Geofísica Internacional (2003), Vol. 42, Num. 3, pp. 523-528

Effects of El Niño on the dynamics of Lake Alchichica, central Mexico

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Received: September 3, 2000; accepted: March 5, 2003

RESUMEN

Se presenta evidencia empírica que muestra los efectos contemporáneos del fenómeno El Niño Oscilación del Sur sobre Alchichica, un lago profundo, monomíctico cálido. Se comparan los patrones anuales de temperatura del agua, el oxígeno disuelto y la concentración de clorofila *a* bajo condiciones de presencia y ausencia del ENOS. Los efectos del ENOS sobre el lago tropical Alchichica conllevan a cambios (valores extremos por encima o por debajo del promedio a largo plazo) en la física, química y por lo tanto en la biología del lago (i.e. hipolimnion más estrecho y frío, gradiente térmico más grande en la termoclina, termoclina más superficial, epilimnion más cálido, la hipoxia/anoxia dio inicio tardíamente, delgada capa anóxica hipolimnética, reducido florecimiento primaveral de cianobacterias). Se requiere de mayor información (i.e. series de tiempo largas) para comprender mejor la dinámica compleja de los lagos tropicales.

PALABRAS CLAVE: ENOS, El Niño, La Niña, temperatura, oxígeno disuelto, clorofila *a*, monomixis, lago cráter tropical, México.

ABSTRACT

Lake Alchichica is a deep, warm-monomictic lake in Puebla State, central Mexico. Water temperature, dissolved oxygen and chlorophyll *a* annual concentration patterns are compared under ENSO and non-ENSO conditions. The effects of ENSO on tropical Lake Alchichica lead to extreme values above or below the long-term averages in the physics, chemistry and biology of the lake. We find a narrower and slightly colder hypolimnion, larger thermal changes along the thermocline, a shallower thermocline, warmer epilimnion, later start of the hypoxic/anoxic condition of the hypolimnion, thinner hypolimnetic anoxic layer, and modest spring cyanobacteria bloom.

KEY WORDS: ENOS, El Niño, La Niña, temperature, dissolved oxygen, chlorophyll *a*, monomixis, tropical crater-lake, Mexico.

INTRODUCTION

The reconstruction of the effects of major ENSO events on lakes is hampered by the scarcity of continuous limnological/meteorological observations. This is the case for tropical inland waters in Mexico. The only monitoring programs (Lake Chapala and Lake Pátzcuaro) consider just a few variables including water level and some climatic data.

Present information on the effect of ENSO on lakes comes from high latitudes. In Canadian lakes (i.e., Lake Opeongo and South Bay of Lake Huron, Lake Ontario), warmer air temperatures associated with ENSO produced an earlier onset of stratification, a warmer epilimnion, a larger thermal gradient, and a shallower thermocline (King *et al.*, 1997, 1999; Rodgers, 1987).

The interannual variation in the ice-breakup dates of Wisconsin lakes is related to the warm phase of ENSO episodes. Ice breakup takes place earlier than in normal years, particularly in southern Wisconsin (Anderson *et al.,* 1996). Contreras *et al.* (1991) measured exceptionally high water temperatures associated with ENSO in Kitiesh Lake, Antarctica. Assel and Rodionov (1998) found that the higher ice cover regime in the Laurentian Great Lakes corresponded in part with hiatuses in ENSO events.

Available information shows that ENSO leads to an above- or below-average behavior of climatic and environmental variables such as precipitation, hydraulic flushing, and timing in the ice breakup (Galat, 1990; Jassby *et al.,* 1990; McGowan and Sturman, 1996). This oscillation is also evident in biotic variables. In the subalpine Castle Lake, California, strong or weak deep chlorophyll maximum (henceforth DCM), and much higher or lower primary production than the long-term average, are likely to occur during ENSO. This fluctuation arises from the direct effect on phytoplankton population of changes in winter snowfall, timing of ice breakup and hydraulic flushing in spring (Goldman *et al.,* 1989; Jassby *et al.,* 1990). Also, the lowest zooplankton biomass in Castle Lake has been associated to El Niño conditions and to the ice-out date (Janik, 1989).

Some lakes have shown to be outstanding climatic sensors of these phenomena. Such is the case of the subtropical Lake Gallocanta, Spain, which shows a positive response to ENSO (Rodo *et al.,* 1997), the tropical Lake Eyre basin, Australia, where the major flooding episodes are most often associated with La Niña phases of the El Niño phenomenon (Kotwicki and Allan, 1998); and Lake Lanao, where a decrease of water inflow is found to be prominent during ENSO events (Jose *et al.,* 1996). Even sedimentological and geochemical analyses carried out on lacustrine deposits of tropical Lake Magadi and Green Crater-Lake, Kenya, have shown that recent lacustrine sequences are related to global climatic variability (Damnati, 1993; Damnati and Taieb, 1995).

