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Temperature, heat, and mixing in Lake Valencia, Venezuela[1]

William M. Lewis, Jr.
Department of Environmental, Population and Organismic Biology,
University of Colorado, Boulder 80309

Abstract

Water temperature profiles, weather data, and lake level data spanning a 2-year period for Lake Valencia, Venezuela (10°N, 67°W), are used in an analysis of thermal regime, mixing, and heat flux. The lake, which has an area of 350 km² and mean depth of 19 m, is warm monomictic; it becomes isothermal annually near the end of November, at the onset of the dry season. The water column during stratification consists of an upper mixed layer, which averages 13 m but varies greatly in thickness, followed by alternating thick layers of positive and negligible density gradients. The number of layers changes through time. Vertical eddy diffusivities during stratification vary from 0.23 $cm^2 \cdot s^{-1}$ at 20 m to 0.09 at 35 m. The mean annual heat budget is 5,308 $cal \cdot cm^{-2}$. Evaporative heat loss and net radiation flux are the two largest heat budget elements; net back radiation and sensible heat loss are important secondary terms. Seasonality is principally traceable to heat budget terms influenced by minimum air temperature, whereas week-to-week variation is influenced by other terms as well. Maximum stability of the water column is about 350 $g\text{-}cm \cdot cm^{-2}$ with little variation between years. Work of the wind in distributing heat is 2,630 $g\text{-}cm \cdot cm^{-2}$ for 1977 and 3,156 in 1978. Stability responds in a significant way to weather changes, even during stratification.

Reduced seasonality makes difficult any a priori judgment about the occurrence of predictable annual thermal and heat flux patterns in tropical lakes. In an early attempt to organize the existing information, Hutchinson and Löffler (1956) predicted the occurrence and distribution of several different kinds of thermal regimes in the tropics. In contrast to their predictions, Talling (1969) showed that African tropical lakes have an almost universal tendency to mix deeply in coincidence with the hemispheric winter on either side of the equator. On the basis of detailed thermal information on Lake Lanao, Philippines, I (Lewis 1973) argued that most lakes in the tropics deep enough to stratify would prove to be warm monomictic, i.e. they would have a single predictable circulation period each year. I also attempted to show that, even though a definite warm monomictic cycle is very likely in tropical lakes, nonseasonal variation in thickness of the mixed layer is an especially important element of the tropical thermal regime. The present work on Lake Valencia (10°N, 67°W) is intended to test these ideas and to provide information on heat flux and eddy diffusion for comparison with the much more extensive data for temperate lakes.

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Methods and study site

Lake Valencia (350 km²) lies in the Aragua Valley (Venezuela) at an elevation of 420 m asl (Fig. 1). Its maximum depth, which has decreased slowly but steadily due to desiccation (Schubert 1979; Lewis and Weibezahn 1981), was 39 m over the period covered by the present study (mean, 19 m). As the lake surface is now well below the outlet sill, water leaves the lake only by evaporation.

The data to be analyzed here cover the 2-year period from 1 January 1977 to 30

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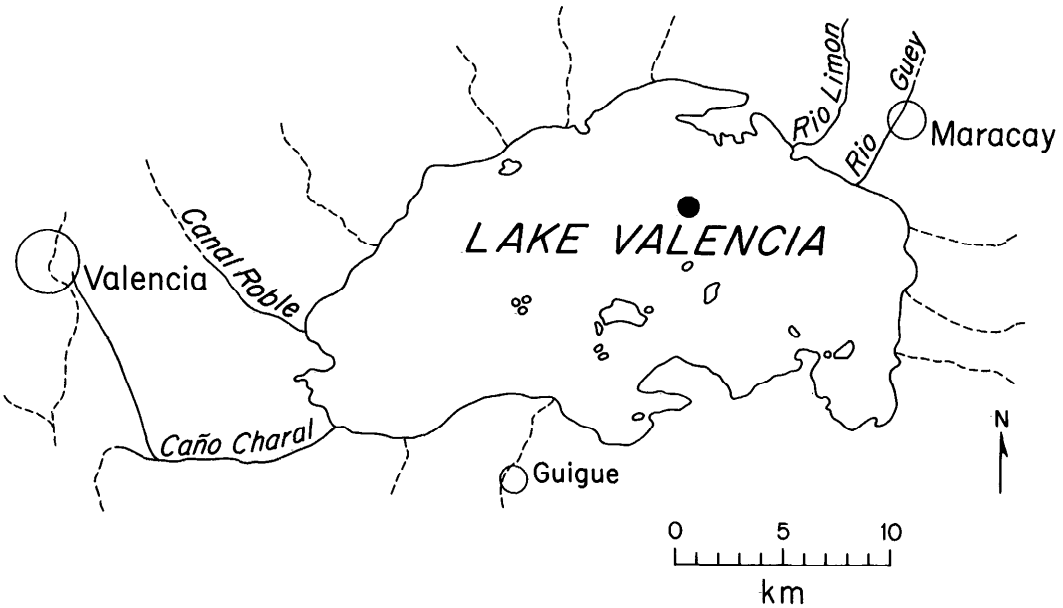

Fig. 1. Map of Lake Valencia.

December 1978. Weather measurements were made at two locations: on the south side of the lake at Macapo, 100 m from the lakeshore in a clearing on a hill 10 m above the lake surface; and at Base Sucre, 0.5 km from the northeast end of the lake, where the Venezuelan Air Force maintains a permanent weather station. Data include daily wind speed, rain, insolation, evaporation, humidity, and max-min temperatures. At Macapo, wind speed was measured 4 m above the ground, rain was collected with a wedge gauge 3 m above the ground, and insolation was measured with a bimetal pyranometer equipped with 24-h gears. Evaporation was measured with a shallow pan 1 m above the ground in a clearing. Air temperatures were measured with a shade-mounted max-min thermometer, 3 m above the ground. At Base Sucre, methods were similar except that evaporation was measured with a standard class A pan and temperatures were taken in a standard shelter 1.5 m above the ground. Base Sucre provides a mean temperature, as well as a maximum and a minimum, and gives mean relative humidity from four daily readings. The data at Macapo correlate well with those from Base Sucre, but because of missing values or superior recording accuracy at one or another, data used in the final analysis were as follows: from Macapo only, wind speed; from both stations, insolation (averaged); from Base Sucre only, all other measurements.

