A Physical Treatment on the Accumulated Materials of the Annual Temperature Variation in Lakes and Ocean

by

Tadao TAKAHASHI

Abstract

A practical procedure based on Namekawa's theory is presented, which takes ingeniously the upward heat flux in cooling stage into consideration. The amount of annual heat exchange and annual mean eddy thermal diffusivity are calculated by this procedure from the materials of annual variation of water temperature in 17 lakes and 113 stations in the sea around Japan. Their vertical and geographical distributions are discussed.

1. Introduction

It is hard to take systematic observations of different elements in lakes or ocean, but great numbers of temperature data, which could be taken with a little effort, have been accumulated. These materials have been scarecely treated physically or climatologically.

A new idea concerning the annual variation of water temperature is manifested by T. Namekawa.[1] It is proposed by him to treat the accumulated materials by a method derived from the idea. The present study is performed in accordance with the proposal.

2. Basic Principle

T. Namekawa questioned why the vertical profile of the annual mean temperature ($\bar{\theta}$) shows always downward gradient ($-\frac{\partial\bar{\theta}}{\partial z}>0$, z positive downwards) in the upper layer of lakes and ocean, notwithstanding the isothermal vertical profile ($\frac{\partial\bar{\theta}}{\partial z}=0$) is established for underground temperature on land. Adopting the well-known eddy equation of $\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(k\frac{\partial\theta}{\partial z}\right)$, where k is eddy thermal diffusivity, to annual mean temperature ($\bar{\theta}$), we have $\frac{\partial}{\partial z}\left(k\frac{\partial\bar{\theta}}{\partial z}\right)=0$ or $k\frac{\partial\bar{\theta}}{\partial z}=C$ (independent of z), since $\frac{\partial\bar{\theta}}{\partial t}=0$. Moreover, annual total flux of heat through the surface of lakes or ocean must be zero; otherwise the water temperature undergoes unidirectional change, which has no physical reality. In fact, this condition of $k\frac{\partial\bar{\theta}}{\partial z}=0$ or $C=0$ is satisfied by observed annual mean underground temperature which shows $\bar{\theta}=$const. (independent of z). However, the actual annual mean water temperature does not show $k\frac{\partial\bar{\theta}}{\partial z}=0$, which is the first point in question. Furthermore, even if we allow $C\neq0$ in $k\frac{\partial\bar{\theta}}{\partial z}=C$

(independent of z), we meet a following serious contradiction. Since the actual profile shows $\frac{\partial\bar{\theta}}{\partial z}\to 0$ in deep layer of lakes or ocean, $k\to\infty$ in such a deep layer where any vigorous stirring cannot be expected.

These paradoxes may be settled by taking into account another kind of heat transfer, existing only during the cooling stage, not included in the expression of $k\frac{\partial\theta}{\partial z}$. Acting surface of the cooling process during the cooling stage is the water surface itself. Accordingly, in the first step a temporary upward gradient $(-\frac{\partial\theta}{\partial z}<0)$ appears in the surface layer. This state, however, shows statical instability at any temperature higher than that of maximum density, whence the overturn or mixing up happens immediately to make an isothermal layer $(-\frac{\partial\theta}{\partial z}=0)$ within the water column in question. Thus the isothermal layer developes from the surface to deeper layer when the cooling proceeds, as shown by the actual observed temperature profile during cooling stage. In this process, we must not miss the existence of upward heat flux caused by the temporary mixing process, maintaining the condition of $-\frac{\partial\theta}{\partial z}=0$ which indicates no flux of heat. In fact, notwithstanding the surface value of $-\frac{\partial\theta}{\partial z}$ throughout the cooling stage is zero $(-\left.\frac{\partial\theta}{\partial z}\right|_{z=0}=0)$, which indicates no eddy transfer of heat, the observed fact shows that the heat contents within the lakes or ocean decrease as the cooling stage proceeds. On the other hand, through the warming stage the surface value of $-\frac{\partial\theta}{\partial z}$ is positive, showing the prevalence of the downward heat which causes the increase of the heat contents within the whole water column. Thus the maximum heat contents (q_{max}) appears at the epoch when $-\frac{\partial\theta}{\partial z}>0\to-\frac{\partial\theta}{\partial z}=0$ and by the same reason, q_{min} appears when $-\frac{\partial\theta}{\partial z}=0\to-\frac{\partial\theta}{\partial z}>0$. The value of $q_{max}-q_{min}$ can be obtained from the observational data of water temperature at these epochs, by the aid of $q_{max}-q_{min}=\left[\int_0^\infty c\rho\theta dz\right]_{max}-\left[\int_0^\infty c\rho\theta dz\right]_{min}$ assuming $c\rho\fallingdotseq 1$, where c is specific heat of water, and ρ density. This value$(q_{max}-q_{min})$ must be equal to the total amount of upward heat flux under the condition of $-\left.\frac{\partial\theta}{\partial z}\right|_{z=0}=0$ during the cooling stage. On the other hand, the total amount of the apparent downward heat flux due to eddy conduction all the year round is equal to $-k\left.\frac{\partial\bar{\theta}}{\partial z}\right|_{z=0}\cdot T$, where k is annual mean eddy thermal diffusivity or eddy conductivity in kinematic form, and T=a year $=365\frac{1}{4}\times 24\times 60\times 60$ (sec). If we consider that this apparent downward heat flux is compensated by the upward flux due to the mixing process, the complete heat balance can be established and the question is settled; i. e.

$$-k\frac{\partial\bar{\theta}}{\partial z}\bigg|_{z=0}\cdot T=q_{max}-q_{min}. \qquad (1)$$

The relation gives a way for calculating the surface value of the annual mean eddy thermal diffusivity ($k_{z=0}$) from the observed temperature profile within lakes or ocean.

It is clear that the above relation can hold not only at the water surface but also at any depth within the water column, accordingly we have a general working formula of

$$k_z=\frac{q_{max}-q_{min}}{\dfrac{\partial\bar{\theta}}{\partial z}\bigg|_{z}\cdot T}, \qquad (2)$$

where $$q_{max}-q_{min}=\left[\int_z^\infty c\rho\theta dz\right]_{max}-\left[\int_z^\infty c\rho\theta dz\right]_{min},$$

and k_z is annual mean eddy thermal diffusivity at any depth z.

3. Materials and the Procedure of Treatment

In many Japanese lakes some fragmental observations were taken by individual observers, though systematic observations were carried out in Lake Biwa[2] (1936–1941, 1947–1955) and Lake Sai[3] (1936–1947). We get among them the data for 10 lakes[4] which can be used for our immediate purpose and add the data for 7 European lakes from several publications.[5] The surface minimum temperature of these selected lakes is not below 4°C. The observing depths in each lake are not all the same one another, but observations at 0, 10, 20, 40, and 100 meters in depth are taken in many lakes.

In the sea around Japanese Islands, the regular observations (once or twice a month) have been continued at many localities for many years. Adding some data taken from the reports of some fragmental observations to give the geographical distribution of the behavior of annual variation of water temperature, the author preferes the data for 113 stations[6] in the sea around Japanese Islands.

The procedure of treatment is shown by the following examples. The data of the systematic observations in Lake Biwa is employed as the first example. The basic data which give the normal behavior of the annual variation of water temperature in Lake Biwa is derived from 15 year observations by taking the mean values of observed monthly temperature for consecutive years. The results are shown in Tabe 1 and Fig. 1. By the aid of Fig. 1, we can calculate the value of $q=\int_z^\infty \theta dz$ for every month and every depth. Then, we can find the epochs of the maximum and minimum of q and the amount of the annual heat exchang, $Q(=q_{max}-q_{min})$, for each depth. These values are listed in Table 2.

Table 1.

Monthly mean temperature in Lake Biwa (°C) (1936–1941, 1947–1955)

Depth(m)	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
0	8.37	7.13	7.69	9.82	15.45	20.90	24.89	28.35	24.84	19.87	15.50	11.70	16.21
5	8.35	7.14	7.07	8.80	13.69	19.16	23.61	27.06	24.40	19.51	15.45	11.65	15.49
10	8.31	7.09	7.02	8.55	12.22	17.25	19.92	22.65	24.06	19.53	15.36	11.64	14.47
15	8.34	7.10	7.00	8.36	11.03	13.70	16.02	17.32	19.20	19.22	15.39	11.69	12.86
20	8.34	7.07	6.94	8.12	9.72	11.28	12.34	13.03	14.28	15.71	15.32	11.65	11.15
30	8.32	7.09	6.93	7.78	8.38	9.27	9.62	9.88	9.65	10.00	10.84	11.56	9.11
40	8.31	7.03	6.90	7.55	7.82	8.34	8.50	8.31	8.51	8.35	8.53	9.46	8.13
50	8.08	7.03	6.89	7.31	7.40	7.87	7.95	7.89	7.84	7.75	7.94	8.26	7.68
60	7.92	7.07	6.88	7.23	7.20	7.41	7.56	7.44	7.54	7.43	7.60	7.93	7.43
70	7.66	7.06	6.83	6.99	7.05	7.32	7.39	7.21	7.29	7.22	7.40	7.71	7.26

Table 2.

The amount of annual heat exchange in Lake Biwa

Depth (m)	Time of q_{max}	Time of q_{min}	$Q(10^3$ cal.)
0	Sept.	March	39.0
5	Sept.	March	30.3
10	Sept.	March	21.8
15	Nov.	March	15.6
20	Dec.	March	12.2
30	Dec.	March	7.5
40	Dec.	March	3.9
50	Dec.	March	2.2
60	Dec.	March	1.0

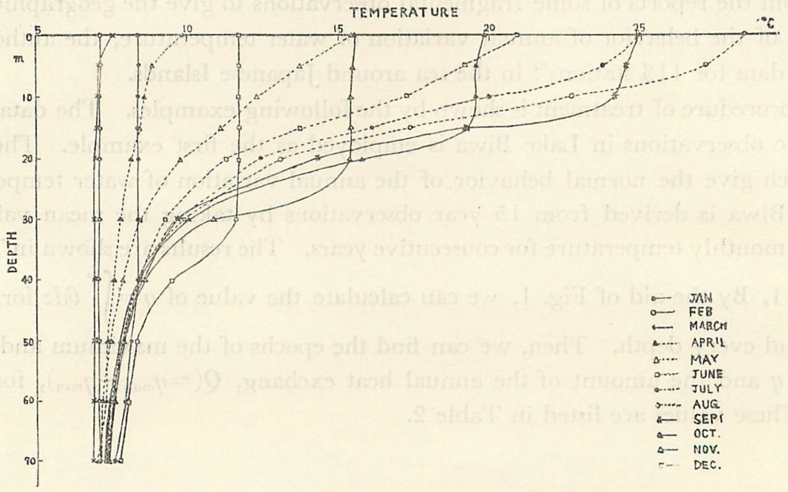

Fig. 1. Monthly temperature profiles in Lake Biwa.

The annual mean eddy thermal diffusivity at a specified depth (k_z) can be found by the basic equation (2) when we know the value of $-\frac{\partial\bar{\theta}}{\partial z}$ at the depth. However, the accurate determination of $-\frac{\partial\bar{\theta}}{\partial z}$ is difficult from our basic data. The determination of a tangent on the temperature profile curve involves individual ambiguities in drawing the curve passing the observed values, because the distances between the successive observing depths are not sufficiently small. For the same reason, the approximation putting $\frac{\partial\bar{\theta}}{\partial z} \fallingdotseq \frac{\Delta\bar{\theta}}{\Delta z}$ causes erroneous results, where $\Delta\bar{\theta}$ is annual mean temperature difference between the distance of Δz.

