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Vertical eddy diffusivities in a large tropical lake[1]

Abstract—Vertical eddy diffusivities below the thermocline were estimated for Lake Lanao, Philippines, from vertical heat transport. Mean values range from 1.08 $cm^2 \cdot s^{-1}$ at 22 m to 0.22 at 44 m. The values are not notably divergent from expected values in temperate lakes of similar sizes and depth.

Tropical lakes of moderate to great depth are typically stratified much of the year, but the density difference across the thermocline is almost always less than for stratified temperate lakes. Thus it is possible that vertical transport across thermoclines in tropical lakes is more pronounced. This hypothesis cannot be tested comprehensively at present, as there is very little information on vertical eddy diffusivity in tropical lakes that can be compared with existing estimates for temperate lakes. Estimates are made here for vertical eddy diffusivity in Lake Lanao, Philippines, as a first step toward comparisons between lakes of different latitude.

Lake Lanao is on Mindanao (8°00′N, 123°50′E) at 702 m ASL. Climate, morphometry, and limnology are given by Frey (1969) and Lewis (1973, 1979). Statistics most relevant to the present purpose include: maximum depth, 112 m; mean depth, 60 m; surface area, 363 km^2; hydraulic residence time, 6.5 yr. Minimum water temperature varies slightly between years but is near 24.2°C. When the lake is stratified, the upper and lower water column differ by at most 2°C.

The annual thermal cycle is described in detail by Lewis (1973). The lake lacks stable thermal structure between the end of December and the end of March; stratification persists the rest of the year, even during strong typhoon winds. Stratification differs in important ways from that in temperate lakes, however. The epilimnion is extremely thick (40 m), but secondary thermoclines develop within it, dividing it into two or more compartments for periods of several weeks. The mixed layer thus varies between 40 and 15 m during stratification, according to the presence and position of secondary thermoclines.

Eddy diffusivities were calculated from weekly temperature profiles taken between July 1970 and October 1971 at a station near the 50-m contour (Fig. 1). Methods of data collection are given by Lewis (1973). The method of eddy diffusion estimation closely follows that of Jassby and Powell (1975). A major simplification was possible for the solar warming correction. Although neglect of the direct solar warming correction may lead to serious error for some lakes, a calculation of the upper bound on solar warming in Lanao showed that it need not be considered.

The upper bound for direct solar warming was estimated as follows. Maximum incident irradiance over any week is near 500 $cal \cdot cm^{-2} \cdot d^{-1}$ (Lewis 1973). Median vertical extinction coefficient is near 0.35 ln $units \cdot m^{-1}$ (Lewis 1979). Thus at 20 m, there will be at most 0.46 $cal \cdot cm^{-2} \cdot d^{-1}$ entering directly. At 21 m the comparable figure is 0.32, leaving at most 0.14 $cal \cdot cm^{-2} \cdot d^{-1}$ in the 20–21-m layer. This amount of heat would account for a temperature rise of 0.0014°$C \cdot d^{-1}$. It may be augmented by as much as 8% due to sediment interception of irradiance between 20 and 21 m, but will still be below

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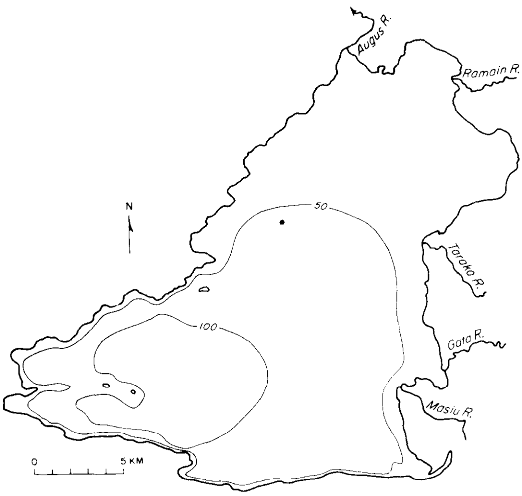

Fig. 1. Location of main station in relation to bathymetry.

0.0016°C·d⁻¹. This upper bound would be further reduced by an allowance for change in angle of incidence of the sun, which increases path length. The observed warming rates at 20–21 m below thermoclines are 0.01°C·d⁻¹ or more, which is much higher than the upper bound on direct warming, so direct warming cannot be an important consideration. Thermoclines are not often found above 20 m, so eddy diffusivities are not approximated between 0 and 20 m. Below 20 m, upper bound approximations similar to the one given here for 20–21 m show that direct heating accounts for <10% of warming.

The estimation, simplified by omission of the solar warming correction, is

$$K_z = -\frac{1}{(\partial\theta_z/\partial z)}\cdot\left(\frac{d}{dt}\int_z^{z_m} A_u\theta_u\, du\right)/A_z$$

where K_z is the coefficient of eddy diffusivity ($cm^2 \cdot s^{-1}$), θ_z and θ_u are temperatures at depths z and u (°C, cm), A_z and A_u are lake areas at depths z and u (cm^2, cm), and t is time (s). Following Jassby and Powell (1975), I have smoothed thermal gradient and heat flux terms over depth and time. Moving averages of 3 were used for both dimensions, rather than 5 for time and 3 for depth, as by Jassby and Powell.