Lake temperatures were measured weekly at the index station (Fig. 1: •) with a calibrated expanded-scale thermistor, read to the nearest 0.05°C. Care was taken to equilibrate the probe at each depth. These profiles were always taken between 0700 and 0900 hours, before significant morning heat accumulation. Several synoptic series were also made to ensure that thermal structure at the index station was representative of the lake. Lake levels were obtained from the daily records of the Instituto para la Conservacion del Lago de Valencia, in Valencia.

Results and discussion

The annual cycle of weather and water temperature—Figure 2 shows a 2-year record of weather data. The year is sharply divided into a 7–8-month rainy season and a 4–5-month dry season (Lewis 1981). Moisture is not the sole basis for season-

ality, but the wet and dry seasons provide a convenient terminology that will be used here. Average wind speed shows a seasonal pattern; in general, the dry season is windy and the wet season is calm. There is some significant nonseasonal variation as well, as shown by the very high value for early August 1978.

Air temperature is seasonal, but in a more complex manner than wind speed. Daily maximum temperature increases during the dry season and peaks just before the rains start. A marked decline comes with the first rains. Slightly higher average maxima return after the early, heaviest rains have passed. Maximum temperature shows a great deal of nonseasonal variation around these trends, minimum air temperature less. Minimum values are lowest in January, during the first half of the dry season, then climb until the beginning of the wet season, peak, and become steady around 20°C for the last half of the rainy season.

Insolation shows less seasonal trend than any other weather variable. There is some indication of a drop in average insolation at the very beginning of the wet season when rains are heaviest, a climb through the dry season, and a small latitudinal effect in December. These tendencies are minor by comparison with random week-to-week variation. Evaporation climbs during the dry season, declines abruptly with the onset of rain, and shows little trend during the rainy season. There is substantial week-to-week scatter.

The lake becomes isothermal in almost perfect coincidence with the onset of the dry season, near the end of November (Fig. 3). For the first few weeks, water temperature declines rapidly. After 6–8 weeks of isothermal cooling, water temperature begins to rise, in parallel with minimum air temperature, but the lake continues to circulate under the influence of the steady dry season winds. Thermal stratification begins to appear, sporadically at first, a few weeks before the rainy season as the wind abates and the minimum air temperature climbs.

Heat uptake continues weeks beyond the onset of thermal stratification, but eventually reaches a plateau that is marked by steady temperature in the upper water column. In 1977 the rate of warming was low, so the lake was slow to reach maximum temperatures and the thermal plateau lasted only about 3 months. In 1978, warming was faster and the plateau lasted about 6 months, but was characterized by pronounced temperature changes connected with nonseasonal weather changes. The thermal limits were quite similar for the two years. Sea-

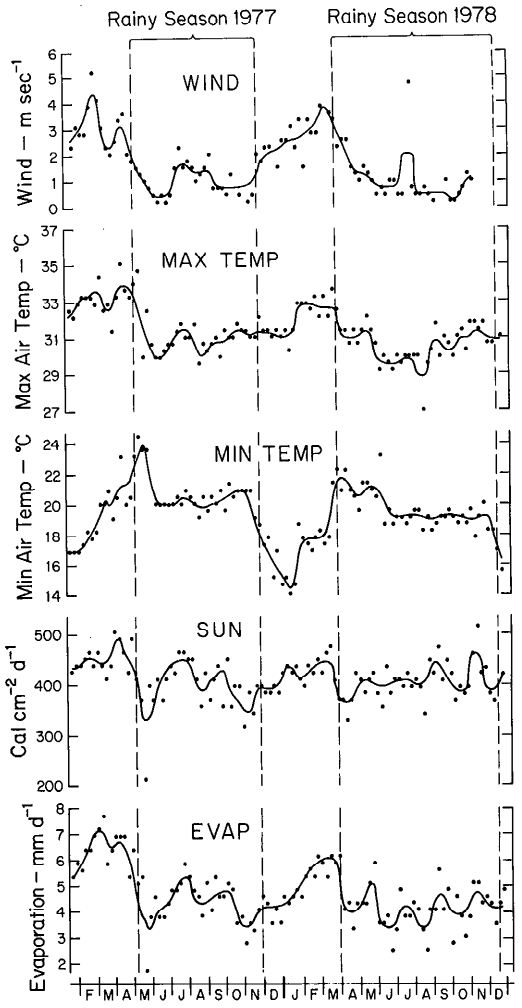

Fig. 2. Weather variables related to the seasonal thermal cycle in Lake Valencia. Points—weekly totals or weekly averages; solid lines—smoothed running mean of 3 weeks.

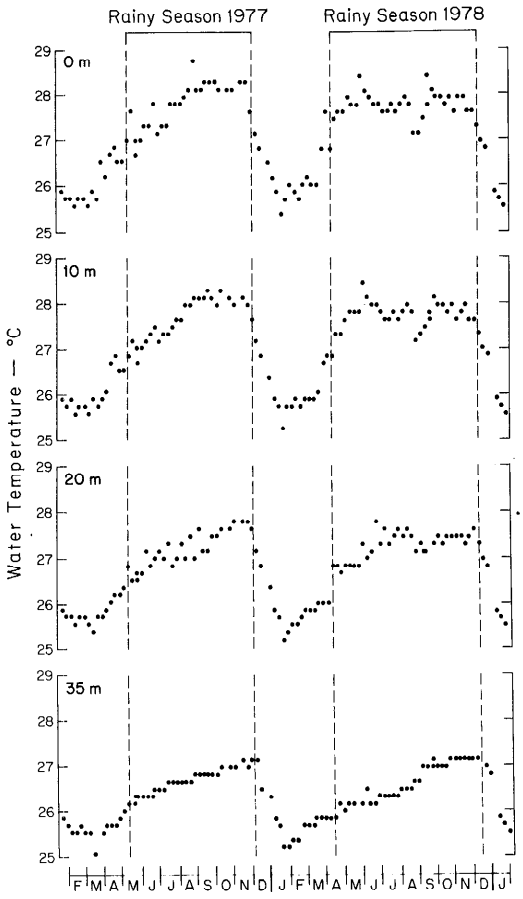

Fig. 3. Weekly water temperatures at four depths in Lake Valencia.

sonal maxima, taken in early morning and thus not reflecting temporary daytime heat gain, were 28.5°–29.0°C, and minima were 25.0°–25.5°C.

