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A survey of the physical and chemical limnology of Lake Titicaca

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With 4 figures and 1 table in the text

Introduction

The largest high altitude lake in the world, Lake Titicaca (Perú—Bolivia), lies in the southern tropics (15° 14′ — 16° 35′ S). With a surface area of 7,800 km^2, the lake is at an elevation of 3,800 m. This condition of high altitude and tropical latitude provides an interesting study area for physical limnology. Tropical physical limnology has been developed extensively in some lakes, but in general has been neglected (TALLING 1966; LEWIS 1973). During 1973, our study surveyed physical and chemical parameters in the main basin of Lake Titicaca. These efforts coincided with a study of biological limnology (see WIDMER et al. 1975).

Scientific work on Lake Titicaca has occurred sporadically since at least 1875 (AGASSIZ & GARMAN 1876). The major work to date was done by the PERCY SLADEN Trust Expedition in 1937 (GILSON 1939, 1940, 1955), and, in 1955, MONHEIM (1956) did an extensive study of the lake basin hydrology and climate. GILSON (1964) reviews this literature.

The Lake Titicaca region has a tropical subalpine climate. The annual range of monthly mean temperatures is small compared to the diurnal range, with minimum winter air temperatures rarely dropping below — 5 °C. There is a marked annual cycle of a cloudy rainy summer, December to March, and a dry sunny winter, May to August. Much of the year is dominated by evaporation, and MONHEIM (1956) estimates that evaporation accounts for 95 % of water lost from the lake, and that 5 % leaves by Rio Desaguadero.

Methods

Sampling runs were done approximately once every two weeks at station "D" (see Fig. 1, WIDMER et al. 1975), 10 km east of the village of Capachica, in waters of 175 to 200 m depth. Temperature measurements were made with a thermistor (February—May, September—December), and a water bottle thermometer (January, June—August), calibrated against a laboratory standard thermometer. Temperature profiles were adjusted to a 11.1 °C hypolimnetic temperature to remove small remaining inconsistencies in the measurements. Heat content was calculated from these temperature data and from a hypsographic curve derived from contours in NEWELL (1949) based on GILSON (1939) soundings.

In addition to SECCHI disk depths, a homemade photometer, sensitive to visible light, was used to make rough measurements of light penetration. Light extinction coefficients were then determined from the slope of light penetration vs. depth plotted on semi-log paper (HUTCHINSON 1957). Meteorological data were obtained from the weather station in Puno. Concentrations of major ions (Ca^{+2}, Mg^{+2}, $SO_4^{=}$, Cl^-), dissolved oxygen, and silica were determined with an Hach DR-EL Kit and Colorimeter. A 12 litre sample of lake water was evaporated and analysed for some of the major cations.

Thermal regime

Lake Titicaca is a warm monomictic lake according to HUTCHINSON's (1957) system of thermal types. During the summer and fall, the lake was stratified with the thermal discontinuity layer extending from 40 to 70 m in March and from 70 to 100 m in June (Fig. 1). By mid-winter, the lake had become isothermal at 11.1 to 11.2 °C. Stratification was re-established in September and

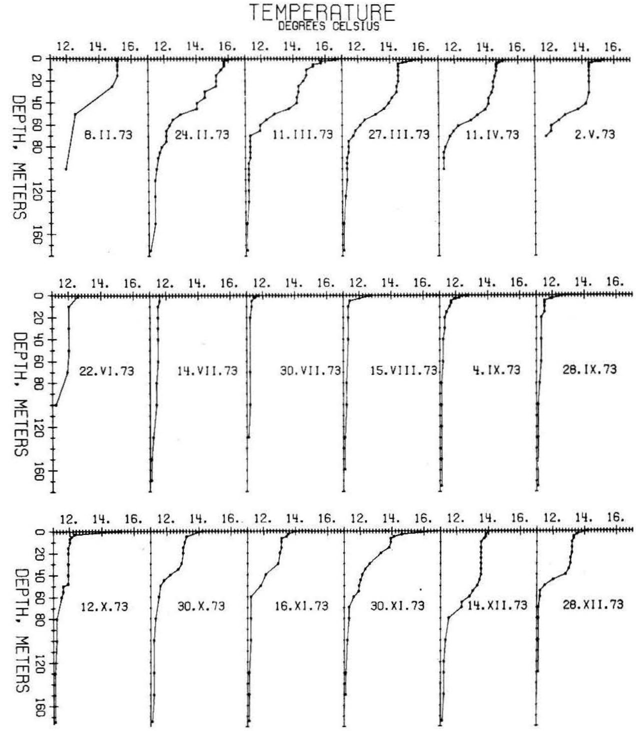

Fig. 1. Changes in thermal stratification during 1973 shown by temperature depth-profiles.

continued into the following summer. There was only a small difference between epilimnetic (12.0—15.7 °C) and hypolimnetic (11.1—11.6 °C) temperatures during stratification. At times, multiple-stepped thermoclines occurred in the epilimnion (24 February, 11 March, and 30 November). This was soon followed by atelomixis (27 March and 14 December), the mixing of chemically divergent layers in the epilimnion without erosion of the main thermocline (LEWIS 1973).