Available information suggests that the effects of ENSO on tropical inland waters lead to large changes (extreme values above or below the long-term average) in the physics, chemistry and thus biology of lakes. It also seems that ENSO effects are more pronounced in lower than in higher latitudes, so special attention must be given to tropical waters. In spite of this fact, there is no information on the contemporary effects of ENSO on Mexican inland tropical waters. Studies in this direction are being conducted on the shallow, warm-polymictic Lake Chapala (Tereschenko *et al.,* 2003, this volume).

This article shows empirical evidence of ENSO effects on the tropical warm-monomictic Lake Alchichica, Puebla, Mexico. This is the first study of the potential link between ENSO and the limnological dynamics of a deep tropical Mexican lake.

AREA OF STUDY

Alchichica crater-lake is a volcanic feature located at 19° 24' N and 97° 24' W, in the Oriental basin at an altitude of 2300 m above sea level (Figure 1). It is the deepest known natural Mexican lake (i.e., z_{MAX} = 64 m, mean depth = 38.6 m). With a 1.81 km^2 surface area (l_{MAX} = 1.7 km and b_{MAX} =1.4 km), its basin holds 69 920 000 m^3 of saline (TDS = 8.3-9 $g.l^{-1}$) and alkaline (pH = 8.7-9.2) water, dominated by sodium-magnesium and chloride-bicarbonate ions (Alcocer *et al.,* 1993; Arredondo-Figueroa *et al.,* 1983; Vilaclara *et al.,* 1993). Annual temperature fluctuates from -5.5 to 30°C with a mean value of 14.4°C (García, 1988). An arid climate, with an annual precipitation regime of less than 400 mm and an annual evaporation rate of 500-600 mm, describes this high-altitude plateau named Los Llanos de San Juan, as a "cold desert".

MATERIALS AND METHODS

Midday evaluation of depth, temperature and dissolved oxygen were carried out monthly with a calibrated Hydrolab Datasonde4/Surveyor4 multiparameter water quality data logger and logging system. Sampling took place in the central and deepest part of the lake. Ten samples were obtained with a Niskin water sampler at 0, 3, 5, 10, 15, 20, 30, 40, 50 and 60 meters. Chlorophyll *a* was evaluated by filtering through 0.45 μm pore-size Millipore membrane filters. After twenty-four hours, cold (4°C), 100% methanol extraction (Marker *et al.,* 1980) absorbance of the extract was measured in a spectrophotometer. The monthly sampling period covered from January 1998 (El Niño) to December 1999 (La Niña); previous published records (Alcocer *et al.,* 2000; Arredondo *et al.,* 1984, 1995; Lugo *et al.,* 1999) and unpublished reports dating from 1978 to 1997 were considered herein as well. Non-ENSO years were considered as "normal" and used to defined average values to compare with. Average values from non-ENSO years were used to draw the monthly vertical profiles.

RESULTS AND DISCUSSION

A comparison between 1998-1999 (El Niño and La Niña years, respectively) and the "long-term" average values (calculated from normal years) were carried out for the following limnological variables: a) temperature (Figure 2), b) dissolved oxygen (Figure 3), and c) phytoplankton biomass express as chlorophyll *a* (Figure 4).

Temperature

Alcocer *et al.* (2000) present the average thermal pattern of Lake Alchichica, shown here in Figure 2a. Mixing takes place from the end of December or beginning of January until the onset of the stratification period by the end of April or beginning of May. A well-developed thermocline is present from June-July up to October-November. After November, the thermocline becomes deeper and weaker until its breakup in late December or early January.

The general thermal pattern (circulation and stratification periods) of Lake Alchichica was similar during El Niño and La Niña years (Figure 2a and 2b). Water temperature of the epilimnion was slightly higher in El Niño and La Niña (18.8-19.5 and 18.7-19.5°C, respectively) years than the average (18.2-19.1°C). The width of the hypolimnion in El Niño and La Niña years was narrower (29 m) and slightly colder (14.5°C) than in normal years (i.e., 39 m and 14.8°C).

In the average pattern (Figure 2a), the depth of the thermocline increases from its onset (about 11m depth) until just before the circulation period (around 35 m depth). The width of the thermocline fluctuates from four meters in the summer time up to 12 m in autumn. Once more, these characteristics did not differ between El Niño years and normal years (Figure 2a and 2b). A larger thermal change along the thermocline (top to bottom) was found in El Niño (1.78-3.77°C) and La Niña (1.76-3.6°C), when compared with normal years (1.65 a 2.91°C).