Thermal structure of the water column—Figure 4 shows the gross thermal structure of the water column for the last week in each month. The 2 years are superimposed to facilitate comparison. The water column shows no structure, or very transitory structure, in the November–February profiles. The early genesis of stable stratification is evident in the March profiles. The stratification period, arbitrarily defined here as that part of the year during which there is no complete mixing over an interval of >3 weeks, begins in the last half of March, and the lake does not mix to the bottom until November. There was an unusual near approach to complete mixing in August 1978 due to very strong winds (Fig. 2), but oxygen and thermal profiles show that complete mixing did not occur. At no other time during the stratification season of either year did the lake come so close to mixing. Of 101 weekly profiles, 25 showed a small (0.1°–0.2°C) increase of temperature between 0 and 1 m. Usually these unstable surface conditions were typical of the cooling season.

The lake frequently has two or more thermoclines and is typified by major changes in gross thermal structure. Distinct layers are especially clear from expanded-scale plots of temperature against depth (Fig. 5). The upper mixed layer is defined here as the maximum depth of wind mixing within the previous 24 h, and is identified empirically as the thickness of the upper isothermal layer in an early morning temperature profile. Both wind and convection contribute to turbulence in the upper water column at night. As these two sources of turbulence usually act together, their relative importance in maintaining the upper mixed layer typically cannot be determined. Dates on which wind speed is very low, however, provide information about the influence of convection in maintaining the mixed layer. When wind speed is lowest, the mixed layer remains thin (5–7 m) for days, despite nocturnal convection. Penetration of convective turbulence thus appears to be quite low, at most affecting the top 5–7 m. The role of convection in maintaining mixed layers in tropical lakes is often mentioned and has probably been overstated (e.g. Beadle 1974). This impression is reinforced by a review of oceanic mixing by Faller (1971, p. 212), who concluded that ". . . contrary to general misconceptions this source of energy [convection] is relatively small . . . ."

Below the upper mixed layer there is an abrupt switch to a layer which has a sustained negative thermal gradient; it typically gives way to another layer in which the thermal gradient is zero or nearly so, and this may in turn be suc-

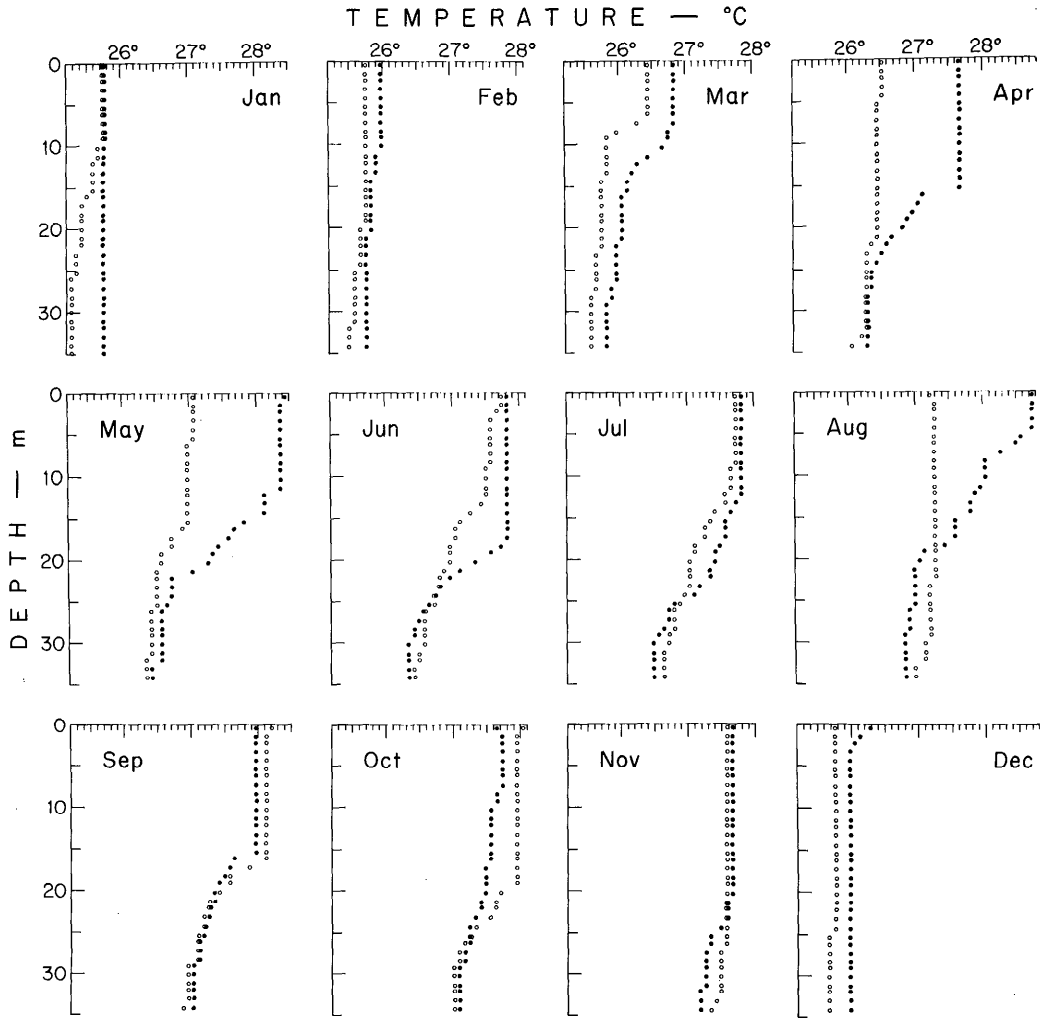

Fig. 4. Thermal profiles for the last week in each month, plotted to a common scale. •—1977 data; o—1978 data.

ceeded by another layer of negative thermal gradient. The pattern is repeated through as many as seven layers. Lake Valencia does not have a recognizable hypolimnion. If the lake were 100 m deep, as is Lake Lanao at the same latitude (Lewis 1973), the lowermost thermally uniform layer would probably be very thick and essentially unchanging during stratification and could logically be called a hypolimnion.