Avoiding the difficulty, a practical procedure of treatment proposed by the author is as follows. Divide the whole water column into several standard layers which are assumed to have the constant eddy thermal diffusivity (k) within the specified layer. The standard layers are conveniently selected as 0–10, 10–20, 20–40, 40–100, and below 100m, which are bounded by the observing levels of temperature for almost all the lakes. Then we have from equation (2) for a specified standard layer ($z_1 \sim z_2$)

$$kT\Delta\bar{\theta} = \int_{z_1}^{z_2} Q(z)\, dz,$$

where $\Delta\bar{\theta}(\equiv\bar{\theta}_{z_1} - \bar{\theta}_{z_2})$ is the difference of annual mean water temperature at the depths z_1 and z_2 which are known directly from the basic data. A practical procedure for evaluation of $\int_{z_1}^{z_2} Q(z)dz$, proposed by the author is as follows.

If there exist some observing levels within a specified layer, divide it by the observing levels. And assuming that Q_i is constant within the subdivided layer (Δz_i) and equal to the average of those at the top and the bottom of Δz_i, we have

$$\int_{z_1}^{z_2} Q(z)dz \fallingdotseq \sum_i Q_i \Delta z_i,$$

then

$$kT\Delta\bar{\theta} \fallingdotseq \sum_i Q_i \Delta z_i. \qquad (3)$$

The detailes of the actual calculation by this method can be understood by an example for the standard layer of 0–10m at Lake Biwa shown in Table 3, and the values of eddy thermal diffusivity for Lake Biwa found by this method are listed in Table 4.

Lake Ikeda is picked up, as the second example, to illustrate the procedure of treatment of the data of fragmental observations. In this example, no observation was taken in April, June, and September. Now we are obliged to fill the lacking portions by an interpolative method. The author finds the interpolated values on the annual variation curves by the graphical manner and the results are given in Table 5. From these values of temperature, the amount of the annual heat exchange and the annual mean eddy thermal diffusivity are found by the similar procedure to the previous example. They are shown in Tables 6 and 7 respectively. The values of k in deeper layers are more or less unreliable.

There are only the observations at the upper and the lower boundaries of the standard layer of 10–20m in Lake Ikeda or $i=1$. In such a case the value of k may be somewhat unreliable. A criterion of the reliability may be given by the following comparison. Using only the data at 0, 10, 20, 40, and 70 meter levels in Lake Biwa, i. e. assuming that i is unity within each standard layer, the amount of annual heat exchange and the annual mean eddy thermal diffusivity are calculated. The results are shown in Table 8. Comparing these results with those, shown in Tables 2–4, obtained from the detailed data, we see that differences of k values in each corresponding standard layer are 0.03, 0.01, 0.02, and 0.06 respectively.

Table 3.

Calculation of the annual mean eddy thermal diffusivity in 0–10m layer in Lake Biwa

Depth (m)	Q (10^3 cal.)	Q_i (cal.)	Δz_i (cm)	$Q_i\ \Delta z_i$	$\Sigma\ Q_i\ \Delta z_i$	$\Delta\bar{\theta}$ (°C)	k ($\mathrm{cm^2 sec^{-1}}$)
0	39.0						
		0.347 × 10^5	5 × 10^2	1.735 × 10^7			
5	30.3				3.040 × 10^7	1.74	0.55
		0.261 〃	5 〃	1.305 〃			
10	21.8						

Table 4

Calculation of the annual mean eddy thermal diffusivity in standard layers in Lake Biwa

Layer (m)	$\Sigma\ Q_i\ \Delta z_i$	$\Delta\bar{\theta}$ (°C)	k ($\mathrm{cm^2\ sec^{-1}}$)
0–10	3.040 × 10^7	1.74	0.55
10–20	1.630 〃	3.32	0.16
20–40	1.560 〃	3.02	0.16
40–70	0.520 〃	0.87	0.19

Table 5

Monthly mean temperature in Lake Ikeda (°C)

Depth (m)	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
0	13.6	11.0	12.8	(16.3)	19.9	(23.5)	26.6	30.4	(28.6)	24.6	22.3	16.0	20.5
5	13.2	11.0	12.7	(16.1)	19.6	(22.8)	25.6	29.8	(28.1)	24.5	21.0	15.7	20.0
10	13.1	11.0	12.6	(15.8)	19.0	(22.0)	24.6	26.0	(26.6)	24.4	20.5	15.7	19.3
20	13.1	10.9	12.3	(13.4)	14.1	(13.7)	13.4	15.6	(16.6)	17.5	20.2	15.5	14.7
30	12.9	10.8	12.1	(12.2)	12.3	(11.9)	11.5	12.2	(12.3)	12.4	12.5	12.8	12.2
40	11.9	10.8	11.8	(11.8)	11.7	(11.4)	11.2	11.2	(11.4)	11.5	11.5	11.0	11.4
50	11.4	10.7	11.5	(11.6)	11.7	(11.3)	10.8	11.0	(11.1)	11.1	11.3	(11.3)	11.2
75	11.1	10.5	10.9	(10.8)	(10.7)	(10.7)	10.6	(10.6)	(10.7)	(10.8)	(10.9)	(11.0)	10.8
100	10.9	10.5	10.8	(10.7)	(10.6)	(10.5)	10.5	10.6	(10.6)	(10.6)	(10.7)	(10.8)	10.7
200	10.6	10.5	10.6	(10.6)	(10.5)	(10.5)	10.5	10.5	(10.5)	(10.5)	(10.5)	(10.6)	10.5

Note: Values in parentheses are interpolated.

Table 6
The amount of annual heat exchange in Lake Ikeda

Depth (m)	Time of q_{max}	Time of q_{min}	Q (10^3 cal.)
0	Sept.	Feb.	33.8
5	Sept.	Feb.	25.1
10	Nov.	Feb.	19.8
20	Nov.	Feb.	10.5
30	Jan.	Feb.	6.8
40	Jan.	Feb.	5.2
50	Jan.	Feb.	4.4
75	Jan.	Feb.	2.9
100	Jan.	Feb.	1.7

Table 7.
Calculation of the annual mean eddy thermal diffusivity in standard layers in Lake Ikeda

Layer (m)	$\Sigma Q_i \Delta z_i$	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})
0–10	2.600×10^7	1.2	0.69
10–20	1.520 〃	4.6	0.10
20–40	1.510 〃	3.3	0.15
40–100	1.980 〃	0.7	0.90*
100–200	0.900 〃	0.2	1.43*

* Unreliable

Table 8
The amount of annual heat exchange and the annual mean eddy thermal diffusivity calculated from observations at 0, 10, 20, 40, and 70m depths in Lake Biwa

Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal.)	$\Sigma Q_i \Delta z_i$	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})
0	16.21	Sept.	March	40.6	3.200×10^7	1.74	0.58
10	14.47	Sept.	March	23.4	1.830 〃	3.32	0.17
20	11.15	Nov.	March	13.1	1.760 〃	3.02	0.18
40	8.13	Dec.	March	4.5	0.690 〃	0.87	0.25
70	7.26	—	—	—			

Even imperfect observed materials must be utilized for the climatological study of this subject. The general discussion of the degrees of reliability of such imperfect data is not easy. However, the following examples give some informations in this respect.

If the data of every three months are available, we proceed as follows. Calculate the average of the four observed values and assume it as the annual mean temperature ($\bar{\theta}$). Draw the vertical temperature profile for each observation, and find the value of q at each observing level for each observing epoch. Refering that q_{max} appears in early autumn and q_{min} in early spring and the former is delayed with depth, complete the annual variation curves of q with interpolative principle, then we can find the amount of annual heat exchange (Q) by the aid of these estimated annual curves. Picking up the data of February, May, August, and November at 0, 10, 20, 40, and 70 meter depths among the detailed data of Lake Biwa, the reliability of the estimation of k is examined. The results are shown in Table 9 and we see the appearance of errors of -0.12, $+0.02$, -0.02, and -0.02 in each standard layer respectively.

When we are obliged to use the data of twice a year, one at the nearly warmest month and the other at the nearly coldest month, we can find no other way to assume that the mean of these two observations gives the annual mean state and that the state of the nearly warmest and the nearly coldest months represent the state at the maximum and the minimum amounts of heat contents respectively. The very rough method of estimation of k above-mentioned is examined as follows. The materials are taken up again from the data of Lake Biwa, and assuming that the amounts of heat contents in August and February are given for the nearly warmest and the nearly coldest months respectively, the calculated values of k show the errors of -0.24, -0.08, -0.04, and -0.06 in each standard layer respectively (see Table 10). The errors amount to about 4/10 of accurate values of k. Thus, the roughly calculated values of k cannot be reliable in quantitative sense, however, we can trust the order of the values and the qualitative characters of the vertical distribution of k.

Table 9

The amount of annual heat exchange and the annual mean eddy thermal diffusivity calculated from observational data in February, May, August, and November at 0, 10, 20, 40, and 70m depths in Lake Biwa

Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal.)	$\Sigma Q_i \Delta z_i$	$\Delta\bar{\theta}$ (°C)	k (cm² sec⁻¹)
0	16. 61	Sept.	March	40. 3	3. 120 × 10⁷	2. 28	0. 43
10	14. 33	Oct.	March	22. 0	1. 730 〃	3. 04	0. 18
20	11. 29	Nov.	March	12. 6	1. 520 〃	3. 37	0. 14
40	7. 92	Dec.	March	2. 6	0. 390 〃	0. 74	0. 17
70	7. 18	—	—	—			

Table 10

The amount of annual heat exchange and the annual mean eddy thermal diffusivity calculated from observed data in February and August in Lake Biwa

Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal.)	$\Sigma Q_i \Delta z_i$	$\Delta\bar{\theta}$ (°C)	k (cm² sec⁻¹)
0	17. 74	Aug.	Feb.	37. 7	2. 765 × 10⁷	2. 87	0. 31
5	17. 10	Aug.	Feb.	27. 3			
10	14. 87	Aug.	Feb.	18. 2			
15	12. 21	Aug.	Feb.	11. 7	1. 240 〃	4. 82	0. 08
20	10. 05	Aug.	Feb.	7. 8			
30	8. 49	Aug.	Feb.	3. 8	0. 870 〃	2. 38	0. 12
40	7. 67	Aug.	Feb.	1. 9			
50	7. 46	Aug.	Feb.	0. 9	0. 220 〃	0. 53	0. 13
60	7. 26	Aug.	Feb.	0. 3			
70	7. 14	—	—	—			

The standard layers for the ocean are conveniently selected as 0–25, 25–50, 50–100, and 100–200m, which are bounded by the observing levels of temperature for almost all the stations.

4. Amount of Annual Exchange of Heat and Annual Mean Eddy Thermal Diffusivity for Lakes

The numerical values of Q and k for 17 lakes are calculated by the above-mentioned procedure and are listed in Table 11.

The amounts of annual heat exchange at surface (Q_0) come within 11.3–46.0 (10^3 cal) with the mean value of 31.1 (10^3 cal). These amounts roughly increase with increasing latitude and the relation can be represented by the regression equations, if we separate the Japanese lakes and European,

$$Q_0 = 2.74\varphi - 62.1 \ (10^3 \text{ cal}) \quad \text{for Japanese lakes}$$

and $$Q_0 = 1.15\varphi - 20.7 \ (10^3 \text{ cal}) \quad \text{for European lakes,}$$

where φ is latitude in degree (see Fig. 2).

It can be shown that a lake makes a better thermal reservoir than land area. The nearest land area with available earth-temperature data[7] is selected in comparison for each lake and the amount of annual heat exchange is calculated in the similar way to that of lakes. The results listed in Table 12 show that $Q = 1.3 - 2.3$ (10^3 cal) and the mean value is 1.8×10^3 cal which is 1/17 of that of lakes (31.1×10^3 cal).

It can be also shown that a qualitative fact in limnology, i. e. $Q(z)$ damps with depth, may be roughly represented by

$$Q(z) = Q_0 e^{-\alpha z}$$

from the values listed in Table 11 and the numerical values of damping coefficient (α) and the appropriateness of the expression are shown in Table 13 and Fig. 3.