Lake Titicaca mixed during isothermy to at least 100 m by 30 July. Low concentrations of dissolved oxygen (Fig. 2) and high concentrations of silica at 150 to 200 meters before and after mixing indicate that the lake probably did not mix to 150 m during the 1973 winter. Oxygen data from this past winter (16 July 1974), however, evidenced mixing to at least 150 m (WAYNE WURTSBAUCH pers.

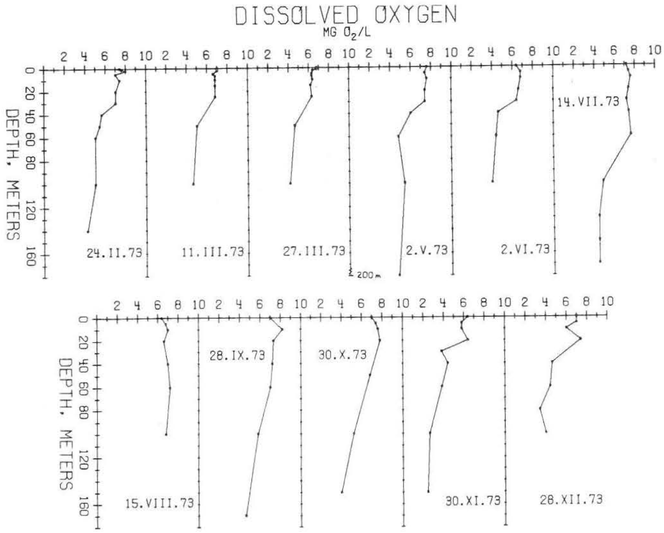

Fig. 2. Dissolved oxygen (mg O_2/l) depth-profiles for 1973.

Tab. 1. Physical parameters — Lake Titicaca, 1973.

Date	Heat content cal · cm^{-2}	SECCHI depth m	Light extinction coefficient, m^{-1}
Summer			
8 Feb	150,400	4.5	—
24 Feb	150,800	4.75	0.173
11 Mar	147,100	4.5	0.140
Autumn			
27 Mar	146,500	5.8	0.135
11 Apr	147,100	6.5	0.121
3 May	147,000	7.4	0.080
18 May	—	7.0	0.078
2 Jun	—	8.25	0.071
Winter			
22 Jun	138,300	8.5	0.074
15 Jul	132,300	8.75	0.068
30 Jul	131,900	10.0	0.084
15 Aug	132,600	10.5	0.077
4 Sep	132,100	10.5	0.064
Spring			
28 Sep	132,600	8.75	0.055
12 Oct	135,300	9.25	0.059
30 Oct	139,100	9.25	0.050
16 Nov	138,400	7.5	0.048
30 Nov	140,100	6.2	0.060
14 Dec	144,800	6.0	0.068
Summer			
28 Dec	138,800	6.0	0.087

comm.). The variation from year to year in the extent of deep mixing in Lake Titicaca is an interesting question for further research.

Heat budget

The heat content of Lake Titicaca declined as the lake became isothermal and later increased during restratification (Tab. 1 and Fig. 3). Approximately 18,900 cal · cm^{-2} of heat was lost from the February maximum to the July minimum. Because of decreased seasonality from temperate to equatorial zones, Lake Titicaca's annual heat budget is lower than that of large temperate lakes such as Baikal, 65,500, Michigan, 52,400, and Tahoe, 34,800 cal · cm^{-2} (Hutchinson 1957) and is high compared to that of equatorial Lake Victoria (0° 05′ S), 9,000—11,000 cal · cm^{-2} (Talling 1966). The Titicaca budget resembles more that of the tropical Lake Atitlan (Guatemala, 14° 40′ N), 22,110 cal · cm^{-2} (Hutchinson 1957).