Some objective method is required for identifying layer boundaries. The thermal range of Lake Valencia is about 2.0°C. A gradient that accounts for 0.1°C is thus a small fraction of the thermal range, yet it is large enough to be measured with confidence. Distance resolution here is 1 m. A significant gradient is defined as any section of the water column showing a sustained (≥1 m) decrease in temperature totaling 0.1°C or more. At temperatures in the vicinity of 25°C, the density changes resulting from 0.1°C change in temperature are larger than at lower temperatures. Thus a gradient of $0.1°C \cdot m^{-1}$

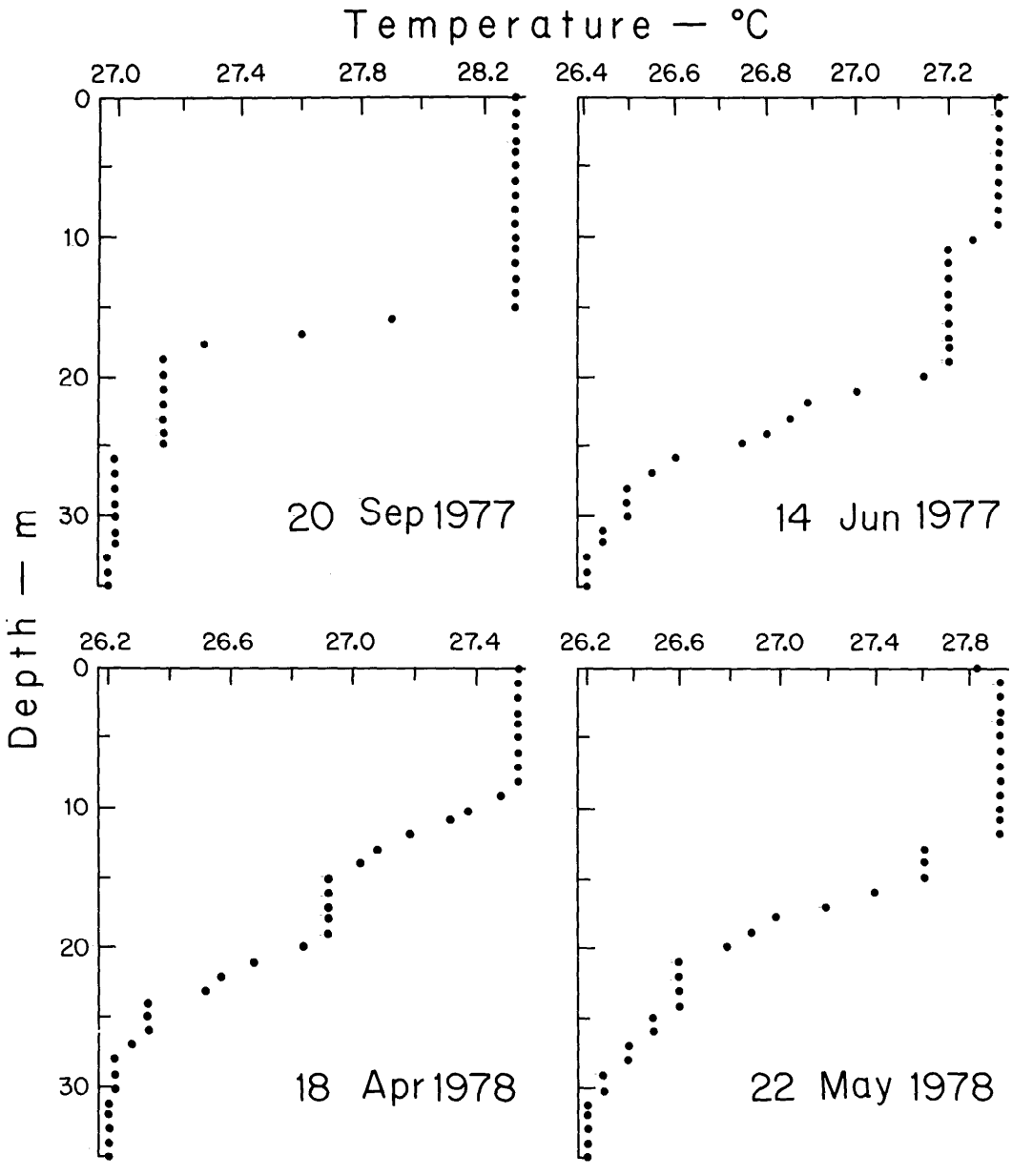

Fig. 5. Selected thermal profiles plotted full scale to show complex layering.

at 25°C is equivalent in terms of density to a gradient of $0.3°C \cdot m^{-1}$ at 10°C.

The criteria for identifying layers were tested on the uppermost thermal gradient to determine whether resolution of layers would be adequate (Fig. 6). Gradients thinner than 1 m will all show up in the 1-m category of Fig. 6. The proportion of these is small (ca. 5%), indicating satisfactory resolution of layering with the 1-m increments. Similarly, inadequate thermal resolution of layers would be indicated by clustering of points near the lowest slopes, but this is not the case. The

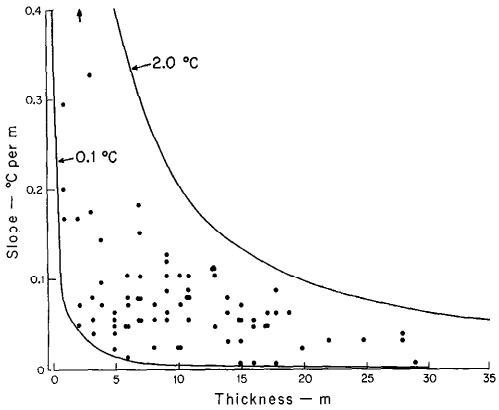

Fig. 6. Data for uppermost thermal gradient, showing slope of thermal profile against thickness of the thermocline. Lines of envelope show maximum and minimum limits of layers.

Table 1. Statistics on the layers of Lake Valencia, based on weekly measurements for 2 years.