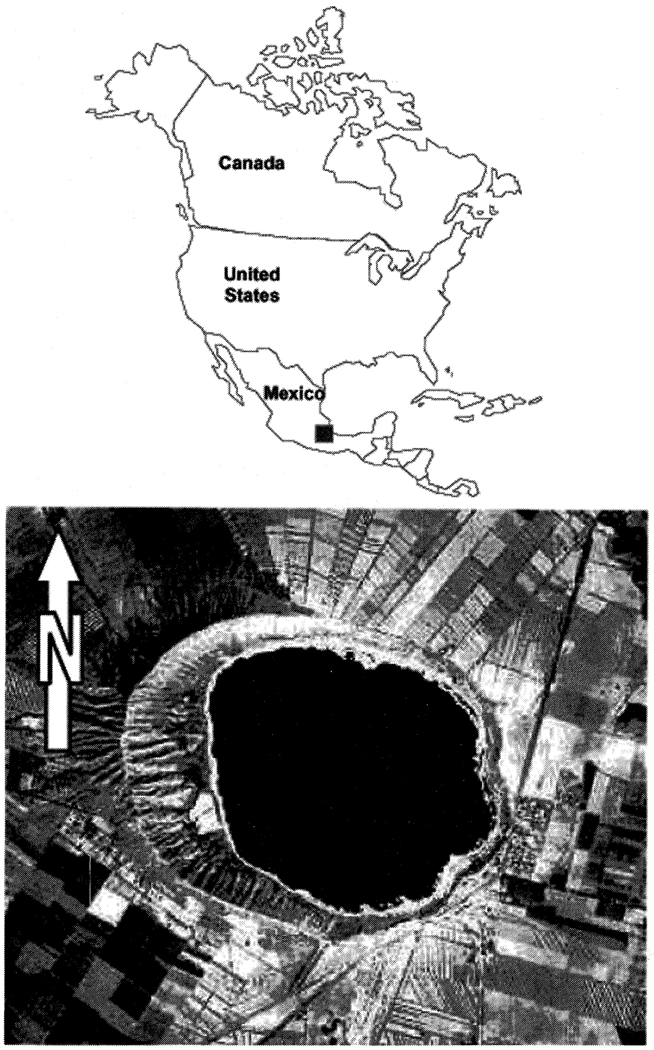

Fig. 1. Location and aerial photograph of Lake Alchichica, Puebla, Mexico.

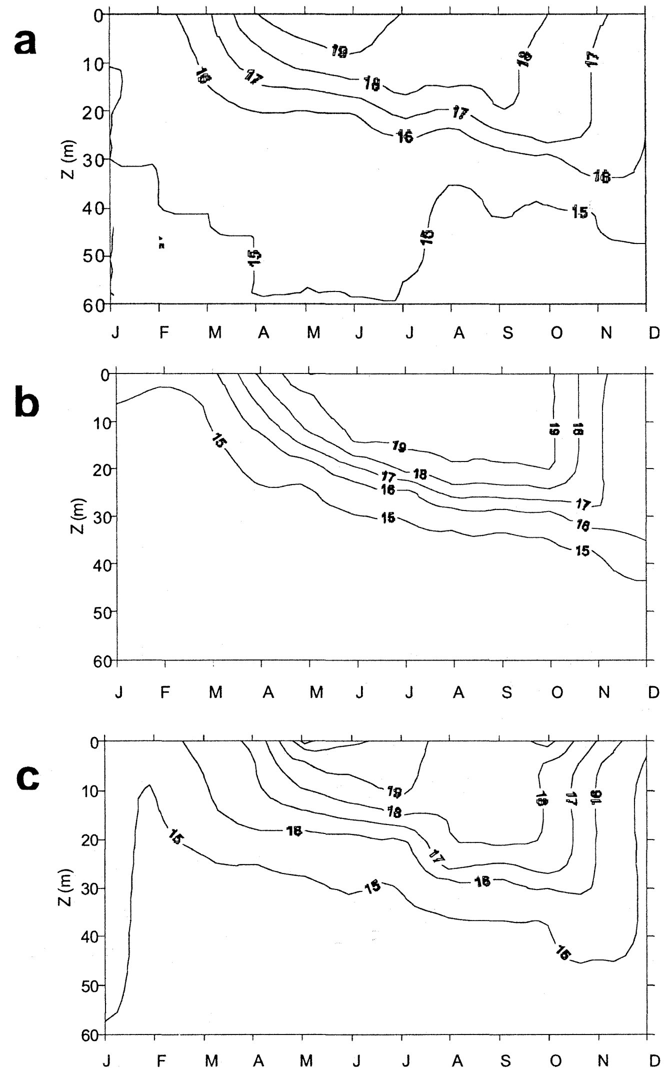

Fig. 2. Depth-time diagram of isotherms (°C) in Lake Alchichica. (a) Average, (b)1998 El Niño, (c) 1999 La Niña.