The numerical values of eddy thermal diffusivity (k) for almost all the lakes are less than 1.0 (c. g. s.), while some exceptions are found for 0–10m layer in Lake Motosu, for 10–25m layer in Lake Brienz, and for somewhat unreasonable values of the deepest layer (below 100m) in four lakes.

Table 11

The amount of annual heat exchange and the annual mean eddy thermal diffusivity in lakes

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm² sec⁻¹)	Remark
Kagami-ike	0	20.4	Aug.	Feb.	23.0	1.4	0.20	c
31°–12′N	5	19.0	Aug.	Feb.	11.7	4.2	0.03	
130°–36′E	10	14.8	Aug.	Feb.	4.8	1.5	0.02	
Max. Depth 15m	14	13.3	—	—	—			
Unagi - ike	0	18.6	Aug.	Feb.	25.4	4.1	0.13	c
31°–13′N	10	14.5	Jan.	Feb.	10.6	3.8	0.07	
130°–37′E	20	10.7	Jan.	Feb.	6.6	1.4	0.17	
Max. Depth 57m	55	9.3	—	—	—			
	0	20.5	Sept.	Feb.	33.8	1.2	0.69	b
Lake Ikeda	10	19.3	Nov.	Feb.	19.8	4.6	0.10	
31°–15′N	20	14.7	Nov.	Feb.	10.5	3.3	0.15	
130°–34′E	40	11.4	Jan.	Feb.	5.2	0.7	0.90*	
Max. Depth 233m	100	10.7	Jan.	Feb.	1.7	0.2	1.43*	
	200	10.5	—	—	—			

Table 11 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})	Remark
Sumiyoshi-ike 31°-46′N 130°-36′E Max. Depth 31m	0	19.1	July	Feb.	11.3	5.7	0.02	c
	5	13.4	Dec.	Feb.	4.2	3.3	0.02	
	10	10.1	Jan.	Feb.	2.2	0.9	0.03	
	15	9.2	Jan.	Feb.	1.0	0.3	0.05	
	30	8.9	—	—	—			
Mi-ike 31°-53′N 130°-58′E Max. Depth 91m	0	19.2	Aug.	Feb.	22.2	4.8	0.09	d
	10	14.4	Aug.	Feb.	6.1	4.3	0.03	
	20	10.1	Aug.	Feb.	1.5	0.9	0.06	
	40	9.2	Aug.	Feb.	0.3	0.2	0.07	
	90	9.0	—	—	—			
Reservoir Karasubara 34°-40′N 135°-10′E Max. Depth 26m	0	16.45	Aug.	Feb.	34.9	1.41	0.33	a
	5	15.04	Sept.	Feb.	24.0	2.34	0.14	
	10	12.70	Oct.	Feb.	16.1	1.69	0.12	
	15	11.01	Oct.	Feb.	9.6	4.15	0.03	
	25	6.86	—	—	—			
Lake Biwa 35°-19′N 136°-08′E Max. Depth 96m	0	16.21	Sept.	March	39.0	1.74	0.55	a
	10	14.47	Sept.	March	21.8	3.32	0.16	
	20	11.15	Dec.	March	12.2	3.02	0.16	
	40	8.13	Dec.	March	3.9	0.87	0.19	
	70	7.26	—	—	—			
Lake Motosu 35°-27′N 138°-36′E Max. Depth 126m	0	14.5	Aug.	Feb.	37.5	0.5	1.79	d
	10	14.0	Aug.	Feb.	19.0	6.1	0.07	
	20	7.9	Aug.	Feb.	7.5	2.3	0.11	
	40	5.6	Aug.	Feb.	1.7	0.7	0.08	
	100	4.9	—	—	—			
Lake Sai 35°-29′N 138°-42′E Max. Depth 75m	0	13.83	Aug.	Feb.	34.8	2.21	0.38	a
	10	11.62	Oct.	Feb.	18.9	4.36	0.10	
	20	7.26	Nov.	Feb.	9.5	2.07	0.18	
	40	5.19	Dec.	Feb.	3.5	0.20	0.82*	
	70	4.99	—	—	—			
Lake Tazawa 39°-43′N 140°-40′E Max. Depth 425m	0	12.0	Aug.	Feb.	44.1	1.8	0.63	a
	10	10.2	Sept.	Feb.	27.7	3.1	0.23	
	20	7.1	Oct.	Feb.	16.8	2.0	0.39	
	40	5.1	Oct.	Feb.	6.5	1.0	0.78	
	100	4.1	Nov.	Feb.	1.7	0.1	2.53*	
	200	4.0	—	—	—			
Lake Albano (Lago di Albano) 41°-44′N 12°-40′E Max. Depth 170m	0	15.2	Oct.	March	25.4	0.9	0.73	c
	10	14.3	Nov.	March	15.8	2.9	0.14	
	20	11.4	Dec.	March	9.2	2.5	0.13	
	40	8.9	Dec.	March	2.4	0.7	0.18	
	100	8.2	—	—	—			

Table 11 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})	Remark
Lake Como	0	12.5	Aug.	Jan.	35.7	1.5	0.61	b
(Lago di Como)	10	11.0	Sept.	Jan.	22.0	1.0	0.55	
46°-00′N	20	10.0	Nov.	Jan.	12.8	1.6	0.42	
9°-15′E	40	8.4	Dec.	Jan.	7.3	1.4	0.49	
Max. Depth 414m	100	7.0	—	—	—			
Lake Lugano	0	13.9	Aug.	Feb.	26.8	3.6	0.18	d
(Luganersee)	10	10.3	Sept.	Feb.	12.9	3.8	0.08	
46°-00′N	20	6.5	Sept.	Feb.	7.3	0.6	0.33	
9°-00′E	30	5.9	Sept.	Feb.	5.0	0.6	0.44	
Max. Depth 288m	70	5.3	—	—	—			
Lake Geneva	0	11.6	Sept.	Jan.	46.0	1.5	0.83	a
(Lac Léman)	10	10.1	Sept.	Jan.	33.0	1.5	0.60	
46°-25′N	20	8.6	Oct.	Jan.	23.9	1.9	0.60	
6°-30′E	40	6.7	Nov.	Jan.	13.0	1.5	0.94	
Max. Depth 310m	100	5.2	Dec.	Jan.	3.2	0.4	2.53*	
	300	4.8	—	—	—			
Lake Brienz	0	10.5	Aug.	Jan.	32.0	2.9	0.29	a
(Brienzersee)	10	7.6	Sept.	Jan.	21.3	0.7	1.17	
46°-43′N	25	6.9	Sept.	Jan.	13.4	1.2	0.59	
7°-55′E	50	5.7	Dec.	Jan.	5.6	0.9	0.43	
Max. Depth 259m	100	4.8	—	—	—			
Lake Lucerne	0	12.1	Sept.	Jan.	26.8	2.8	0.22	c
(Vielwaldstättersee)	10	9.3	Oct.	Jan.	14.8	1.5	0.23	
46°-58′N	20	7.8	Nov.	Jan.	7.8	2.0	0.14	
8°-30′E	40	5.8	Nov.	Jan.	1.9	0.8	0.23	
Max. Depth 214m	100	5.0	—	—	—			
Lake Constance	0	11.52	Sept.	March	30.3	1.93	0.41	a
(Bodensee)	10	9.59	Oct.	March	19.9	2.35	0.21	
47°-35′N	20	7.24	Nov.	March	10.5	2.17	0.27	
9°-30′E	50	5.07	Dec.	March	3.2	0.53	0.25	
Max .Depth 252m	100	4.54	Jan.	March	1.9	0.17	2.21*	
	250	4.37	—	—	—			
Mean of Q_0					31.1			

* unreliable,
a complete material,
b inclusive of interpolated temperature data,
c amount of annual heat exchange is obtained by graphical estimation,
d observations taken in the nearly warmest and coldest months.

Table 12

The amount of annual heat exchange at soil surface

Locality	Lat. (N)	Long.(E)	Time of q_{max}	Time of q_{min}	Q_0 (10^3 cal)
Kagoshima	31°34′	130°33′	Sept.	Feb.	1.3
Miyazaki	31 55	131 26	Aug.	Feb.	1.7
Kōbe	34 41	135 11	Aug.	Feb.	2.1
Hikone	35 16	136 15	Aug.	Feb.	2.2
Kōhu	35 38	138 34	Sept.	Feb.	1.7
Akita	39 43	140 06	Aug.	March	2.3
Suttsu	42 48	140 13	Sept.	March	1.8
Obihiro	42 55	143 12	Aug.	Feb.	1.6
Ōdomari	46 39	142 46	Sept.	Feb.	1.7
Ochiai	47 20	142 47	Sept.	March	1.5
Mean					1.8

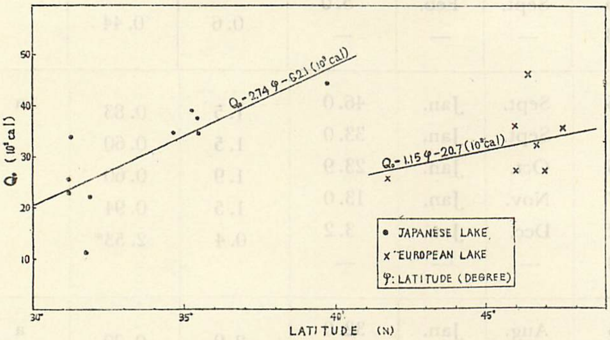

Fig. 2. Latitudinal change of the amount of annual heat exchange at lake surface.

Table 13

The numerical value of the damping coefficient (α)

Lake	α
Kagami-ike	1.458×10^{-3}
Unagi-ike	0.774 〃
Lake Ikeda	0.469 〃
Sumiyoshi-ike	1.744 〃
Mi-ike	1.234 〃
Reservoir Karasubara	0.794 〃
Lake Biwa	0.574 〃
Lake Motosu	0.753 〃
Lake Sai	0.599 〃
Lake Tazawa	0.436 〃
Lake Albano	0.525 〃
Lake Como	0.465 〃
Lake Lugano	0.647 〃
Lake Geneva	0.310 〃
Lake Brienz	0.368 〃
Lake Lucerne	0.623 〃
Lake Constance	0.419 〃