Layer	Mean depth (m)	Variability*	Occurrence %
Upper mixed layer—			
all dates	17.0	58	100
excluding circulation	13.3	47	83
First gradient—top	13.3	47	83
bottom	23.9	35	83
Second uniform layer—top	22.2	34	72
bottom	29.0	26	72
Second gradient—top	21.6	25	32
bottom	29.0	17	32
Third uniform layer—top	27.0	15	24
bottom	33.7	9	24
Third gradient—top	27.3	10	4
bottom	33.3	6	4
Fourth uniform layer—top	31.5	2	2

* C.V.: $(s/\bar{x}) \times 100$.

graph also shows the absolute boundary conditions for gradients estimated from 1-m spacing of measurements: the product of thickness and slope must lie between 0.1° and 2.0°C. The points are thoroughly scattered within this space, but the steepest gradients are underrepresented.

Figure 7 shows layer boundaries as a function of time, and Table 1 provides a numerical summary. The main station is near the node of uninodal seiches on the main lake axis, which minimizes, but does not preclude, seiche displacement of layers. The major changes in layer numbers and dimensions must be explained principally by variations in turbulence and heat transport, but some variations in layer thickness may be due to seiches.

The maximum thickness of the mixed layer during stratification is 25–30 m even though the average is only 13 m. The

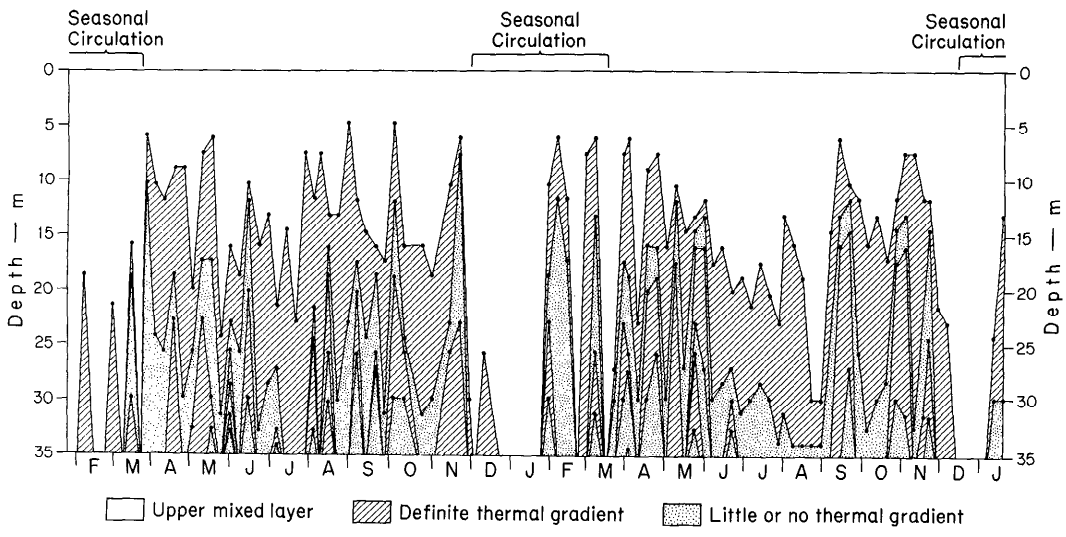

Fig. 7. Layer boundaries as a function of time, 1977–1978.

Table 2. Autocorrelation in the thickness of the upper mixed layer of Lake Valencia.

Timespan	Lag (week) 1	2	3	4
All weeks	0.44*	0.26*	0.27*	0.25*
Stratification only	0.31*	−0.04	−0.23*	0.07

* Significant at $P < 0.05$.

variation, and especially the occasional thickening of the mixed layer to 25–30 m, is greater than would be expected in a stratified temperate lake of similar size. Lewis (1973) has shown that the same is true of Lake Lanao, as have Richerson et al. (1977) for Lake Titicaca. Changes in mixing depth are to a large degree dependent on weather variations of rather brief duration. Week-to-week variation in mixed layer thickness is not entirely random, however. Table 2 shows by means of autocorrelation using Pearson product-moment coefficients the relation of mixed layer thickness on a given week to that of previous weeks. For the entire year, there is a significant relation for lags up to 4 weeks, but this is partly explained by the uniform mixed layer of the seasonal circulation. For the stratification season, there is a highly significant correlation of mixed layer thicknesses 7 days apart, but not so at 14-day intervals. An unexpected significant negative correlation appears for dates 21 days apart, presumably because the weather variables that control mixing are more likely to show significant change over 21 days than over shorter or longer intervals. Although only a minor amount of variance is explained in this way, the assumption that week-to-week nonseasonal variation is random would clearly be in error. Stauffer (1980) gives an interesting parallel example of nonrandomness in weather patterns affecting a temperate lake.

When cool windy weather gives way to calm sunny weather, uneven heat distribution often leads to formation of a stable gradient in the upper mixed layer, thus increasing the number of layers by two. This may occur two or three times sequentially. The uppermost gradient can be sharpened by erosion from the upper mixed layer, probably as a result of Langmuir circulation (Faller 1966, 1971). Deeper gradients are embedded and cannot be sharpened in this way. They tend to become diffuse with time because of turbulence. Thus an internal gradient or part of such a gradient can be converted to or merge with a thermally uniform layer without ever coming under the direct influence of the wind. Thermal gradients and internal thermally uniform layers can also disappear when the upper mixed layer increases in thickness, as during seasonal or nonseasonal cooling periods. The number of layers at any given time during stratification is thus controlled partly by variation in mixed layer thickness, which can create or destroy layers, and partly by deep-water turbulence, which can merge layers.

