The heat budget of a large tropical lake, Lake Titicaca (Peru-Bolivia)

20

TIMOTHY KITTEL and PETER J. RICHERSON

With 3 figures and 1 table in the text

Introduction

The annual cycle of a lake's chemical and biological regime is driven by the pattern of stratification and circulation. Factors that control the extent and timing of mixing are best understood through studying the heat budget sources and sinks. Though thermal stratification has been studied in several tropical lakes (e. g., TALLING 1966; LEWIS 1973) work lags behind that in temperate lakes and analytical heat budgets have been neglected. In addition, year-to-year and long-term variability in the frequency and depth of circulation is an important environmental parameter that has received little attention in either tropical or temperate lakes. This paper presents the analytical budget for Lake Titicaca for 1973 and a preliminary estimate of the budget's variability based on 10 years of weather records available from the lake basin.

Lake Titicaca is a large $(8,100 \text{ km}^2, 281 \text{ m} \text{ max. depth})$, high altitude (elev. 3803 m) lake that lies at 16° S latitude. Lake Titicaca's surface heat fluxes are strongly influenced by the region's cool, semi-arid, and equable climate. There is a prominent though variable annual cycle of a cloudy rainy summer, December to March, and a dry sunny winter, May to August. A survey of physical, biological, and chemical parameters was undertaken in 1973 and has been reported by RICHERSON et al. (1975, 1977) and WIDMER et al. (1975).

The pattern of mixing in 1973 resembled the warm monomictic type of HUTCHINSON'S (1957) thermal classification. However, the lake was never quite isothermal in 1973 and chemistry data indicate that mixing to 150 m did not occur. Thermal profiles in Lake Titicaca resemble those of other tropical lakes, having a thick epilimnion only a few degrees warmer than the hypolimnion.

Methods

Temperature profiles were obtained on eighteen dates from February to December 1973, at a station 10 km east of the village of Capachica (Departamento de Puno, Perú) in waters of 175 to 200 m depth. Measurements were made with a thermistor or with a water bottle thermometer, both calibrated against a laboratory standard thermometer. Heat content for the main basin was calculated from the temperature data and from a hypsographic curve as the heat required to be lost to cool the lake to 0 °C. These data are presented in RICHERSON et al. (1975). The heat content data are revised in RICHERSON et al. (1977).

Using data from the Capachica weather station, estimates were made of the various components of the heat budget. The equation used for the heat budget of a water body was:

$$S = R_n - LE - H + \Delta$$

where S is storage rate, R_n net radiation, LE is evaporative heat loss, H is sensible heat transfer, and Δ is a residual term. This equation neglects advective effects. Monthly averages of S were calculated from the heat content data. R_n was calculated as the

sum of short-wave radiation, R_{sw} , incoming long-wave radiation, $I \downarrow$, and outgoing long-wave radiation, $I \uparrow$. R_{sw} was computed from per cent insolation data from the Puno weather station (based on pyrheliograph measurements), extraterrestrial radiation (from LIST 1951), and surface albedo (assumed 6 % in summer, 7 % in winter; SELLERS 1965). $I \downarrow$ was calculated using SWINBANK'S (1963) equation with GEIGER'S (1965) modification for cloud cover (see SELLERS 1965). The STEFAN-BOLTZMANN equation was used to determine I \uparrow . Evaporative heat loss was estimated using JACOBS' (1951) empirical equation for the ocean. Sensible heat transfer was estimated from the BOWEN ratio, B, and LE. See RICHERSON et al. (1977) for a discussion of estimates of total annual evaporation. Correlation coefficients and linear regressions were determined using the regression program of NIE et al. (1975).

Results

The heat budget for Lake Titicaca in 1973 is summarized in Fig. 1 and Table 1. Net radiation (R_n) shows a definite seasonal pattern (though small compared to temperate regions) that was dominated by changes in solar radiation (R_{sw}) . Though extraterrestrial radiation (R) was high in the summer months, with the sun passing overhead in February and October, extensive cloud cover reduced R_{sw} during the rainy season (February—March, December). The fall peak of R_n in April resulted from increasing R_{sw} due to decreased cloud cover and from decreasing I \downarrow due to decreased cloud cover and air temperatures. Soon afterwards, R_{sw} also decreased, following more closely the annual curve of R, with a winter minimum and a rise in the spring, due to high sun angle and low cloudiness.

The storage rate had a moderately seasonal pattern that closely followed net radiation (r = .90, p < .01, n = 11) (Fig. 1). Seasonal changes of heat storage rate vs. depth are shown in Fig. 2 a. During the summer R_n minimum, the lake lost stored heat, and epilimnetic thermal discontinuities (of 0.2–0.7 °C) were



Fig. 1. Summary of the analytical heat budget of Lake Titicaca, 1973.