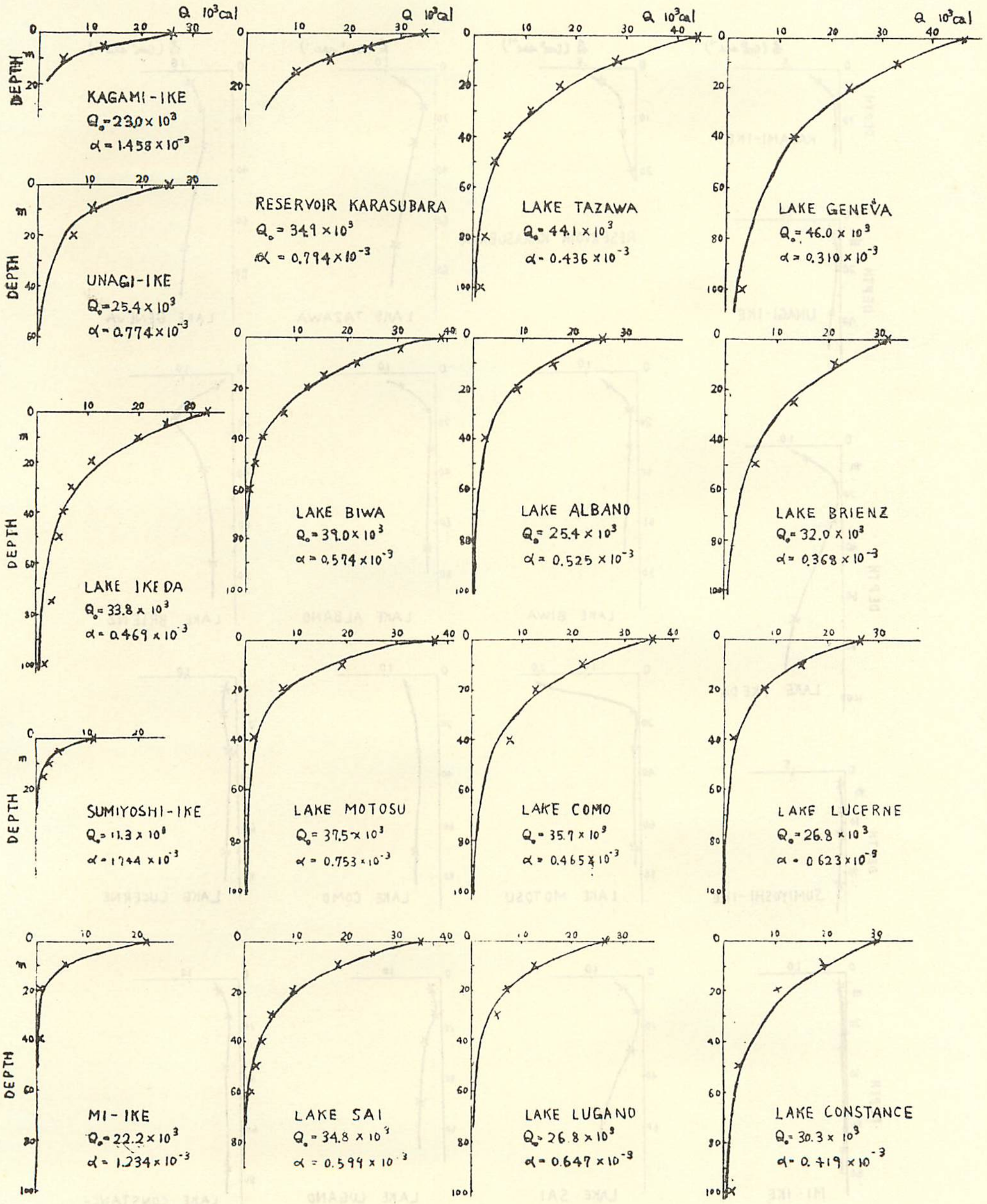

Fig. 3. Exponential decrease of the amount of annual heat exchange at a specified depth with increasing depth ($Q_0e^{-\alpha z}$: curve). Observed values indicated by crosses.

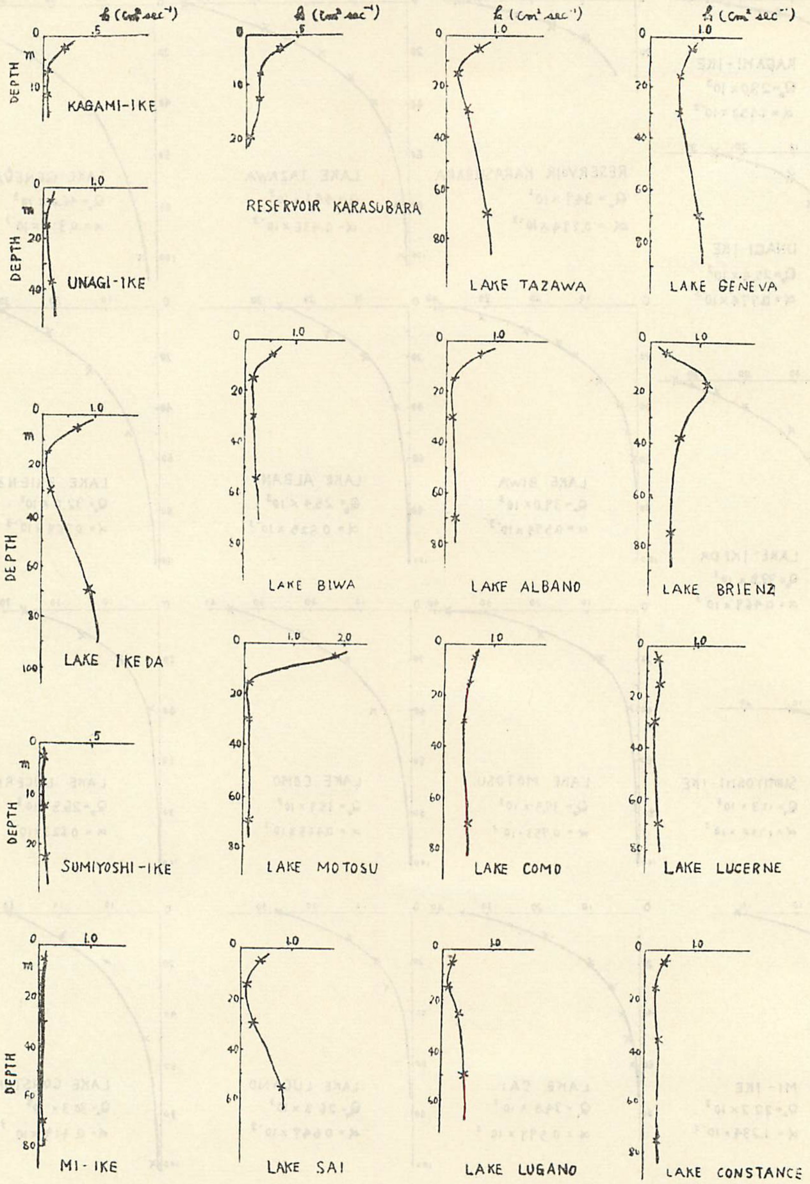

Fig. 4. Vertical profiles of annual mean eddy thermal diffusivity in lakes.

Generally speaking, the vertical variation of k within the lakes is insensible, or k is nearly constant with depth, except for the surface layer showing the high values of k which is commonly considered as the wind effect over the lake area (see Fig. 4).

It must be added that this method fails for the tropical lakes where the range of the annual temperature variation almost vanishes.[8)]

5. Amount of Annual Exchange of Heat and Annual Mean Eddy Thermal Diffusivity for Ocean

The amounts of annual heat exchange at surface (Q_0) for ocean, listed in Table 14, come within 31.3–220.5 (10^3 cal) excepting the one lowest value of 9.2 (10^3 cal). The mean value of 101.2 (10^3 cal) roughly corresponds to three times of that for lakes (31.1×10^3 cal).

The vertical profiles of Q for ocean are drawn from the values listed in Table 14, and it can be found that those have the similar characters as those for lakes, however somewhat lesser appropriateness appears in the exponential damping law or $Q(z) = Q_0 e^{-\alpha z}$.

Numerical values of k for ocean listed in Table 14 take 0.1–29.9 (c. g. s.), which are higher than those for lakes, and have profiles showing decrease with depth in general.

If we inspect Fig. 5 which shows the geographical distribution of k for the surface layer (0–25m), we can know the following facts.

(1) Along the Kuroshio Current, we can find the areas showing comparatively high values of k (10–29.9 c. g. s.), and the areas having $k > 20$ (c. g. s.) are located from west off Okinawa Islands to south off Shiono-misaki via south off Yaku-jima, around Hachijō-jima, and east off Inubō-misaki.

(2) On the contrary, along the coastal counter-current from Ise Bay to Ōarai-misaki, the lower valued region with $k < 10$ (c. g. s.) is located.

(3) Along the Tsushima Current, k distributes rather uniformly, and k is lower than 10 (c. g. s.) for the whole areas over Japan Sea excepting several scattered areas near the Japanese coast. The wide areas of the northwestern part of Japan Sea are characterized by the lower value of k less than 5 (c. g. s.).

(4) The areas of the low values of k less than 5 (c. g. s.) can be also found over Yellow Sea and northern part of East China Sea, while the area with a protuberance of high value above 10 (c. g. s.) is found at the west off Kyūshū.

The similar characters can be found on the geographical distributions for the layers of 25–50m and 50–100m (see Fig. 6 and 7 respectively), however the general tendency of the decrease of the numerical values of k with depth appears.

6. Remarks

It is well-known that the data of annual variation of water temperature are utilized to find the eddy thermal diffusivity (k). The prevailing method for finding k depends upon the formula derived from a periodic solution of the equation for linear flow of heat within the medium with constant diffusivity,

$$k=\frac{\pi}{T}\left(\frac{z_2-z_1}{\ln\,(a_1/a_2)}\right)^2 \quad (\text{say } k_A)$$
$$=\frac{\pi}{T}\left(\frac{z_2-z_1}{\mathcal{E}_1-\mathcal{E}_2}\right)^2 \quad (\text{say } k_p),$$

where a_1 and a_2 are the amplitudes, and $\mathcal{E}_1$ and $\mathcal{E}_2$ are the phase angles at the depths z_1 and z_2 of the annual term of the variation respectively, T is the period ($365\frac{1}{4}\times 24\times 60\times 60$ sec) and $\pi \doteqdot 3.14$. It is already noticed that this method begins with a physically illogical principle and, moreover, the disagreement of the numerical values between k_A and k_p appears frequently and also to extract the annual term from the whole variation, a troublesome procedure of harmonic analysis of the data must be carried out.

Putting away the restriction of the constancy of k with depth, modifications of the method are carried out by H. Jeffreys[9)] and J. Fjeldstad.[10)] Jeffreys obtained the following results;

$$k\frac{\partial A}{\partial z}=\sigma\int B dz \quad \text{and} \quad k\frac{\partial B}{\partial z}=-\sigma\int A dz,$$

Table 14

The amount of annual heat exchange and the annual mean eddy thermal diffusivity in the sea around Japan

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\varDelta\bar{\theta}$ (°C)	k (cm² sec⁻¹)	Remark
off Garampii 21°-20′N 121°-27′E	0	27.6	Aug.	Feb.	35.9	0.6	4.1	b
	25	27.0	Oct.	Feb.	25.4	0.7	2.3	
	50	26.3	Nov.	Feb.	15.9	1.2	0.9	
	100	25.1	—	—	—			
150mi. E off Seikō-ō 23°-10′N 124°-07′E	0	26.5	Aug.	Feb.	53.3	0.4	9.2	b
	25	26.1	Aug.	Feb.	39.4	0.6	4.3	
	50	25.5	Oct.	Feb.	25.6	2.1	0.9	
	100	23.4	—	—	—			
100mi. E off Seikō-ō 23°-10′N 123°-12′E	0	26.6	Sept.	Feb.	51.3	0.3	11.5	b
	25	26.3	Oct.	Feb.	36.1	0.4	5.8	
	50	25.9	Oct.	Feb.	22.8	1.6	1.1	
	100	24.3	—	—	—			
50mi. E off Seikō-ō 23°-10′N 122°-18′E	0	26.1	Sept.	March	58.5	0.3	13.3	b
	25	25.8	Oct.	March	42.5	0.5	5.5	
	50	25.3	Oct.	March	27.3	1.9	1.1	
	100	23.4	—	—	—			
56mi. from Sou-ō to Yonakuni-jima 24°-28′N 122°-51′E	0	26.1	Sept.	March	47.0	0.3	10.3	a
	25	25.8	Sept.	March	31.3	0.7	2.8	
	50	25.1	Oct.	March	19.0	1.4	1.0	
	100	23.7	—	—	—			
30mi. from Iriomote-jima to Keelung 24°-34′N 123°-14′E	0	25.7	Sept.	Feb.	50.1	0.2	16.9	a
	25	25.5	Sept.	Feb.	35.3	0.5	4.5	
	50	25.0	Oct.	Feb.	21.4	1.1	1.5	
	100	23.9	—	—	—			
90mi from Iriomote-jima to Keelung 25°-00′N 122°-14′E	0	22.4	Sept.	March	63.9	0.8	5.3	a
	25	21.6	Sept.	March	42.5	1.0	2.6	
	50	20.6	Nov.	March	24.2	2.9	0.6	
	100	17.7	—	—	—			