The layering phenomena described here are similar to several kinds of phenomena that have been described for temperate lakes and for oceans. Where gross thermal structure is concerned, multiple thermoclines stable for more than 24 h are known from temperate lakes (e.g. Hutchinson 1957; Smith 1975). This is most likely to be observed during early seasonal warming, however, and does not seem to be a persistent feature of the stratification period in most temperate lakes, as it is in Valencia or Lanao (Lewis 1973). Also, many temperate lakes may show daytime reductions in mixing depth that are caused by uneven heat distribution in the upper water column (e.g. Harris et al. 1979; Reynolds 1976). These mixing changes are probably very important biologically, but are distinct from the more persistent changes documented here for Valencia. Finally, it is known that lakes and oceans show a great deal of thermal microstructure in and below the thermocline (e.g. Simpson and Woods 1970; Thorpe 1977), including alternating isothermal and thermal gradient zones ("sheets and layers"). This structure appears to be for the most part very compact spatially, although layers thicker than 1 m are not unknown. The structure docu-

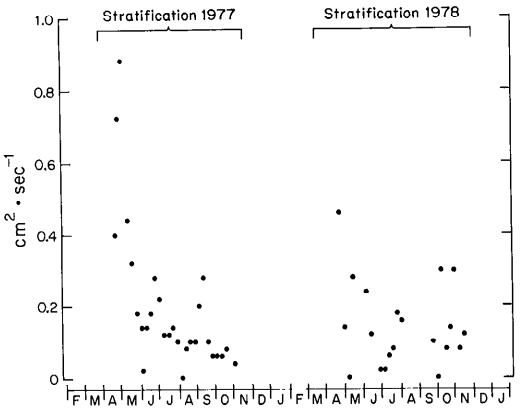

Fig. 8. Eddy diffusivity in the 28–29-m stratum as a function of time.

Table 3. Average vertical eddy diffusivities ($cm^2 \cdot s^{-1}$) for lower water column of Lake Valencia for entire stratification period and excluding first 5 weeks.

Stratum (m)	Entire		Excluding first 5 weeks	
	K_z	SE	K_z	SE
20–21	0.234	0.054	0.114	0.014
21–22	0.181	0.031	0.108	0.011
22–23	0.161	0.024	0.111	0.010
23–24	0.146	0.019	0.105	0.010
24–25	0.163	0.029	0.102	0.010
25–26	0.200	0.042	0.112	0.011
26–27	0.212	0.038	0.133	0.014
27–28	0.203	0.031	0.133	0.014
28–29	0.186	0.025	0.132	0.013
29–30	0.177	0.027	0.115	0.010
30–31	0.170	0.024	0.117	0.011
31–32	0.158	0.023	0.105	0.009
32–33	0.131	0.016	0.101	0.013
33–34	0.107	0.010	0.089	0.009
34–35	0.094	0.010	0.092	0.011

mented for Valencia may have similar origins, but shows a stronger element of gross or mesoscale structure, perhaps because of the narrow range of densities from top to bottom (the very small thermal range more than compensates for the higher rate of density change at the high base temperature of Valencia). Most important from the biological viewpoint, there seems to be no temperate counterpart to the major shifts that Valencia shows in mixing depth over periods >24 h during the stratification season: 24-h mixing depths in stratified temperate lakes are probably much more constant.

Vertical eddy diffusion—Vertical eddy diffusion coefficients were calculated for points below the upper mixed layer from the weekly thermal profiles by the method of Jassby and Powell (1975). Only points below 20 m in Lake Valencia can be considered to meet the minimum requirements for eddy diffusivity approximation by the heat transfer method (low convective or advective heat transfer). Bachmann and Goldman (1965) and Jassby and Powell (1975) have shown that direct solar heating below the thermocline must be taken into account in such approximations. However, a computation of the upper bound for direct solar heating shows that the method of Jassby and Powell (1975) can be simplified in the present case by assuming negligible direct heating. The maximum amount of warming caused by direct solar heating at 20–21 m, as determined from extinction coefficients and incident irradiance, is 3.4×10^{-10}°C·d^{-1} in Valencia. The observed heating at 20 m during stratification is at least 7.5×10^{-3}°C·d^{-1} (*see Fig. 3*); obviously direct solar heating is negligible in this case.

As the direct solar heating can be ignored, vertical eddy diffusivity is approximated by

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

where K_z is the coefficient of vertical eddy diffusivity ($cm^2 \cdot s^{-1}$), θ_z and θ_u are temperatures at depths z and u, A_z and A_u are lake area (cm^2) at any specific depth z or u, and t is time. As was done by Jassby and Powell (1975), thermal gradient and heat flux terms in the equation were smoothed by a moving average of five measurements across time, and the final K_z values are a moving average of three measurements across depth.

Eddy diffusivity in Lake Valencia varies with time and depth. The coefficients

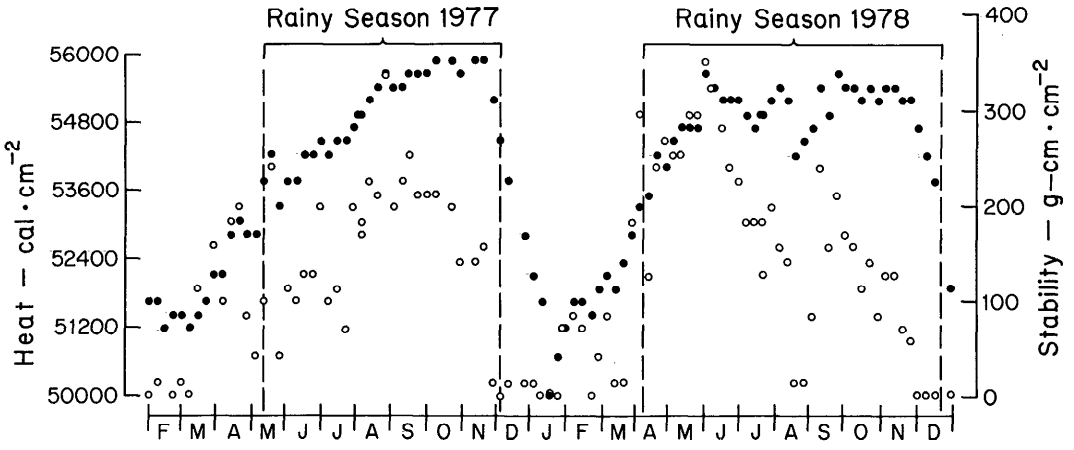

Fig. 9. Total heat above 0°C (Birgean—•) and stability of the water column (o) on a weekly basis.

at any particular depth are higher at the beginning of the stratification season and decline in curvilinear fashion to the end of the stratification season, although there is considerable scatter around the trend line. Figure 8 shows the pattern in the 28–29-m stratum. The most dramatic decline occurs in the first 4–6 weeks. The gap in the record for the second year is explained by an exceptionally thick mixed layer in August which precluded estimates of eddy diffusion.