Relative humidity and insolation were correlated with changes in heat content (Fig. 3). During the months of greatest heat loss, May to July, relative

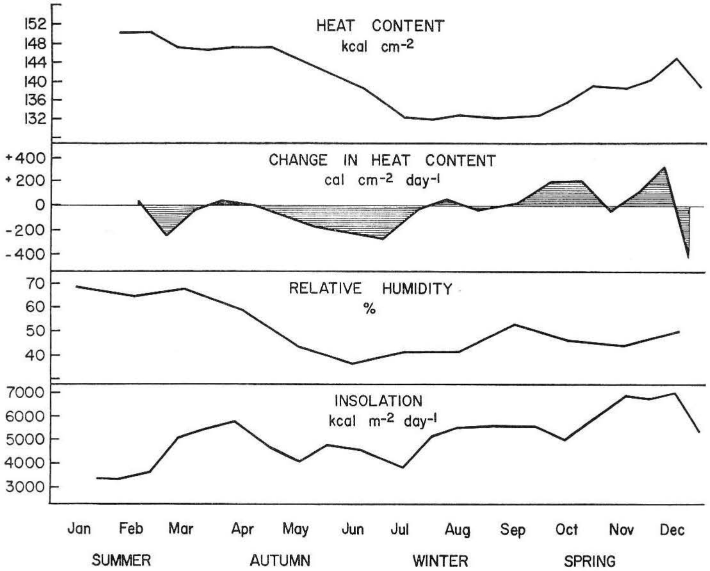

Fig. 3. Lake Titicaca, 1973. Heat content and related parameters. Relative humidity data are monthly averages from 7.00 hr, 13.00 hr, and 19.00 hr readings. Insolation data are from spot measurements.

humidity was decreasing and daily insolation was low. Mean air temperatures were also lowest during this time. In the spring, when there was increasing relative humidity and high insolation, heat was gained. With a low heat budget, Lake Titicaca's heat balance is potentially sensitive to small variations of input and output terms from year to year. In this regard, long term investigations of the heat budgets of this and other tropical lakes should prove interesting.

Light penetration

SECCHI disk depths and light extinction coefficients (Tab. 1 and Fig. 4) were correlated to rainfall and phytoplankton biomass (WIDMER et al. 1975). SECCHI depth was 4.5—5 m in February, but as the rainy season ended, clarity increased

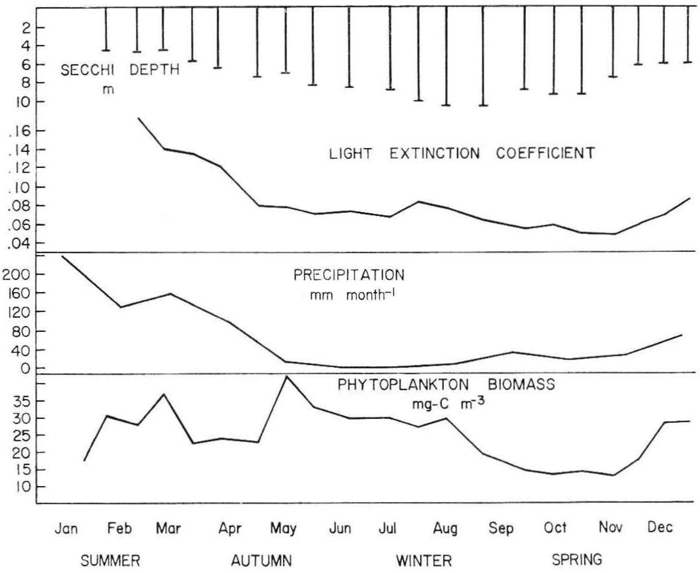

Fig. 4. Lake Titicaca, 1973. Light penetration and related parameters.

and the SECCHI depth gradually went to a maximum of 10.5 m in August. With the onset of light spring rains in September, followed by an increase of phytoplankton biomass, SECCHI depth decreased to 6 m by December. Extinction coefficients followed a pattern influenced by rainfall during the first half of the year and by phytoplankton biomass during the latter half.

Chemistry

Major ion concentrations determined from the evaporated mid-lake sample and from Hach Kit measurements averaged over the year varied only slightly from values determined by the PERCY SLADEN Expedition (GILSON 1964).

Conclusions

The limnology of Lake Titicaca is most influenced by the tropical equability of its environment. Characteristic of tropical lakes, Titicaca's changes in heat content are dominated by evaporation. In addition, the lake has a small difference between epilimnetic and hypolimnetic temperatures and a moderately high primary production (WIDMER et al. 1975). Unlike temperate alpine lakes, seasonality is muted and extreme low temperatures are lacking. For these reasons, Lake Titicaca would be best described as an high altitude tropical lake rather than a low latitude alpine lake.

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