Table 14 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})	Remark
200mi. from Tung Yang Is. to Ikema-jima 25°–19′N 123°–58′E	0	25.8	Sept.	Feb.	51.1	0.6	5.7	b
	25	25.2	Oct.	Feb.	35.8	0.5	4.5	
	50	24.7	Nov.	Feb.	21.5	1.5	1.1	
	100	23.2	—	—	—			
140mi. from Tung Yang Is. to Ikema-jima 25°–37′N 122°–55′E	0	25.9	Aug.	Jan.	31.3	0.8	2.5	b
	25	25.1	Nov.	Jan.	19.3	1.2	1.0	
	50	23.9	Nov.	Jan.	9.9	1.9	0.4	
	100	22.0	—	—	—			
80mi from Tung Yang Is. to Ikema-jima 25°–56′N 121°–53′E	0	24.2	Aug.	Jan.	39.1	0.5	5.1	b
	25	23.7	Aug.	Jan.	25.3	0.9	1.7	
	50	22.8	Nov.	Jan.	13.0	3.9	0.2	
	100	18.9	—	—	—			
20mi. from Tung Yang Is. to Ikema-jima 26°–16′N 120°–50′E	0	22.5	Oct.	Feb.	70.6	0.5	9.3	b
	25	22.0	Oct.	Feb.	46.8	0.3	9.2	
	50	21.7	Oct.	Feb.	23.1	0.2	4.6	
	75	21.5	—	—	—			
5mi. S off Tyanzaki 25°–59′N 127°–41′E	0	24.8	Sept.	March	81.6	0.5	11.4	a
	25	24.3	Oct.	March	62.6	0.5	8.5	
	50	23.8	Nov.	March	45.0	1.2	4.2	
	100	22.6	Dec.	March	19.1	1.1	1.4	
	150	21.5	—	—	—			
51mi. W off Tyan-zaki 26°–05′N 126°–43′E	0	25.3	Aug.	Feb.	80.3	0.4	14.1	c
	25	24.9	Sept.	Feb.	62.0	1.1	4.0	
	50	23.8	Nov.	Feb.	49.5	1.8	3.3	
	100	22.0	Nov.	Feb.	24.6	3.0	1.1	
	200	19.0	—	—	—			
102mi. W off Tyan-zaki 26°–05′N 125°–50′E	0	26.1	Sept.	Feb.	56.9	0.2	20.3	c
	25	25.9	Sept.	Feb.	45.3	0.5	6.3	
	50	25.4	Oct.	Feb.	33.8	1.3	3.1	
	100	24.1	Oct.	Feb.	16.1	2.9	0.5	
	200	21.2	—	—	—			
153mi. W off Tyan-zaki. 26°–05′N 124°–55′E	0	26.1	Sept.	Feb.	89.2	0.3	21.5	c
	25	25.8	Sept.	Feb.	73.2	0.4	13.1	
	50	25.4	Sept.	Feb.	58.9	1.9	3.9	
	100	23.5	Sept.	Feb.	35.3	4.0	1.3	
	200	19.5	—	—	—			
20mi. NW off Naha 26°–26′N 127°–23′E	0	24.2	Aug.	Feb.	98.8	0.4	17.9	b
	25	23.8	Aug.	Feb.	81.5	0.6	9.3	
	50	23.2	Sept.	Feb.	59.5	1.4	4.8	
	100	21.8	Nov.	Feb.	28.8	2.1	1.8	
	200	19.7	—	—	—			
60mi. NW off Naha 26°–52′N 126°–49′E	0	24.6	Aug.	Feb.	84.9	0.3	19.8	b
	25	24.3	Aug.	Feb.	64.8	0.7	6.5	
	50	23.6	Oct.	Feb.	51.0	1.6	3.8	
	100	22.0	Nov.	Feb.	26.3	2.5	1.4	
	200	19.5	—	—	—			
100mi. NW off Naha 27°–17′N 126°–19′E	0	24.7	Sept.	March	95.3	0.3	23.1	a
	25	24.4	Sept.	March	79.8	0.3	19.9	
	50	24.1	Sept.	March	71.3	2.0	4.4	
	100	22.1	Nov.	March	40.8	3.3	1.5	
	200	18.8	—	—	—			
140mi. NW off Naha 27°–44′N 125°–46′E	0	23.4	Aug.	Feb.	71.1	0.7	6.6	b
	25	22.7	Sept.	Feb.	45.6	1.5	1.8	
	50	21.2	Nov.	Feb.	22.9	2.9	0.5	
	100	18.3	—	—	—			

Table 14 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})	Remark
180mi. NW off Naha 28°-10′N 125°-13′E	0	21.8	Aug.	April	90.7	0.7	8.6	b
	25	21.1	Sept.	April	61.7	0.7	5.4	
	50	20.4	Nov.	April	34.4	2.8	0.8	
	100	17.6	—	—	—			
40mi. W off Yokoate-jima 28°-48′N 128°-13′E	0	24.8	Sept.	March	103.0	0.4	19.3	b
	25	24.4	Sept.	March	91.8	0.3	21.8	
	50	24.1	Sept.	March	73.3	0.7	13.5	
	100	23.4	Sept.	March	44.5	0.5	13.5	
	200	22.9	—	—	—			
100mi. W off Yokoate-jima 28°-48′N 127°-06′E	0	24.7	Sept.	Jan.	112.8	0.4	20.5	b
	25	24.3	Sept.	Jan.	94.0	0.4	17.0	
	50	23.9	Sept.	Jan.	77.5	0.5	19.6	
	100	23.4	Sept.	Jan.	46.8	1.0	6.9	
	200	22.4	—	—	—			
80mi. SSW off Nagata-misaki 29°-07′N 129°-53′E	0	24.6	Sept.	Jan.	111.5	0.6	13.8	b
	25	24.0	Sept.	Jan.	96.8	0.3	23.1	
	50	23.7	Sept.	Jan.	78.3	0.6	15.9	
	100	23.1	Sept.	Jan.	44.3	0.8	8.3	
	200	22.3	—	—	—			
50mi. from Yakushima to Ō-shima 29°-27′N 130°-07′E	0	24.5	Sept.	Feb.	83.5	0.2	29.9	b
	25	24.3	Sept.	Feb.	67.5	0.3	15.7	
	50	24.0	Sept.	Feb.	51.3	1.0	5.8	
	100	23.0	Sept.	Feb.	22.0	1.3	1.3	
	150	21.7	—	—	—			
120mi. W off Gajya-jima 29°-54′N 127°-39′E	0	23.88	Aug.	Jan.	67.4	0.41	11.7	c
	25	23.47	Aug.	Jan.	43.0	0.40	6.5	
	50	23.07	Sept.	Jan.	22.4	4.05	0.4	
	100	19.02	—	—	—			
100mi. WSW off Noma-misaki 30°-54′N 128°-27′E	0	23.03	Sept.	March	84.6	0.64	9.3	b
	25	22.39	Sept.	March	65.7	0.56	8.2	
	50	21.83	Oct.	March	50.6	2.10	2.7	
	100	19.73	Nov.	March	20.9	5.15	0.3	
	200	14.58	—	—	—			
50mi. WSW off Noma-misaki 31°-11′N 129°-22′E	0	22.30	Aug.	March	108.2	0.37	20.8	a
	25	21.93	Sept.	March	85.8	0.78	7.7	
	50	21.15	Oct.	March	65.5	1.91	4.0	
	100	19.24	Dec.	March	30.5	3.58	1.0	
	200	15.66	—	—	—			
25mi. SSW off Kaimon-misaki 30°-46′N 130°-22′E	0	22.6	Sept.	March	121.8	0.3	29.1	b
	25	22.3	Sept.	March	98.8	0.7	9.9	
	50	21.6	Oct.	March	76.8	1.5	2.5	
	100	20.1	Oct.	March	38.0	2.6	1.1	
	150	17.5	—	—	—			
Kagoshima Bay 31°-25′N 130°-38′E	0	21.80	Sept.	April	71.3	1.80	2.6	a
	25	20.00	Oct.	April	46.3	1.54	2.0	
	50	18.46	Nov.	April	31.0	2.27	1.6	
	100	16.19	Dec.	April	16.1	0.66	2.7	
	200	15.53	—	—	—			
140mi. S off Toi-misaki 29°-02′N 131°-20′E	0	23.9	Sept.	April	145.0	0.4	26.5	b
	25	23.5	Sept.	April	122.8	0.4	22.0	
	50	23.1	Sept.	April	99.8	0.7	17.8	
	100	22.4	Oct.	April	57.5	2.7	2.9	
	200	19.7	—	—	—			

Table 14 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})	Remark
40mi. S off Toi-misaki 30°-40′N 131°-20′E	0	23.3	Sept.	March	123.8	0.4	22.5	b
	25	22.9	Sept.	March	103.0	0.3	24.3	
	50	22.6	Sept.	March	81.0	0.9	11.1	
	100	21.7	Oct.	March	45.8	3.7	1.8	
	200	18.0	—	—	—			
100mi. E off Kurazaki 31°-32′N 133°-24′E	0	23.4	Sept.	March	105.6	0.4	18.4	a
	25	23.0	Sept.	March	80.5	0.4	14.0	
	50	22.6	Oct.	March	61.3	1.3	5.6	
	100	21.3	Dec.	March	31.3	2.1	2.2	
	200	19.2	—	—	—			
50mi. E off Kurazaki 31°-32′N 132°-24′E	0	23.4	Sept.	March	118.0	0.4	20.5	a
	25	23.0	Sept.	March	88.5	0.5	12.3	
	50	22.5	Sept.	March	67.3	1.2	3.9	
	100	21.3	Nov.	March	37.0	2.6	2.1	
	200	18.7	—	—	—			
200mi. SSE off Ashizuri-misaki 29°-37′N 134°-35′E	0	23.0	Aug.	March	78.3	0.4	13.2	c
	25	22.6	Sept.	March	55.0	1.3	2.9	
	50	21.3	Nov.	March	40.8	1.6	2.8	
	100	19.7	Dec.	March	17.5	1.4	1.6	
	200	18.3	—	—	—			
100mi. SSE off Ashizuri-misaki 31°-10′N 133°-44′E	0	23.0	Aug.	March	92.8	0.6	10.8	c
	25	22.4	Sept.	March	69.5	1.0	4.7	
	50	21.4	Nov.	March	48.8	1.4	4.1	
	100	20.0	Dec.	March	25.0	1.5	2.1	
	200	18.5	—	—	—			
50mi. SSE off Ashizuri-misaki 31°-56′N 133°-22′E	0	23.4	Aug.	March	94.8	0.3	22.2	a
	25	23.1	Aug.	March	73.0	0.7	7.1	
	50	22.4	Oct.	March	52.0	1.6	3.4	
	100	20.8	Dec.	March	26.0	2.5	1.4	
	200	18.3	—	—	—			
30mi. SSE off Ashizuri-misaki 32°-16′N 133°-14′E	0	23.0	Sept.	Feb.	130.5	0.7	13.4	c
	25	22.3	Oct.	Feb.	105.6	1.0	7.5	
	50	21.3	Nov.	Feb.	83.3	1.7	6.2	
	100	19.6	Dec.	Feb.	50.0	3.7	2.0	
	200	15.9	—	—	—			
Fixed Ship Station "T" 29°-00′N 135°-00′E	0	23.31	Aug.	Feb.	81.8	0.21	26.4	a
	25	23.10	Sept.	Feb.	58.0	1.08	3.6	
	50	22.02	Nov.	Feb.	38.8	1.84	2.4	
	100	20.18	Dec.	Feb.	17.3	2.12	0.9	
	200	18.06	—	—	—			
100mi. S off Shiono-misaki 31°-48′N 135°-45′E	0	22.4	Sept.	March	101.8	0.3	24.7	a
	25	22.1	Sept.	March	85.3	0.5	11.9	
	50	21.6	Oct.	March	64.8	1.2	6.4	
	100	20.4	Dec.	March	34.0	1.3	3.6	
	200	19.1	—	—	—			
50mi. S off Shiono-misaki. 32°-35′N 135°-45′E	0	23.0	Sept.	Feb.	104.8	0.4	18.7	a
	25	22.6	Sept.	Feb.	83.8	0.6	9.9	
	50	22.0	Oct.	Feb.	66.3	1.3	6.2	
	100	20.7	Oct.	Feb.	37.5	1.9	3.0	
	200	18.8	—	—	—			
180mi. SE off Goza-misaki 32°-08′N 139°-17′E	0	21.6	Sept.	Feb.	117.8	0.6	13.3	b
	25	21.0	Sept.	Feb.	83.0	1.3	4.2	
	50	19.7	Nov.	Feb.	56.0	1.3	5.1	
	100	18.4	Nov.	Feb.	30.5	4.0	1.2	
	200	14.4	—	—	—			