Table 3 shows the average values of K_z for all depths. Averages were first computed over all weeks in the stratification period and then recomputed after exclusion of the first 5 weeks of very high values. Between 20 and 30 m, average K_z does not change in any systematic way. Below 30 m, eddy diffusivities decline.

Comparisons with other tropical lakes are possible only for Lanao (Lewis 1982) and Lake McIlwaine (Robarts and Ward 1978). The values for Lake McIlwaine (mean, 0.21 $cm^2 \cdot s^{-1}$), a reservoir whose turbulence may be raised by flow-through, are similar to the Valencia values even though McIlwaine is smaller. The values shown in Table 3 are about 20% of those for Lanao, although Lanao has the same latitude and surface area. The average depth of Lanao is three times greater, however, and Lanao is windier. The Valencia values are much like those characteristic of the deepest parts of Lake Kinneret (Lerman and Stiller 1969).

Heat budget and heat flux—The total heat above 0°C was computed for each week from the hypsographic curve and the thermal profiles (Fig. 9). Seasonal heating occurs at an average rate of about 30 $cal \cdot cm^{-2} \cdot d^{-1}$, cooling at about 80 $cal \cdot cm^{-2} \cdot d^{-1}$. Seasonal cooling is monotonic, but seasonal heating is not. The unusual nonseasonal loss of heat in August of the second year is particularly notable. The total annual heat budget (Θ_{ba}) is 4,755 $cal \cdot cm^{-2}$ for the first year and 5,862 for the second year; the average is thus 5,308. Lake Lanao, which has the same area and latitude but is deeper, averaged 5,875 $cal \cdot cm^{-2}$ for 2 years (Lewis 1973).

The combination of weather data, thermal profiles, and lake levels for Lake Valencia allows major elements of the heat budget to be computed. The heat budget elements are of special interest because their relative importance in controlling heat flux, and thus layering and mixing, is not well known for tropical lakes. The heat budget elements can be represented as follows:

$$Q_\theta = (Q_S + Q_H + Q_R + Q_U) + (Q_A + Q_M + Q_W) + Q_s + Q_i + Q_e + Q_E.$$

Terms are assumed to be positive or negative in a particular interval according to

whether they bring heat to (+) or take heat from (−) the lake. In the equation, Q is energy flux ($cal \cdot cm^{-2} \cdot d^{-1}$) and subscripts have the following indications (from Hutchinson 1957): S—direct sun; H—sky; R—reflection; U—back scatter; A—atmosphere (longwave); M—mountains (longwave); W—lake back radiation (longwave); s—sensible heat (conductive); i—advection; e—nonevaporative heat transferred with water vapor; E—evaporation; θ—total heat (lake and sediments). Large surface area, low transparency, and high mean depth reduce the role of sediments to a minimum, so the water column is assumed to represent the entire lake.

The pyranometer reading is assumed to be the composite of Q_S and Q_H. The accuracy of this assumption was checked against the Smithsonian Meteorological Tables for selected cloudless days during the study period. The measured values were within a few percentage points of the expected values from the tables in all cases. Q_R and Q_U are combined for present purposes; the composite is taken as 7% of $Q_S + Q_H$, and is unlikely to be in error by >2% (Hutchinson 1957). Q_M is assumed negligible. Q_A and Q_W are treated together as a net flux, assuming blackbody radiation for both (Hutchinson 1957).

The last four terms of the budget (Q_s, Q_i, Q_e, and Q_E) all require estimates of evaporation at the lake surface. Comparison of pan evaporation with lake level change during the dry season (Lewis and Weibezahn unpubl.) showed that pan evaporation does not accurately represent lake surface water loss, even if a fixed correction factor is used. The four terms related to evaporation were thus recomputed from the difference between the net radiation surplus, which takes into account all of the other terms, and the observed heat change. The computation requires the assumption that the sensible and evaporative heat loss are distributed according to the Bowen ratio (cf. Anderson 1952). Given this assumption, and the simplifying fact that Lake Valencia does not lose any heat by advection, we can express three of the terms as a function of the fourth (evaporation):

$$Q_s = Q_E \times P \times (\theta_w - \theta_a) \times (P_{w'} - P_w)^{-1} \times 0.00061; \quad (2)$$

$$Q_i = (\theta_i \times K) - (\theta_i \times Q_E \times L_e - 1); \quad (3)$$

$$Q_e = Q_E \times \theta_e \times L_e^{-1}; \quad (4)$$

where P is barometric pressure, $P_{w'}$ is saturation pressure of water at θ_w, P_w is the observed water vapor pressure, K is the change in lake level ($cm \cdot d^{-1}$), θ_i and θ_e are temperatures of advected and evaporated water, and L_e is the latent heat of evaporation at the temperature of interest. Solution of these equations gives distribution of residual heat flux among the four terms.

Figure 10 shows a time plot of the four most important parts of the heat budget. The heat budget elements differ considerably in the degree to which they show seasonal change. Although net radiation flux shows considerable week-to-week variation, the seasonal component is weak or even absent, except for a repeated tendency for low values just as the rainy season begins. Evaporative heat loss shows a definite seasonal trend, but there is considerable scatter explained by variations in humidity and wind speed. Net back radiation and conductive heat loss show the strongest seasonality because of their dependence on the difference between air and water temperature.