Table 1. Heat budget for Lake Titicaca, 1973. Negative values represent loss of heat from the lake. Energy fluxes are given in cal \cdot cm⁻² \cdot day⁻¹. E is the calculated estimate of daily evaporation. Monthly plan evaporation, E_{pan} (mm \cdot day⁻¹), and mean wind speed, \overline{W}_{a_2} (m \cdot sec⁻¹), data from the Capachica station are also given.

	S	R_{sw}	I↓	—I↑	—LE	-H	\triangle	В	Е	E_{pan}	\overline{W}_a
Feb	- 14	442	651		-267	65	+ 13	.24	4.6	5.3	3.0
Mar	-103	440	616	795	-271	-72	- 21	.26	4.6	4.2	2.8
Apr	+ 12	506	617	-783	-269	-62	+ 3	.23	4.6	4.4	2.9
May	-181	531	548	-776	300	-71	-113	.23	5.1	4.2	3.0
Jun	-186	478	519	-759	-258	66	-100	.26	4.4	4.5	2.6
Jul	-138	501	513	-747	-312	-82	- 11	.26	5.3	4.1	3.4
Aug	+ 12	530	549	-754		-82	+102	.25	5.7	5.4	3.7
Sep	+ 24	511	589	757	-308	72	+ 61	.23	5.2	4.9	3.7
Oct	+197	621	615	-774	-335	-67	+137	.20	5.7	6.2	3.5
Nov	+ 51	559	620		-369	72	+ 90	.20	6.3	6.5	3.8
Dec	— 96	486	617		-372	-77	+ 26	.21	6.3	5.7	4.0



Fig. 2. Heat storage rate vs. depth, 1973. a, seasonal profiles. b, winter cooling period. c, spring development of stratification. Depths are in meters.

removed by mixing to 30 m. The April rise of S to slightly above zero coincides with the fall R_n peak. In the winter, high net long-wave radiation loss, high evaporative heat loss, and low short-wave gain caused a large loss of stored heat from May to July (Fig. 2 a, profile II). The loss of stored heat from progressively deeper depths during this period is illustrated in Fig. 2 b. Profile C (Fig. 2 b) shows that heat was transferred upwards from at least 100 m. Changes of \pm 0.006 cal \cdot cm⁻³ \cdot day⁻¹ are within measurement error.

During the late winter, surface heat fluxes were nearly balanced and there was little change in storage (Fig. 2 a, profile III). The spring radiation maximum resulted in high rates of storage (October—November, Fig. 1 and Fig. 2 a, pro-

file IV). Fig. 2 c shows that the development of stratification as heat storage gain was limited to a progressively shallower epilimnion.

Evaporative loss was high and relatively constant during the year. The pattern of LE only loosely follows R_n (r = .60, p \cong .05, n = 11), and is not significantly correlated to the storage term (r = .36, p \geq .05, n = 11). Because of this pattern and the high magnitude of both LE and R_n , the storage flux results mainly from the small imbalances of these two terms during the course of the year. Sensible heat transfer was small and positive (a loss) throughout the year, with little or no fluctuation. This resulted from the lake being consistently warmer than the mean air temperature for all months. The average difference between mean air and epilimnetic (3-40 m) temperatures was 5.1 °C, with a standard deviation of 1.1 °C. The Bowen ratio was nearly constant and averaged 0.23 (s.d. = 0.02).

The storage term is correlated to the sum of source and sink terms, R_n —LE—H (r = .79, p < .01, n = 11). However, during some months the residual was high relative to other budget terms. This discrepancy may be in part the result of some of the simplifying assumptions. Advective heat flux from rivers, advection from precipitation, and the change in heat content per unit surface area caused by the seasonal fluctuation of lake volume are probably each responsible for no more than $\pm 5 \text{ cal} \cdot \text{cm}^{-2} \cdot \text{day}^{-1}$. The residual term is correlated with the storage term (r = .90, $p \le .01$, n = 11), which indicates that, while the pattern of the fluctuation of S is explained by the source and sink terms, the magnitude of the fluctuation is not accurately estimated. The residual is probably largely the result of having to use western shore-station weather data rather than accurate overwater data to estimate the terms. Errors or biases may also arise from applying JACOBS' (1951) evaporation equation to a high elevation lake and from the use of relatively few temperature profiles to estimate S. Residuals in heat budgets can usually be made small only by using long-term averages of parameter estimates (T. Powell pers. comm.).