Table 14 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})	Remark
105mi. SE off	0	21.8	Sept.	Feb.	115.0	0.9	9.0	a
Goza-misaki	25	20.9	Oct.	Feb.	89.8	0.9	7.2	
33°-02′N	50	20.0	Oct.	Feb.	73.8	1.7	5.3	
	100	18.3	Oct.	Feb.	40.5	2.7	2.3	
138°-12′E	200	15.6	—	—	—			
40mi. SE off	0	21.3	Sept.	Feb.	86.3	1.1	5.3	a
Goza-misaki	25	20.2	Oct.	Feb.	61.0	1.3	3.1	
33°-48′N	50	18.9	Oct.	Feb.	40.6	2.0	2.1	
	100	16.9	Jan.	Feb.	15.3	3.5	0.5	
137°-18′E	200	13.4	—	—	—			
25mi. SE off	0	21.1	Sept.	Jan.	91.0	0.8	7.9	a
Goza-misaki	25	20.3	Oct.	Jan.	69.3	1.4	3.4	
33°-58′N	50	18.9	Dec.	Jan.	49.8	1.8	3.2	
	100	17.1	Dec.	Jan.	23.6	2.6	1.0	
137°-07′E	200	14.5	—	—	—			
Ago Bay	0	19.1	Aug.	Jan.	9.2	0.4	0.12	a
34°-17′N	2	18.7	Aug.	Jan.	5.5	0.3	0.09	
136°-46′E	5	18.4	—	—	—			
90mi. SSE off	0	22.2	Sept.	March	196.0	0.5	28.6	a
Irō-zaki	25	21.7	Sept.	March	165.0	0.5	23.8	
33°-13′N	50	21.2	Sept.	March	135.3	1.5	11.9	
	100	19.7	Nov.	March	90.5	2.6	5.4	
139°-30′E	200	17.1	—	—	—			
30mi. SSE off	0	21.1	Sept.	March	105.3	1.0	7.5	a
Irō-zaki	25	20.1	Oct.	March	84.9	1.2	4.9	
34°-08′N	50	18.9	Oct.	March	63.5	2.0	3.5	
	100	16.9	Dec.	March	28.2	3.2	1.0	
139°-04′E	200	13.7	—	—	—			
Suruga Bay	0	19.9	Sept.	Feb.	91.5	1.0	6.4	b
35°-00′N	25	18.9	Oct.	Feb.	69.6	1.0	4.7	
138°-40′E	50	17.9	Nov.	Feb.	49.5	1.9	2.9	
	100	16.0	Nov.	Feb.	21.0	1.2	1.4	
	150	14.8	—	—	—			
220mi. SE off	0	22.3	Aug.	March	90.0	0.9	7.1	b
Nojima-zaki	25	21.4	Sept.	March	70.5	1.4	3.6	
32°-17′N	50	20.0	Oct.	March	57.8	1.4	4.5	
	100	18.6	Nov.	March	26.8	1.3	2.9	
143°-00′E	200	17.3	—	—	—			
100mi. SE off	0	22.1	Sept.	April	140.0	0.5	14.1	b
Nojima-zaki	25	21.6	Sept.	April	74.3	0.7	7.3	
33°-44′N	50	20.9	Nov.	April	54.0	1.4	4.3	
	100	19.5	Dec.	April	24.3	2.2	1.2	
141°-17′E	200	17.3	—	—	—			
20mi. SE off	0	20.9	Sept.	April	81.3	0.8	7.3	b
Nojima-zaki	25	20.1	Oct.	April	65.5	1.4	3.3	
34°-39′N	50	18.7	Nov.	April	52.5	1.7	3.6	
	100	17.0	Dec.	April	27.0	3.3	1.1	
140°-10′E	200	13.7	—	—	—			
200mi. E off	0	21.1	Sept.	March	192.0	0.6	23.2	b
Inubō-misaki	25	20.5	Sept.	March	158.5	0.6	19.2	
35°-42′N	50	19.9	Sept.	March	132.8	2.0	8.6	
	100	17.9	Dec.	March	85.0	2.7	5.3	
145°-00′E	200	15.2	—	—	—			

Table 14 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\varDelta\bar{\theta}$ (°C)	k (cm² sec⁻¹)	Remark
100mi. E off Inubō-misaki 35°-42′N 142°-57′E	0	22.2	Sept.	March	142.5	0.4	26.0	b
	25	21.8	Sept.	March	119.8	0.8	10.7	
	50	21.0	Oct.	March	95.8	1.5	8.0	
	100	19.5	Nov.	March	59.3	1.5	5.9	
	200	18.0	—	—	—			
30mi. E off Inubō-misaki 35°-42′N 141°-29′E	0	20.1	Sept.	Feb.	118.8	1.1	7.7	b
	25	19.0	Oct.	Feb.	95.8	1.8	3.7	
	50	17.2	Nov.	Feb.	70.3	1.7	5.1	
	100	15.5	Nov.	Feb.	39.8	3.1	2.0	
	200	12.4	—	—	—			
50mi. E off Ōarai-misaki 36°-19′N 141°-37′E	0	17.7	Aug.	April	119.5	1.6	5.5	a
	25	16.1	Sept.	April	103.8	1.5	5.0	
	50	14.6	Oct.	April	86.8	2.2	5.2	
	100	12.4	Dec.	April	55.5	2.8	3.0	
	200	9.6	—	—	—			
20mi. E off Ōarai-misaki 36°-19′N 141°-00′E	0	17.8	Sept.	April	120.0	1.5	5.6	a
	25	16.3	Oct.	April	93.5	1.4	4.9	
	50	14.9	Oct.	April	79.3	1.3	8.2	
	100	13.6	Nov.	April	53.0	2.9	2.0	
	200	10.7	—	—	—			
200mi. E off Shioya-zaki 37°-00′N 145°-07′E	0	16.8	Aug.	March	123.2	2.3	3.7	b
	25	14.5	Nov.	March	93.5	1.4	4.8	
	50	13.1	Nov.	March	75.0	2.6	3.5	
	100	10.5	Nov.	March	41.5	2.9	2.1	
	200	7.6	—	—	—			
100mi. E off Shioya-zaki 37°-00′N 143°-03′E	0	16.6	Sept.	March	217.3	2.4	6.6	b
	25	14.2	Oct.	March	181.1	1.4	9.5	
	50	12.8	Oct.	March	152.8	2.6	6.9	
	100	10.2	Nov.	March	95.0	2.4	6.3	
	200	7.8	—	—	—			
30mi. E off Shioya-zaki 37°-00′N 141°-36′E	0	15.1	Aug.	March	142.1	1.7	5.8	b
	25	13.4	Nov.	March	105.6	1.3	5.6	
	50	12.1	Nov.	March	79.7	1.4	7.0	
	100	10.7	Nov.	March	45.7	3.5	1.9	
	200	7.2	—	—	—			
200mi. E off Kinkwazan 38°-16′N 145°-43′E	0	16.5	Aug.	Feb.	62.7	1.4	2.9	b
	25	15.1	Nov.	Feb.	38.3	1.1	2.3	
	50	14.0	Dec.	Feb.	25.4	1.8	1.5	
	100	12.2	Dec.	Feb.	10.7	2.4	0.5	
	200	9.8	—	—	—			
150mi. E off Kinkwazan 38°-16′N 144°-41′E	0	16.1	Aug.	March	59.0	1.7	2.2	b
	25	14.4	Nov.	March	34.9	1.1	2.2	
	50	13.3	Dec.	March	26.3	2.0	1.8	
	100	11.3	Dec.	March	18.4	2.8	1.0	
	200	8.5	—	—	—			
100mi. E off Kinkwazan 38°-16′N 143°-39′E	0	15.7	Sept.	March	175.0	1.6	7.9	b
	25	14.1	Sept.	March	145.0	1.0	10.6	
	50	13.1	Sept.	March	123.3	1.8	9.0	
	100	11.3	Sept.	March	81.5	1.4	9.2	
	200	9.9	—	—	—			
50mi. E off Kinkwazan 38°-16′N 142°-38′E	0	13.9	Sept.	March	220.5	1.6	9.9	b
	25	12.3	Sept.	March	179.0	1.4	8.7	
	50	10.9	Oct.	March	147.0	1.4	13.4	
	100	9.5	Oct.	March	92.8	1.5	9.5	
	200	8.0	—	—	—			

Table 14 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k ($\mathrm{cm}^2\ \mathrm{sec}^{-1}$)	Remark
Fixed Ship Station "X" 39°-00′N 153°-00′E	0	16.08	Sept.	March	76.5	0.48	10.1	a
	25	15.60	Oct.	March	45.3	1.79	1.5	
	50	13.81	Nov.	March	23.8	1.71	1.6	
	100	12.10	Dec.	March	12.0	2.27	0.8	
	200	9.83	—	—	—			
200mi. E off Same 40°-34′N 145°-56′E	0	10.8	Aug.	March	115.9	2.3	3.4	b
	25	8.5	Nov.	March	80.4	1.5	3.6	
	50	7.0	Jan.	March	54.8	2.1	2.8	
	100	4.9	Jan.	March	24.2	1.4	2.4	
	200	3.5	—	—	—			
100mi. E off Same 40°-34′N 143°-42′E	0	11.6	Sept.	March	170.5	1.5	7.8	b
	25	10.1	Sept.	March	125.0	1.9	4.5	
	50	8.2	Sept.	March	90.5	1.8	6.1	
	100	6.4	Oct.	March	49.3	1.7	4.2	
	200	4.7	—	—	—			
30mi. E off Same 40°-34′N 142°-13′E	0	12.4	Oct.	Feb.	131.3	1.7	5.4	b
	25	10.7	Oct.	Feb.	102.3	0.9	8.0	
	50	9.8	Nov.	Feb.	78.8	1.1	8.2	
	100	8.7	Dec.	Feb.	36.9	2.1	2.0	
	200	6.6	—	—	—			
11mi. E off Same 40°-34′N 141°-49′E	0	13.45	Sept.	March	111.5	0.85	8.8	a
	25	12.60	Oct.	March	77.3	1.36	5.6	
	90	11.24	—	—	—			
50mi. S off Noshappu-misaki 42°-33′N 145°-49′E	0	9.4	Sept.	April	72.4	2.2	2.0	b
	25	7.2	Oct.	April	39.2	2.6	1.0	
	50	4.6	Nov.	April	24.5	1.9	1.2	
	100	2.7	Dec.	April	7.0	0.3	1.7	
	200	2.4	—	—	—			
100mi. WSW off Onikizaki 31°-30′N 128°-15′E	0	22.1	Sept.	March	128.5	0.4	23.6	a
	25	21.7	Sept.	March	109.8	0.5	14.8	
	50	21.2	Sept.	March	77.5	1.4	6.4	
	100	19.8	Nov.	March	33.5	3.4	0.9	
	200	16.4	—	—	—			
24mi. WSW off Onikizaki 32°-03′N 129°-33′E	0	21.0	Sept.	March	99.0	0.6	11.1	a
	25	20.4	Sept.	March	69.5	0.6	7.5	
	50	19.8	Oct.	March	43.8	1.2	2.8	
	100	18.6	—	—	—			
Gotō-nada 32°-48′N 129°-20′E	0	20.4	Aug.	Feb.	93.5	0.7	8.9	a
	25	19.7	Aug.	Feb.	63.5	0.6	6.6	
	50	19.1	Sept.	Feb.	36.5	2.2	1.2	
	100	16.9	—	—	—			
Tsushima Strait 34°-00′N 129°-39′E	0	20.0	Sept.	March	96.8	0.8	8.2	a
	25	19.2	Oct.	March	69.5	0.7	6.4	
	50	18.5	Oct.	March	43.0	1.6	2.0	
	100	16.9	—	—	—			
10mi. from Kawa-shiri-misaki to Urusaki 34°-32′N 130°-50′E	0	19.3	Sept.	March	99.6	0.4	16.8	a
	25	18.9	Sept.	March	69.8	1.0	4.6	
	50	17.9	Oct.	March	45.9	1.2	3.6	
	100	16.7	Nov.	March	8.9	0.4	0.5	
	113	16.3	—	—	—			
30mi. from Kawa-shiri-misaki to Urusaki 34°-45′N 130°-31′E	0	19.2	Sept.	March	81.4	0.9	6.0	a
	25	18.3	Oct.	March	55.8	1.4	2.7	
	50	16.9	Nov.	March	38.8	1.2	3.4	
	100	15.7	Dec.	March	13.1	0.8	0.9	
	136	14.9	—	—	—			