The mean values for all terms in the heat budget are shown in Table 4 along with the observed heat change. In terms of magnitude, net radiation flux and evaporative heat loss are the dominant terms. Net back radiation and sensible heat loss are important secondary terms, and advected heat and loss of heat as water vapor are both minor. Average absolute value may be more important than average value for terms which vary in the vicinity of 0, but this is not the case for any of the heat budget terms shown in the table because each tends to retain the same sign continuously or in the vast majority of weeks. This is not true of the observed heat change; it has a mean magnitude of

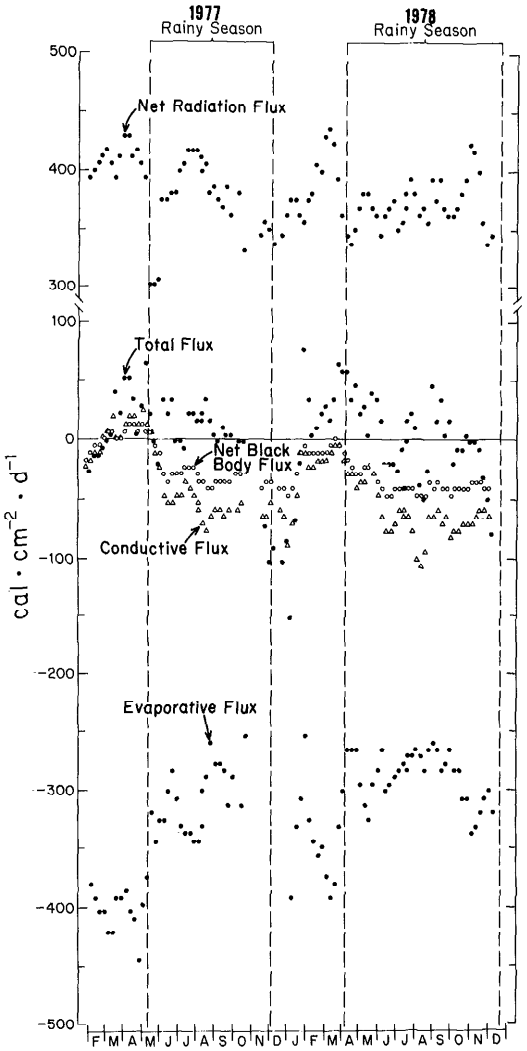

Fig. 10. Important heat budget elements on a common scale.

2 cal·cm^{-2}·d^{-1} and a mean absolute magnitude of 45.

Magnitude is not the only index of importance for the heat budget elements as they relate to the seasonal dynamics of the lake. The standard deviation is probably more important, as it indicates the amount of variation to be expected for each term. The heat budget elements group somewhat differently by standard deviation than by absolute magnitude. Evaporative heat loss is by a considerable margin the most important; it is followed in descending order by the net radiation flux, the sensible heat loss, and the net back radiation.

Table 4. Mean values (cal·cm^{-2}·d^{-1}) for heat budget elements computed at weekly intervals over the study period.

Variable	Mean	SD
Sun + sky (Q_s+Q_H)	409	43.5
Surface loss (Q_R+Q_u)	−29	3.0
Net radiation flux	380	40.4
Net back radiation ($Q_A+Q_M+Q_W$)	−26	19.0
Net radiation surplus	354	47.7
Conductive (sensible) (Q_s)	−43	34.0
Advected (Q_i)	12	13.1
Water vapor (Q_e)	−10	0.21
Evaporative (Q_E)	−308	57.8
Observed heat change (Q_θ)	2	60.3

The relative importance of the different heat budget elements in controlling the annual cycle can be estimated by multiple regression. In a multiple regression analysis with observed heat change as the dependent variable, net back radiation accounts for 22% of the total variance and net radiation flux for an additional 4%. The variance attributable to evaporative loss and sensible heat loss must be computed by difference because the variables themselves are calculated by difference. Their aggregate contribution to total variance must be of the order of 70%, assuming that the measurement errors in net radiation flux and net blackbody radiation are relatively small.

Stability and work of the wind—The work required to distribute the incoming heat during a given heating season was computed according to the original rationale of Birge (1916) as presented by Hutchinson (1957). Work is expressed as g-cm·cm^{-2} of lake surface and depends on heat distribution in the lake at the time of minimum heat content compared with heat distribution at the time of maximum heat content. For 1977, the heat content of Lake Valencia was minimal when the lake was isothermal at 25.55°C; for 1978, when the lake was isothermal at 24.95°C. Table 5 shows the work of the wind and its ratio to the annual heat budget.

Table 5. Statistics related to stability and work of the wind in Lake Valencia.

	1977	1978
Work of the wind ($g\text{-}cm \cdot cm^{-2}$)	2,639	3,156
Annual heat budget ($cal \cdot cm^{-2}$)	4,755	5,862
Efficiency of heating ($g\text{-}cm \cdot cal^{-1}$)	0.55	0.54
Maximum stability ($g\text{-}cm \cdot cm^{-2}$)	345	352

The latter provides an indication of the efficiency of heat distribution. The ratio of work to heat budget (= efficiency of heating) is higher for Valencia than for any of the lakes tabulated by Hutchinson (1957).

Stability calculations follow Schmidt (1915, 1928) as presented by Hutchinson (1957; the formula as shown by Hutchinson provides a result of incorrect sign) and Idso (1973). Stability computations were made for every week of the year (Fig. 9). Table 5 shows the maximum stability for the 2 years. Stability is much more irregular than heat content. Significant vertical movement of heat by wind-generated turbulence offsets to varying degrees the added stability that would otherwise accrue from the accumulation of heat during the warming season. Average stability is lower than in a temperate lake of comparable size; stability is thus more responsive to changes in wind strength.

Conclusions

The time-course of heat and temperature in Lake Valencia over the study period supports the concept that many lakes of the tropics previously thought to be oligomictic will in fact be strongly warm monomictic, with a highly predictable annual overturn and a definite period of seasonal mixing. The duration of seasonal stratification in Valencia, and probably in many other tropical warm monomictic lakes, is considerably longer than that typical of temperate lakes. The longer period of stable stratification implies a longer growing season; about two-thirds of the year could be classified as a growing season for phytoplankton in Valencia. On the other hand, extended stratification implies considerable potential for nutrient stress because of nutrient depletion in the euphotic zone. In Valencia, as in Lanao and perhaps in most tropical lakes, the thickness of the upper mixed layer changes greatly under the influence of nonseasonal weather events. These changes in depth of mixing play a very important role in offsetting loss of nutrients by sedimentation during the extended growing season (Lewis 1974). The extreme variation in thickness of the mixed layer observed during stratification in Lake Valencia is probably a tropical characteristic rather than a general one. In contrast, the lower portion of the water column beyond the reach of the upper mixed layer during the stratification season shows little evidence of exceptional eddy diffusion coefficients in comparison with dimictic temperate lakes of similar size.

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