The year-to-year differences in storage were estimated from a 10-year weather record (1964—1973) from the Puno weather station, 30 km southwest of Capachica. Based on monthly per cent insolation, air temperature, and Piché evaporimeter data, a multiple linear regression equation was formed:

$$S' = 2.13 R_n - 0.60 LE - 563$$

 $(R^2 = 0.72, p \le .01, n = 11)$. The results of this equation are given in Fig. 3 along with estimates of seasonal heat gain and loss. Based on S', the estimate of seasonal heat loss from February 1973 on is 19,000 cal \cdot cm⁻² \cdot yr⁻¹, equivalent to the BIRGEAN annual heat budget, 19,300 cal \cdot cm⁻² \cdot yr⁻¹, determined by RICHERSON et al. (1977).

Though variable, the S' curves show a common annual pattern which consists of two maxima (fall and spring) and two minima (winter and summer), as in 1973. This pattern largely results from the opposing patterns of extraterrestrial radiation and cloud cover. However, the degree and duration of the peaks and troughs vary greatly between years. Apparently, large summer heat losses (and hence deep mixing), comparable to winter losses, occurred in some years (e. g. 1967, 1971). In contrast, there may have been major heat gains during other sum-



Fig. 3. Annual pattern of storage flux for years 1964—1973, calculated with the linear regression equation (see text). The storage term based on 1973 temperature profiles is also presented (open dots). Total heat gain or loss is given at the end of each major heating and cooling period.

mers (1966, 1968) that were followed by the persistence of stratification throughout the winter. It would be reasonable to expect that this variability is the case, as the long-term (~ 10 yr.) oscillation of lake level indicates that the length and intensity of the cloudy rainy season is irregular. The cumulative heat storage over the 10 years appears to have a similarly long-term oscillation about 0, from — 9000 cal·cm⁻² in 1964 to + 28,000 in 1969 and to —29,000 in 1973. These results suggest that the depth and timing of circulation in Lake Titicaca varies greatly year to year.

Discussion and conclusions

The heat budget of Lake Titicaca provides interesting insights into what controls the pattern of mixing and heat exchange in tropical lakes. At low latitudes, seasonality is reduced so that heat inputs and outputs are nearly in equilibrium. Consequently, heat storage results from small fluctuations in the main budget terms, net radiation and evaporative heat loss, and the lake is only weakly stratified. This is strikingly different from temperate lakes where the high annual oscillation of climate produces strong and more or less regular seasonal changes. HUTCHINSON (1957) and GODDEN (1976) have summarized the budgets for several temperate lakes, all of which show very large storage terms, on the same order as R_n .

In Lake Titicaca, epilimnetic temperatures were above median air temperatures for every month in 1973. This was also observed in Lake Lanao (8° N lat.), where mean epilimnetic temperatures were greater each month by an average of 2.1 °C (LEWIS 1973). Elevated water temperature increases all heat outputs, $I\uparrow$, LE, and H, until high radiation inputs are nearly balanced. However, this would only be expected in equable climates, because, in temperate lakes, water temperatures lag behind the season to the extent that H is often a heat input in the summer. We predict that most low latitude lakes will be found to have epilimnetic temperatures above mean air temperatures year round.

Most well studied tropical lakes of intermediate depth appear to have patterns of circulation similar to that of Lake Titicaca, with more or less substantial mixing once annually (TALLING 1969; LEWIS 1973). However, because the annual fluctuations of the heat fluxes that result in storage are small, year-to-year variability in the annual climate pattern can have a strong influence on mixing. Consequently, on certain years, a tropical lake may mix more than once (polymixis) or not at all (oligomixis). In contrast, the seasonal pattern in temperate localities is so strong that climatic variability may have only small effects on circulation. Lake Titicaca apparently circulated more thoroughly in the winter of 1974 (to depths greater than 150 m, W. WURTZBAUCH pers. comm.) than in 1937 (GILSON 1964) and 1973. Irregularity of circulation in Lake Titicaca is also suggested by the 10-year extrapolated storage term results. Highly variable thermal regimes may have substantial consequences for biotic processes (RICHERSON et al. 1977).

As discussed by BAXTER et al. (1965), lake depth is probably more important than altitude in producing departures from the warm monomictic pattern in tropical and equatorial lakes. Pure examples of the polymictic and oligomictic types of HUTCHINSON & LÖFFLER (1956) are apparently limited to shallow or very high altitude lakes (polymictic) and to protected or very deep lakes (oligomictic). Heat loss conditions that give rise to polymixis in shallow lakes are probably the same as those that result in the infrequent deep epilimnetic mixing observed during stratification in deeper lakes, such as Titicaca and Lanao (LEWIS 1973). In regions with climates similar to that of Lake Titicaca, even moderately deep lakes may have two heat storage minima and regularly mix twice a year (e. g. Lake Victoria, TALLING 1966). The classification of circulation behavior may not always be clear-cut. In low latitude regions, a lake's circulation pattern may be highly suspectible to year-to-year differences in climate.