As mentioned above, King *et al.* (1997, 1999), and Rodgers (1987) found in Canadian lakes that warmer air temperatures associated with ENSO produced a) earlier onset of stratification, b) a shallower thermocline, c) a warmer epilimnion, and d) a larger thermal gradient. In Alchichica, the last two alterations were observed.

Dissolved oxygen (DO)

Alcocer *et al.* (2000) discuss the average DO pattern of Lake Alchichica (Figure 3a). During the stratification period, Alchichica develops a clinograde DO profile. The aerobic epilimnion is almost saturated with DO, while the hypolimnion remains anoxic most of the stratification period. DO concentration in the epilimnion was similar to that in normal years (Fiure 3a) in El Niño and La Niña years (Figure 3b and 3c). During normal years, hypoxic/anoxic conditions are generated in April along with the onset of the stratification period, and the hypolimnetic anoxia ends with the beginning of the circulation period in late December or early January (Figure 3a). In El Niño and La Niña years, the hypoxic/anoxic conditions started later, in May and June respectively (Figure 3b and 3c).

The hypolimnetic anoxic layer in normal years can be up to 34 m thick. During El Niño and La Niña years, the hypolimnetic anoxic layer was thinner, with a maximum width of 30 m. The larger hypolimnetic deoxygenation observed in the normal years was associated to higher phytoplankton biomass production. Phytoplankton biomass seems to be mostly exported below the thermocline (as suggested by Escobar Briones *et al.*, 1998) and decomposed in the hypolimnion. Modest cyanobacterial blooms during El Niño and La Niña years explain the lower rates of

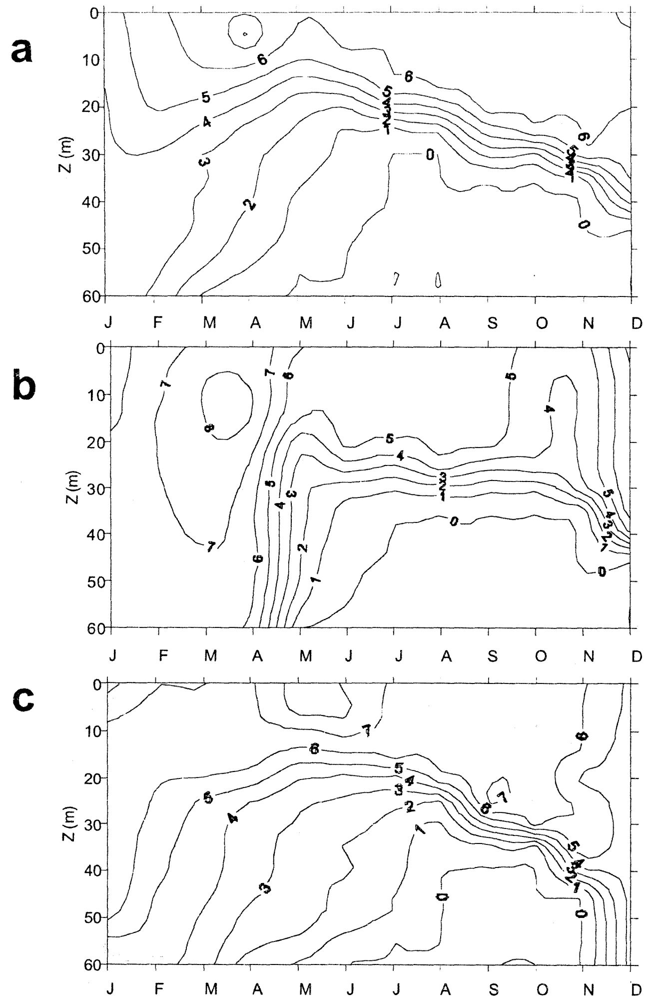

Fig. 3. Depth-time diagram of isopleths of dissolved oxygen concentration (mg/L) in Lake Alchichica. (a) Average, (b) 1998 El Niño, (c) 1999 La Niña.

hypolimnetic deoxygenation when compared to the average. Differences were found between normal years and El Niño (lower) and La Niña (higher) hypolimnetic deoxygenation. A stronger thermal gradient in the thermocline during La Niña resulted in a more efficient physical barrier to DO diffusion to the hypolimnion.