Table 14 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})	Remark
50mi. from Kawa-	0	18.8	Sept.	March	82.1	0.8	6.3	a
shiri-misaki to	25	18.0	Oct.	March	57.8	1.4	2.7	
Urusaki	50	16.6	Nov.	March	38.6	1.6	2.3	
34°-57′N	100	15.0	Dec.	March	9.9	0.9	0.5	
130°-12′E	127	14.1	—	—	—			
70mi. from Kawa-	0	18.6	Sept.	March	74.2	0.8	6.4	a
shiri-misaki to	25	17.8	Oct.	March	54.3	1.4	2.5	
Urusaki	50	16.4	Nov.	March	34.5	1.7	1.9	
35°-10′N	100	14.7	Dec.	March	13.0	4.6	0.2	
129°-53′E	153	10.1	—	—	—			
20mi. NW off	0	19.0	Aug.	March	93.3	0.7	8.7	a
Hamada	25	18.3	Oct.	March	59.8	1.1	3.5	
35°-08′N	50	17.2	Nov.	March	37.5	1.5	2.0	
131°-46′E	100	15.7	—	—	—			
50mi. NW off	0	18.7	Aug.	March	82.8	1.0	5.5	a
Hamada	25	17.7	Oct.	March	54.8	1.2	2.9	
35°-30′N	50	16.5	Nov.	March	31.8	2.2	1.0	
131°-20′E	100	14.3	—	—	—			
100mi. NW off	0	17.5	Sept.	March	82.8	1.1	5.0	a
Hamada	25	16.4	Oct.	March	55.5	1.8	2.0	
36°-05′N	50	14.6	Nov.	March	33.5	2.7	0.9	
130°-36′E	100	11.9	—	—	—			
50mi. N off	0	17.7	Aug.	March	163.8	1.3	9.0	b
Karo	25	16.4	Oct.	March	130.8	1.7	5.6	
36°-23′N	50	14.7	Nov.	March	109.3	1.7	8.1	
134°-12′E	100	13.0	Nov.	March	68.5	7.1	1.6	
	200	5.9	—	—	—			
30mi. N off	0	17.9	Sept.	March	205.5	1.0	14.6	b
Kyō-ga-misaki	25	16.9	Sept.	March	163.3	1.0	11.3	
36°-16′N	50	15.9	Sept.	March	122.5	2.0	7.2	
135°-13′E	100	13.9	Oct.	March	62.0	8.6	1.1	
	200	5.3	—	—	—			
30mi. NNW off	0	17.6	Sept.	March	117.8	0.8	9.8	a
Tateishizaki	25	16.8	Sept.	March	80.3	0.9	5.9	
36°-12′N	50	15.9	Oct.	March	53.2	1.9	2.8	
135°-46′E	100	14.0	Nov.	March	18.1	5.9	0.3	
	200	8.1	—	—	—			
100mi. NNW off	0	16.7	Sept.	March	135.5	1.7	5.2	b
Tateishizaki	25	15.0	Oct.	March	85.7	1.7	3.5	
37°-16′N	50	13.3	Nov.	March	63.8	2.4	3.2	
135°-10′E	100	10.9	Dec.	March	35.2	6.9	0.6	
	200	4.0	—	—	—			
150mi. NNW off	0	15.9	Sept.	March	149.5	2.1	4.9	b
Tateishizaki	25	13.8	Nov.	March	111.4	2.7	2.7	
38°-02′N	50	11.1	Dec.	March	72.1	3.7	2.3	
134°-44′E	100	7.4	Dec.	March	36.8	4.1	1.3	
	200	3.3	—	—	—			
200mi. NNW off	0	13.9	July	April	66.8	2.8	1.6	c
Tateishizaki	25	11.1	Nov.	April	43.2	3.0	0.9	
38°-48′N	50	8.1	Nov.	April	28.3	4.3	0.7	
134°-18′E	100	3.8	Nov.	April	10.6	2.2	0.5	
	200	1.6	—	—	—			

Table 14 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})	Remark
20mi. NNW off	0	17.0	Aug.	April	115.4	1.4	5.5	c
Rokugō-zaki	25	15.6	Aug.	April	78.6	1.3	3.5	
37°-51′N	50	14.3	Nov.	April	51.3	2.0	2.5	
	100	12.3	Nov.	April	13.6	3.3	0.2	
137°-10′E	150	9.0	—	—	—			
50mi. NNW off	0	16.4	Aug.	April	104.0	1.6	4.4	c
Rokugō-zaki	25	14.8	Aug.	April	72.7	1.3	3.8	
38°-18′N	50	13.5	Nov.	April	52.4	3.7	1.7	
	100	9.8	Nov.	April	25.2	5.3	0.6	
136°-56′E	200	4.5	—	—	—			
10mi. NW off	0	16.8	Sept.	April	123.8	1.3	6.4	b
Hajikizaki	25	15.5	Oct.	April	87.0	1.7	3.3	
38°-28′N	50	13.8	Nov.	April	60.5	1.6	4.0	
	100	12.2	Dec.	April	26.3	4.8	0.7	
138°-22′E	200	7.4	—	—	—			
50mi. NW off	0	16.3	Sept.	March	140.0	2.1	4.7	b
Hajikizaki	25	14.2	Oct.	March	107.0	2.2	3.3	
38°-55′N	50	12.0	Nov.	March	77.5	2.3	4.5	
	100	9.7	Nov.	March	52.0	4.3	1.9	
137°-48′E	200	5.4	—	—	—			
30mi. W off	0	16.5	Sept.	April	141.5	1.3	7.7	a
Kamo	25	15.2	Oct.	April	111.0	1.6	6.8	
38°-46′N	50	13.6	Nov.	April	83.8	1.7	5.9	
	100	11.9	Nov.	April	42.8	4.0	1.3	
139°-05′E	200	7.9	—	—	—			
30mi. W off	0	15.7	Sept.	March	162.5	1.0	11.4	a
Tsuchizaki	25	14.7	Oct.	March	126.3	1.1	8.0	
39°-46′N	50	13.6	Nov.	March	94.8	2.1	5.5	
	100	11.5	Dec.	March	52.5	3.4	2.2	
139°-24′E	200	8.1	—	—	—			
50mi. W off	0	15.9	Sept.	March	151.3	1.5	7.1	a
Tsuchizaki	25	14.4	Oct.	March	116.5	1.5	5.4	
39°-46′N	50	12.9	Nov.	March	86.0	2.0	5.0	
	100	10.9	Nov.	March	44.0	4.0	1.5	
138°-58′E	200	6.9	—	—	—			
100mi. W off	0	16.2	Sept.	April	176.5	2.3	5.3	b
Tsuchizaki	25	13.9	Sept.	April	132.0	1.4	6.5	
39°-46′N	50	12.5	Oct.	April	96.6	3.9	2.7	
	100	8.6	Oct.	April	41.8	4.7	1.1	
137°-54′E	200	3.9	—	—	—			
20mi. W off	0	15.8	Sept.	April	191.0	0.9	15.1	b
Henashizaki	25	14.9	Oct.	April	151.0	1.9	5.6	
40°-36′N	50	13.0	Nov.	April	118.8	1.8	8.0	
	100	11.2	Nov.	April	62.0	3.6	2.2	
139°-25′E	200	7.6	—	—	—			
15mi. W off	0	14.5	Sept.	March	131.3	1.1	8.1	b
Esashi	25	13.4	Sept.	March	92.8	2.0	3.1	
41°-52′N	50	11.4	Nov.	March	65.0	3.6	2.2	
	100	7.8	Dec.	March	35.8	4.7	1.1	
139°-46′E	200	3.1	—	—	—			
40mi. W off	0	13.7	Sept.	April	90.8	2.3	2.7	b
Esashi	25	11.4	Oct.	April	63.3	3.0	1.4	
41°-52′N	50	8.4	Nov.	April	46.0	4.0	1.3	
	100	4.4	Dec.	April	19.5	2.8	1.0	
139°-16′E	200	1.6	—	—	—			

Table 14 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})	Remark
50mi. NW off Kamoi-misaki 43°-54′N 139°-33′E	0	11.9	Sept.	March	112.3	1.2	6.3	a
	25	10.7	Oct.	March	79.5	2.2	2.5	
	50	8.5	Nov.	March	57.0	2.8	2.3	
	100	5.7	Dec.	March	27.5	3.2	1.2	
	200	2.5	—	—	—			
3mi. W off Rakuma 47°-08′N 142°-00′E	0	7.0	Sept.	March	69.8	2.2	1.9	a
	25	4.8	Oct.	March	38.0	1.3	1.8	
	50	3.5	Oct.	March	21.0	0.6	2.6	
	100	2.9	—	—	—			
21mi. W off Rakuma 47°-08′N 141°-35′E	0	7.5	Aug.	April	75.8	1.4	3.4	a
	25	6.1	Oct.	April	44.8	1.0	3.1	
	50	5.1	Nov.	April	33.3	1.2	3.5	
	100	3.9	Dec.	April	20.3	1.5	2.0	
	200	2.4	—	—	—			
100mi. W off Rakuma 47°-08′N 139°-38′E	0	7.4	Aug.	April	51.3	2.0	1.6	c
	25	5.4	Aug.	April	30.5	2.1	0.9	
	50	3.3	Aug.	April	18.0	0.9	2.4*	
	100	2.4	Sept.	April	9.5	0.8	1.7*	
	200	1.6	—	—	—			
34mi. E off Seishin 41°-46′N 130°-35′E	0	9.4	Sept.	March	109.3	3.2	2.2	a
	25	6.2	Oct.	March	67.0	3.0	1.4	
	50	3.2	Dec.	March	40.9	1.5	3.3*	
	100	1.7	Dec.	March	22.0	0.5	5.9*	
	200	1.2	—	—	—			
14mi. E off Seishin 41°-46′N 130°-10′E	0	9.5	Sept.	March	128.5	2.7	3.1	a
	25	6.8	Oct.	March	82.9	2.9	1.9	
	50	3.9	Dec.	March	52.6	1.8	3.4*	
	100	2.1	Dec.	March	27.4	0.6	7.0*	
	200	1.5	—	—	—			
34mi. SE off Bayō-tō 39°-36′N 128°-46′E	0	11.4	Sept.	March	77.3	3.5	1.3	a
	25	7.9	Oct.	March	40.1	3.8	0.6	
	50	4.1	Nov.	March	19.9	2.3	0.9*	
	100	1.8	Nov.	March	7.1	0.8	1.3*	
	200	1.0	—	—	—			
100mi. SE off Bayō-tō 38°-51′N 129°-41′E	0	12.4	Aug.	March	73.5	3.9	1.1	a
	25	8.5	Nov.	March	31.5	4.0	0.4	
	50	4.5	Dec.	March	13.5	2.0	0.6	
	100	2.5	—	—	—			
45mi. E off Tyūmonshin 37°-54′N 129°-46′E	0	15.5	Sept.	March	56.4	4.2	0.9	a
	25	11.3	Nov.	March	36.5	2.9	0.8	
	50	8.4	Jan.	March	19.5	3.7	0.4	
	100	4.7	—	—	—			
7mi. E off Tyūmonshin 37°-54′N 128°-59′E	0	14.0	Sept.	Feb.	55.2	3.2	0.9	b
	25	10.8	Nov.	Feb.	20.3	4.1	0.3	
	50	6.7	Jan.	Feb.	8.9	3.7	0.2	
	100	3.0	—	—	—			
31mi. E off Geijitsu Bay 36°-06′N 130°-04′E	0	17.8	Sept.	March	44.9	2.1	1.4	b
	25	15.7	Oct.	March	28.0	1.5	1.1	
	50	14.2	Nov.	March	14.9	3.3	0.3	
	100	10.9	—	—	—			
33mi. from Kyo-sai-tō to Tsushima 34°-16′N 128°-59′E	0	19.3	Sept.	March	67.3	0.9	4.8	a
	25	18.4	Oct.	March	42.5	1.9	1.4	
	50	16.5	Nov.	March	24.8	1.9	1.7	
	100	14.6	—	—	—			