Acknowledgements

We are deeply indebted to our colleague, CARL WIDMER, without whom this research would not have been possible. We thank Drs. LEONARD O. MYRUP and THOMAS M. POWELL, who gave us valuable advice and criticism. We are especially grateful to ELEODORO AQUIZE, Servicio Nacional de Meterología e Hidrología, who supplied us with weather data.

The authors are grateful for the financial support provided by the National Geographic Society. KITTEL was supported by the University of California and the Foresta Institute for Ocean and Mountain Studies, and RICHERSON was partly supported by National Science Foundation grants GA-34099 and BMS 75—14273 during this study. We are also indebted to the Instituto del Mar del Perú, the Universidad Nacional Técnica del Altiplano, and to individuals including ANTONIO LANDA, EDGAR FARFAN, OSWALDO ZEA, VICTORIA VALCÁRCEL, STA. JULIA VDA. DE ARZE, HOMER CAMPBELL, and LAUREN LANGMEAD. DOLORES DUMONT and CLIFF SHOCKNEY typed the manuscript. Support from the Institute of Ecology and the Division of Environmental Studies, University of California, Davis, is gratefully acknowledged, with thanks to MARILYN CASEY.

References

- BAXTER, R. M., M. V. PROSSER, J. F. TALLING & R. R. WOOD, 1965: Stratification in tropical African lakes at moderate altitudes (1,500 to 2,000 m). — Limnol. Oceanogr. 10: 510—520.
- GEIGER, R., 1965: Climate Near the Ground. Harvard Univ. Press, 611 pp.
- GILSON, H. C., 1964: Lake Titicaca. Verh. Internat. Verein. Limnol. 15: 112-127.
- GODDEN, D. A., 1976: Climatological Estimate of the the Average Monthly Energy Budget of Lake Tahoe. — M. S. thesis, Univ. of California, Davis, 136 pp.
- HUTCHINSON, G. E., 1957: A Treatise on Limnology. 1. Geography, Physics, and Chemistry. — Wiley, N. Y., 1015 pp.
- HUTCHINSON, G. E. & LÖFFLER, H., 1956: The thermal classification of lakes. Proc. Nat. Acad. Sci. 42: 84—86.
- JACOBS, W. C., 1951: The energy exchange between sea and atmosphere and some of its consequences. — Bull. Scripps Inst. Oceanogr. Tech. Ser., Univ. of California 6: 27—122.
- LEWIS, W. M., JR., 1973: The thermal regime of Lake Lanao (Philippines) and its theoretical implication for tropical lakes. Limnol. Oceanogr. 18: 200-217.
- LIST, R. J. (ed.), 1951: Smithsonian Meteorological Tables. Smithsonian Miscellaneous Collections 114: 1—527.
- NIE, N. H., HULL, C. H., JENKINS, J. G., STEINBRENNER, K., & BENT, D. H., 1975: Statistical Package for the Social Sciences. — McGraw-Hill, N. Y., 673 pp.
- RICHERSON, P. J., WIDMER, C. & KITTEL, T., 1977: The Limnology of Lake Titicaca (Peru-Bolivia), a Large, High Altitude Tropical Lake. — Inst. of Ecology, Univ. of California, Davis, Publ. 14: 78 pp.
- RICHERSON, P. J., WIDMER, C., KITTEL, T., & LANDA, C. A., 1975: A survey of the physical and chemical limnology of Lake Titicaca. — Verh. Internat. Verein. Limnol. 19: 1498—1503.
- SELLERS, W. D., 1965: Physical Climatology. Univ. of Chicago Press, 212 pp.
- SWINBANK, W. C., 1963: Long-wave radiation from clear skies. Quart. J. Roy. Met. Soc. 89: 339–348.
- TALLING, J. F., 1966: The annual cycle of stratification and phytoplankton growth in Lake Victoria (East Africa). — Int. Rev. ges. Hydrobiol. 51: 545—621.
 - 1969: The incidence of vertical mixing and some biological and chemical consequences in tropical African lakes. — Verh. Internat. Verein. Limnol. 17: 99—1012.
- WIDMER, C., KITTEL, T. & RICHERSON, P. J., 1975: A survey of the biological limnology of Lake Titicaca. — Verh. Internat. Verein. Limnol. 19: 1504—1510.

Authors' address:

T. KITTEL and P. J. RICHERSON, Division of Environmental Studies, University of California, Davis, California 95616, U. S. A.