable fitting cannot be obtained over the limit of $n=4$.

Furthermore, secular changes in bottom surface temperature are calculated by using the known values of ΔT_0, T_1 as shown in Fig. 10. A temperature rise is found in the period of Little Ice Age from 1500 to 1850, and if the temperature rose rapidly after Little Ice Age, 0 or 1 would be suitable as the value of n.

Table 2 collectively indicates a temperature rise from Little Ice Age to present, whose annual mean bottom temperature is 1.6°C and mean air temperature in winter is 2.1°C.

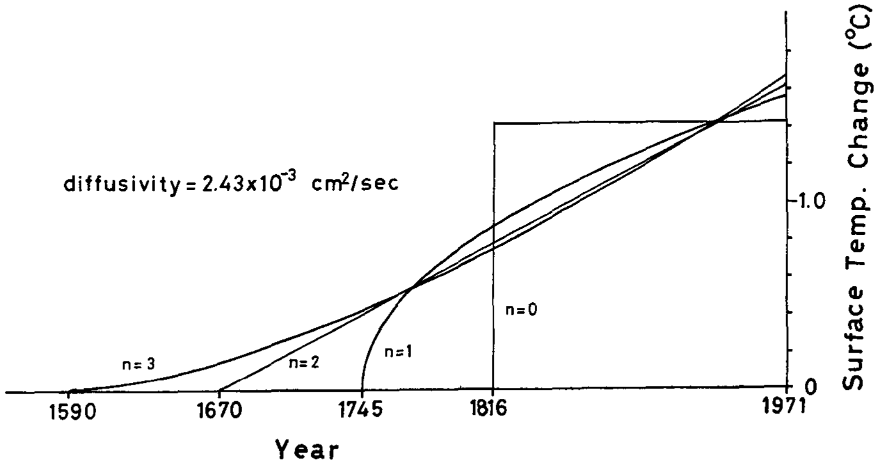

Fig. 10 Secular changes in bottom surface temperature in Lake Biwa after Little Ice Age.

Table 2. Estimated temperature rise from Little Ice Age to present for each value of n.

	bottom temp. change (°C)		air temp. change (°C)	
n=0	1.42	1.5	1.89	2.0
n=1	1.56		2.08	
n=2	1.62		2.16	
n=3	1.66		2.21	

4. Conclusions

As the results of investigating the climatic temperature anomaly in the bottom sediments in Lake Biwa, we obtained significant information with respect to the air temperature in Little Ice Age, which passed through a cold climate worldwide during the period from 1500 to 1850.

It is concluded clearly, as compared with the present time, that in this age the annual mean bottom temperature of the lake was lower by about 1.5°C, accordingly suggesting strongly the lake's retention of the thermal regime characteristics of tropical lakes, and that the mean air temperature in winter was lower by 2°C in the central Japan.

Meanwhile, on the basis of the fact that freezing successively occurred in the River Yodo discharged from Lake Biwa, YAMAMOTO[5] estimated that the mean January air temperature was lower by 1.3°C in the first half of the 19th century than in the present time. A close agreement between this and our results was obtained.

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