Phytoplankton biomass

Lake Alchichica displays three spatial-temporal distribution patterns of phytoplankton biomass (Figure 4a): a diatom bloom, a cyanobacteria bloom, and a deep chlorophyll maximum (DCM).

The diatom winter bloom along the water column is triggered at the early stages of the circulation period. The diatom bloom was present during El Niño and La Niña years

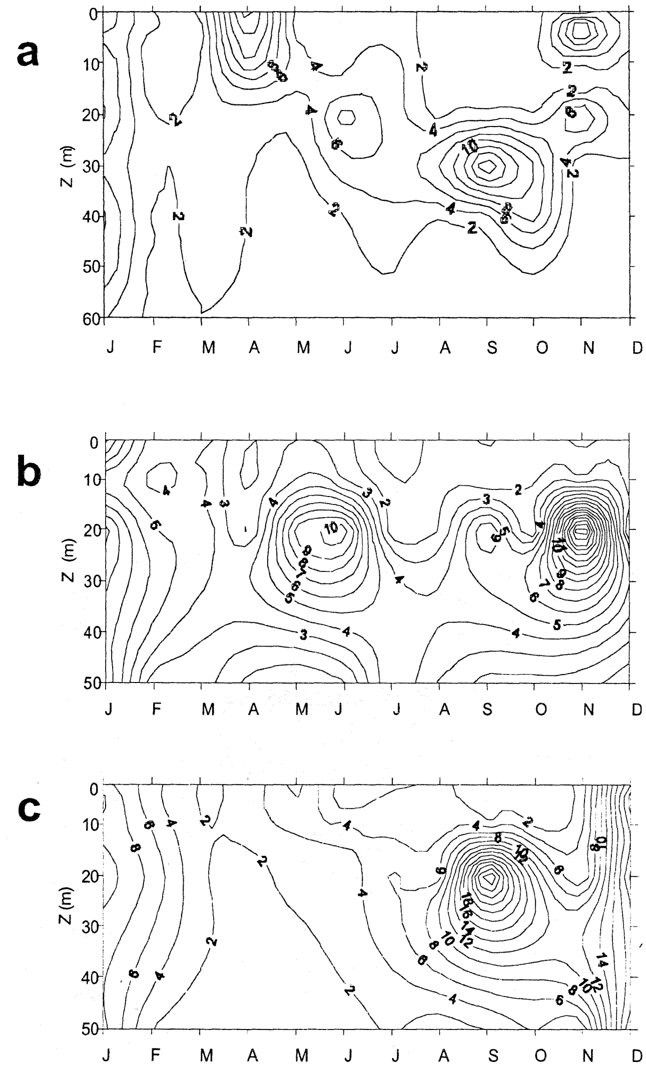

Fig. 4. Depth-time diagram of isopleths of chlorophyll *a* concentration (μg/L) in Lake Alchichica. (a) Average, (b) 1998 El Niño, (c) 1999 La Niña.

(Figure 4b and 4c) with equivalent magnitude (4-8 μg Chl. a/L).

The spring bloom of cyanobacteria, constrained to the uppermost portion of the water column is triggered by the onset of the stratification period. The cyanobacteria bloom was barely developed in El Niño (2-3μg Chl. a/L), and slightly higher in La Niña (2-6μg Chl. a/L), but much lower than in normal years (up to 16μg Chl. a/L).

A DCM at the top of the thermocline ($\approx$1% PAR) is a common feature during the stratification period. The DCM also developed in El Niño and La Niña years displaying lower (up to 12μg Chl. a/L) and higher (up to 24μg Chl. a/L) concentrations, respectively, than in average years (up to 17μg Chl. a/L).

CONCLUSIONS

In conclusion, the empirical evidence available shows that ENSO affected the limnological dynamics of Lake Alchichica by producing extreme values above or below the long-term average (i.e. a narrower and slightly colder hypolimnion, a larger thermal change along the thermocline, a shallower thermocline, a warmer epilimnion, a later start of the hypoxic/anoxic condition of the hypolimnion, a thinner hypolimnetic anoxic layer, and a modest spring cyanobacteria bloom). Further studies are required to understand not only the complex dynamics of tropical lakes from a holistic point of view, but also how meteorological phenomena modify them.

ACKNOWLEDGEMENTS

CONACYT 25430-T and DGAPA-UNAM IN204597 grants supported this work. The authors acknowledge field assistance of Laura Peralta and Luis A. Oseguera.

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