Table 1. Vertical eddy diffusivities below thermoclines in Lake Lanao, estimated from heat flux.

Stratum (m)	K_z ($cm^2 \cdot s^{-1}$)	SE
21–22	1.08	0.02
22–23	1.05	0.03
23–24	1.00	0.17
24–25	0.88	0.19
25–26	0.87	0.26
26–27	0.86	0.23
27–28	0.75	0.19
28–29	0.61	0.14
29–30	0.48	0.18
30–31	0.53	0.26
31–32	0.71	0.38
32–33	0.68	0.21
33–34	0.62	0.22
34–35	0.60	0.28
35–36	0.52	0.23
36–37	0.46	0.15
37–38	0.43	0.15
38–39	0.35	0.13
39–40	0.43	0.17
40–41	0.31	0.15
41–42	0.31	0.16
42–43	0.24	0.14
43–44	0.22	0.14

Estimations of K_z were made only for time intervals and depths representing heat flux across stable thermoclines as shown in fig. 3 of Lewis (1973). The results are summarized in Table 1. Mean values are given for 1-m layers over all weeks meeting the stratification criteria; the standard error of the mean is also shown for each depth as determined from the weekly data. The values generally decrease with depth. All values are quite high, greatly exceeding molecular diffusivity. The high values are partly explained by the large size of the lake, as there is a positive relation between lake size and K_z (Mortimer 1941, 1942).

Comparisons are difficult. The widely cited series of K_z values given by Mortimer (1942) contains temperate lakes both larger and smaller than Lanao, with K_z values both larger and smaller than Lanao. Hutchinson (1957) has shown why Mortimer's values will be overestimates, but this is probably not very important for the larger lakes in the series. The line relating lake size to K_z below the thermocline is so steep that it is difficult to say whether Lanao stands apart from the temperate trend. Loch Lomond is perhaps the closest comparison from Mortimer's series (area 71 km^2, maximum depth 195 m). It has an estimated hypolimnetic K_z of 0.5 $cm^2 \cdot s^{-1}$, close to the ones shown in Table 1 for Lanao. A tentative conclusion is that area is much more important than latitude in controlling vertical transport through the thermocline.

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References

FREY, D. G. 1969. A limnological reconnaissance of Lake Lanao. Int. Ver. Theor. Angew. Limnol. Verh. **17:** 1090–1102.

HUTCHINSON, G. E. 1957. A treatise on limnology, v. 1. Wiley.

JASSBY, A., AND T. POWELL. 1975. Vertical patterns of eddy diffusion during stratification in Castle Lake, California. Limnol. Oceanogr. **20:** 530–543.

LEWIS, W. M., JR. 1973. The thermal regime of Lake Lanao (Philippines) and its theoretical implications for tropical lakes. Limnol. Oceanogr. **18:** 200–217.

———. 1979. Zooplankton community analysis. Springer.

MORTIMER, C. H. 1941, 1942. The exchange of dissolved substances between mud and water in lakes. J. Ecol. **29:** 280–329; **30:** 147–201.

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Lake acidification: Its effect on lead in the sediment of two Adirondack lakes[1,2]

Abstract—Sediment cores from two remote lakes, Sagamore and Woods (Adirondack State Park, New York), were analyzed for lead. A marked increase was found in the top 10 cm of the sediment of both lakes. The effect of lake acidification on the release of lead from the sediments was determined in laboratory studies. Significant lead desorption (>5% of the total) only occurred at a pH <3.0 in sediment from Woods Lake and <2.0 in sediment from Lake Sagamore. Since the pH of the two lakes is always >4.4, lead is not being released from the sediments.

The atmospheric concentration of lead in the U.S. has increased over the past few decades and the rate of lead deposition from the atmosphere has also increased (Galloway et al. 1980*a*), resulting in enhanced concentrations in the sediment of lakes downwind from sources of anthropogenic activities (Galloway and Likens 1979; Norton et al. in prep.).

Acid precipitation has caused the acidification of many lakes over the last 30 years; a 1975 survey of 51 lakes in the Adirondack region showed that 66% of them were acidified to a pH below 5.0. As the pH of a lake decreases, the potential for ion exchange, solubilization, or release of metals from the sediment into the water increases (Brown 1979). We investigate here the effect of lake acidification on lead mobility by trying to define the pH regime under which lead may be released from the sediment.

This is one of a series of investigations into the consequences of acid precipitation on three lakes typical of Adirondack State Park, New York. Results are presented here for two, Lake Sagamore (43°46′N, 74°37′W) and Woods Lake (43°52′N, 74°57′W). Both watersheds have extensive forest cover (>97%). Lake Sagamore is 8 km and Woods Lake 24 km from the nearest paved road (SR 28) and,

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