Table 14 (Continued)

Station	Depth (m)	$\bar{\theta}$ (°C)	Time of q_{max}	Time of q_{min}	Q (10^3 cal)	$\Delta\bar{\theta}$ (°C)	k (cm^2 sec^{-1})	Remark
26mi. W off Sui-tō	0	13.9	Aug.	March	101.3	1.4	4.7	a
	25	12.5	Sept.	March	64.0	1.0	3.9	
34°-42′N	50	11.5	Sept.	March	33.3	0.9	2.0	
125°-25′E	84	10.6	—	—	—			
90mi. from C. Shantung to Shōsei-tō	0	11.8	Sept.	Feb.	83.0	1.8	2.7	b
	25	10.0	Sept.	Feb.	41.6	1.8	1.2	
37°-42′N	50	8.2	Sept.	Feb.	10.8	-0.1	—	
124°-31′E	60	8.3	—	—	—			
60mi. from C. Shantung to Shōsei-tō	0	13.4	Sept.	Feb.	65.8	3.6	1.0	b
	25	9.8	Sept.	Feb.	25.8	2.5	0.5	
37°-36′N	50	7.3	Nov.	Feb.	7.3	-0.1	—	
123°-54′E	65	7.4	—	—	—			
50mi. from Rōkotan to C. Shantung.	0	13.2	Sept.	March	80.3	3.7	1.2	a
38°-09′N	25	9.5	Oct.	March	30.5	2.5	0.4	
122°-11′E	50	7.0	—	—	—			
Mean of Q_0					101.2			

* unreliable

a complete material

b inclusive of interpolated temperature data

c amount of heat exchange is obtained by graphical estimation

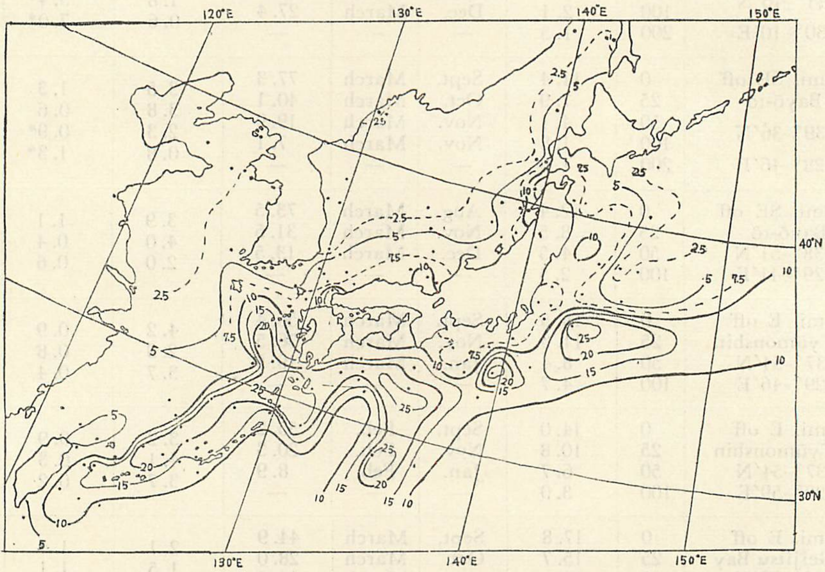

Fig. 5. Geographical distribution of annual mean eddy thermal diffusivity in 0–25m layer of the sea around Japan. Observational stations indicated by dots.

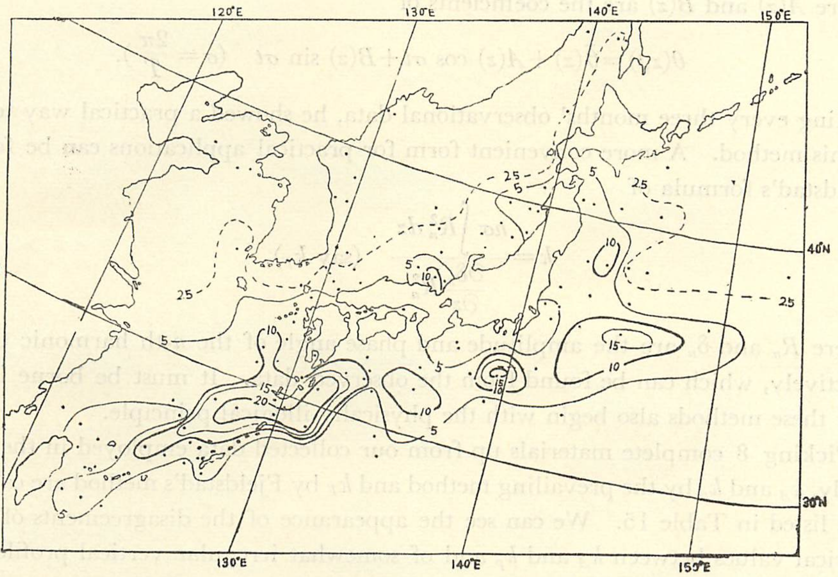

Fig. 6. Geographical distribution of annual mean eddy thermal diffusivity in 25–50m layer of the sea around Japan. Observational stations indicated by dots.

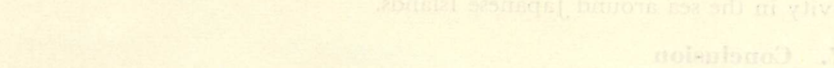

Fig. 7. Geographical distribution of annual mean eddy thermal diffusivity in 50–100m layer of the sea around Japan. Observational stations indicated by dots.

where $A(z)$ and $B(z)$ are the coefficients of

$$\theta(z,t)=\bar{\theta}(z)+A(z)\cos\sigma t+B(z)\sin\sigma t\quad\left(\sigma=\frac{2\pi}{T}\right).$$

Taking every three months' observational data, he showed a practical way to find k by his method. A more convenient form for practical applications can be found in Fjeldstad's formula of

$$k=\frac{n\sigma\int R_n^2\,dz}{\frac{\partial\delta_n}{\partial z}R_n^2}\qquad(\text{say }k_F),$$

where R_n and δ_n are the amplitude and phase angle of the n-th harmonic term respectively, which can be found from the observed data. It must be borne in mind that these methods also begin with the physically illogical principle.

Picking 8 complete materials up from our collected data employed in the present study, k_A and k_p by the prevailing method and k_F by Fjeldstad's method are calculated and listed in Table 15. We can see the appearance of the disagreements of the numerical values between k_A and k_p and of somewhat irregular vertical profiles of k_F. Such irregularities should be attributed to the inadequate methods.

Unreliable values of k obtained by the prevailing method are found also on K. Suda's paper[11)] which discusses the geographical distribution of eddy thermal diffusivity in the sea around Japanese Islands.

7. Conclusion

Introducing a different method for finding the annual mean value of eddy thermal diffusivity in lakes or ocean on Namekawa's very excellent but not well-known paper, entitled "A theory of the annual variation of temperature of ocean or lake" published in 1935, the present author devices a practical working procedure applicable to the complete monthly data and incomplete data (seasonal, and summer and winter observations) showing the annual variation of water temperature.

The annual mean values of eddy thermal diffusivity of 10 Japanese and 7 European lakes and 113 points of the sea surrounding Japanese Islands are calculated by this working method, and the author gets the following facts:

(1) The surface values of annual mean eddy thermal diffusivity for the lakes are generally low compared with those for the sea, i. e. the values are below 2.6 (c. g. s.) even inclusive of unreliable exceptions for the lakes, while for the sea, the maximum value of these reaches to circa 30 (c.g.s.).

(2) The annual mean eddy thermal diffusivity generally decreases with depth both in the lakes and in the sea, but this tendency is not conspicuous for lakes.

(3) The geographical distributions of the annual mean eddy thermal diffusivity in the surrounding sea of Japanese Islands are given. In the region of the Kuroshio or the Japanese Current, these values are especially high (10–29.9c. g. s. for surface layer) and comparatively low values (below 5c. g. s. for surface layer) are found in the northwestern part of Japan Sea, in Yellow Sea, and in the northern part of East China Sea.

Table 15

The annual mean eddy thermal diffusivity calculated by other methods (cm^{2}sec^{-1})

Station	Depth (m)	k_F	k_A	k_p
Lake Biwa	0	1.9	2.9	2.6
	10	0.1	0.2	0.6
	20	0.9	0.1	8.0
	40	3.8	0.6	17.5
	70	—		
100mi. NW off Naha	0	—*	29.5	—*
	25	97.0	—*	20.7
	50	11.1	16.2	11.6
	100	22.9	1.3	—*
	200	—		
100mi. S off Shiono-misaki	0	635.1	31131.3	6917.6
	25	119.8	11.3	54.7
	50	18.6	9.3	81.7
	100	197.7	14.7	—*
	200	—		
40mi. SE off Goza-misaki	0	11.4	17.7	13.2
	25	9.3	5.0	15.4
	50	10.0	2.9	15.8
	100	28.0	1.6	—*
	200	—		
Fixed Ship Station "X"	0	31.2	52.8	33.6
	25	7.0	2.7	4.0
	50	6.7	5.7	6.9
	100	6.6	5.7	2.5
	200	—		
Tsushima Strait	0	8.3	20.7	9.7
	25	26.8	17.7	327.7
	50	48.9	10.3	69.3
	100	—		
30mi. NW off Tateishizaki	0	19.5	43.5	20.4
	25	16.5	26.1	23.0
	50	35.5	7.0	3320.7
	100	444.0	3.1	—*
	200	—		
30mi. W off Kamo	0	10.7	26.7	8.1
	25	10.2	7.3	13.1
	50	27.5	12.7	88.3
	100	45.0	2.0	—*
	200	—		

* Calculation is impossible because the amplitude increases or the phase advances with increasing depth.

In the course of this calculations, the amounts of annual heat exchange at the specified levels are listed in the working sheets. This amount itself shows the degree of annual thermal stirring of the portion in the lake or the sea in question, and its surface value gives the output quantity of heat from the lake or the sea surface during the whole cooling stage. It is noticed, in this paper, that the introduction of this quantity as a climatological parameter may give serious contributions to the climatological study.

As for the quantities in question, the following facts are found in the present study:

(1) The surface value of the amount of annual heat exchange for the lakes generally increases with latitude as far as we concern.

(2) Its mean value for the lakes is circa 30×10^3 cal which is about 17 times as much as that for the ground surface, showing that the lakes make the heat-preservatories.

(3) Its mean value for the sea is circa 100×10^3 cal which is about 3 times as much as that for lakes.

(4) The amount of annual exchange of heat generally decreases with depth in both lakes and the sea, especially for lakes the damping with depth nearly obeys the exponential law.

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