Climatic Change in a Large Shallow Tropical Lake Chapala, Mexico

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Abstract

Measurements of temperature, currents and lake level taken in 2005–2014 are analyzed and discussed. We obtained a conceptually new data set on the formation of the thermocline in Lake Chapala. It is showed that the thermocline in the lake occurs only during the daytime, in the top 0.5–1.0-m layer of the water column, whereby the vertical temperature gradient reaches 2.5°C/m within that layer. At night, the top layer is cooled, which causes strong vertical mixing down to the bottom. Moored measurements of temperature and level from Lake Chapala reveal the presence of seiches oscillations with periods of 5.7 and 2.8 hours with amplitudes of 15.4 and 8.1 mm. Temperature measurements on sections across the lake showed that in the northern part of the lake, the water column is warmer that in southern 2–3°C in all seasons. The lake currents were simulated for wet and dry seasons. The model results are in good agreement with the acoustic Doppler current profiler (ADCP) data. The presence of an anticyclone gyre in the central part of the lake in both seasons is detected.

Keywords: Lake Chapala, level, temperature and current measurements, hydrodynamic modeling, breeze

1. Introduction

Lake Chapala, the largest in Mexico and third largest in Latin America, has an average length and width of 75 × 22 km and an average depth of only 6 m, with a maximum of 11 m (**Figure 1**). Among shallow lakes, Lake Chapala is the largest in the world [1–3]. It plays an important role in the economy of the region. Approximately 20 million people live in the vicinity of Lake Chapala. The area also includes important industrial and cultural sites.

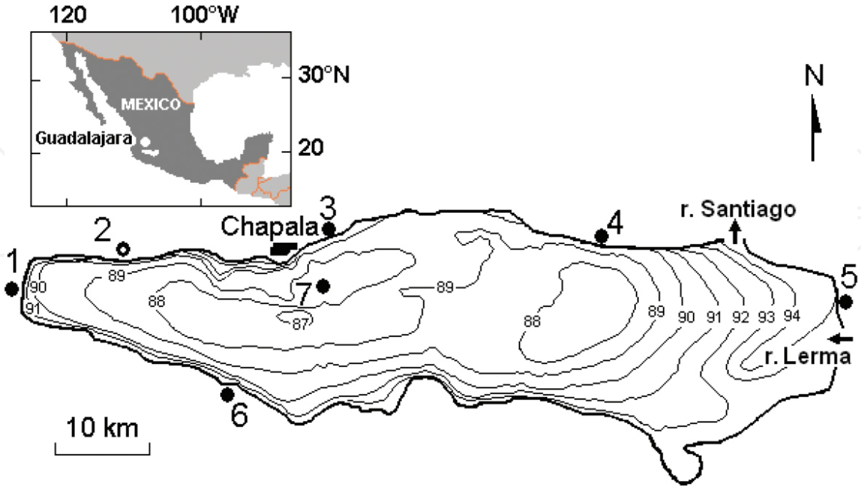

Figure 1. Map of the Lake Chapala. The numbers refer to weather stations: 1. Jocotepec, 2. Atequiza, 3. Chapala, 4. Poncitlán, 5. Jamay, 6. Tizapán and 7. Isla de Alacranes.

The lake provides for a mild climate and establishes a land-lake breeze circulation throughout its costal area. Atmospheric humidity in this area is also moderate, which together with the pleasant landscape, makes the lake a great tourist attraction [2, 3].

The lake's tributary and outflow rivers are the Lerma and Santiago, respectively. Both rivers and the lake form a unique reservoir system covering an area of approximately 47,000 km^2. The annual rainfall is 750 mm, and evaporation from the lake surface ranges from 1000 to 1400 mm per year, resulting in a negative balance [2, 3]. The deficit is offset by inflow from the Lerma River [4–6] in dry years annual rainfall can drop to 500 mm and the lake does not contribute any water to the Santiago River [2, 3, 7]. Tereshchenko et al. [2] mentions that in the high-rainfall years, the annual precipitation can reach 1000 mm and an important volume of water exits through this same river.

The Lerma River is the main tributary of Chapala Lake. Tereshchenko et al. [2] mentions that according to data from the National Water Commission (Comisión Nacional del Agua, México; CNA), approximately 2.75×10^6 m^3 [2, 3, 8] of suspended particles enter the lake via its tributary from the lake's watershed. The size of the particles can reach up to 0.5 μm and are mainly deposited in the eastern part of the lake. The result is a decreasing depth by the accumulation of particles in the bottom of the lake. Suspended particles modify the water transparency.

The principal loss of water from the lake is through evaporation. Tereschenko et al. [2] mentions that during the spring months, from March to May, evaporation brings down the lake water level, on average, 10 mm a day. The shallow depths (1–2 m) and low transparency of water in the east part of the lake create less thermal inertia and allow for stronger heating in comparison with deeper and more transparent portions of the lake, resulting in higher evaporation rates [9]. In this connection, Filonov [8] proposed the construction of a dam to cut off the eastern 20% of the lake to lower these losses. Detailed measurements show [5] that the shallow east sector has a surface water temperature of as much as 3°C above that in the central area of the lake. However, on the basis of these measurements, it is difficult to advance any conclusion about the east sector as being the main evaporation area of the lake. Resolution of this controversy would require a surface water temperature-monitoring program (weekly measurements) of year duration, at least.

Sandoval [1], Tereschenko et al. [2] and Avalos-Cueva et al. [3] mention that the lake has reached its current status due to water usage of the Lerma for irrigation and industrial needs and to cover the domestic demand of Guadalajara city. Also, dewatering for agricultural irrigation and neighboring villages of the lake has a negative balance in storage. Therefore, Sandoval [1] states that the lake will be dry out in a future. However, not all researchers agree with this statement. Filonov [8] puts forward some different arguments based on numerical modeling. He states that the main cause of the long-period-level fluctuation is unfavorable climatic factors and not just anthropogenic influence. But he fails to definitively establish the causes of Chapala Lake water-level fluctuation, as well as of rainfall fluctuations over its watershed.

Filonov [8] also shows that the hydrometeorological regimen of Chapala Lake is influenced by El Niño episodes. The El Niño 1997–1998 event was the strongest of this century [10, 2]. This event registered unusually high air temperatures and consequently a very intense dry season in the west-central Mexico. In Guadalajara, Jalisco the monthly average air temperature from March to May 1998 was 3–4°C higher than the climatological mean for this same season. The atmospheric relative afternoon humidity decreased from 6 to 8% [6]. In the dry season, the lake lost reaches up to 1 m due to evaporation water demand [8].

Studies on the quality of lake water and pollutant dispersion are pretty few and discrete points, while the thermodynamic conditions have not been studied in detail. On such a situation is not that simple to propose strategies to rescue the lake. A modern method for monitoring the thermal regime of epicontinental water bodies has been made through the use of satellite images. Such methods found wide application in physical oceanography [11] and physical limnology [2, 12].

In the past two decades, researchers from the Physical Department of the University of Guadalajara began to study the thermodynamic processes in the Lake Chapala using hydrodynamic modeling and the analysis of data collected with the use of up-to-date oceanographic and meteorological measurement devices. In this work, we discuss the analysis of wind data collected over the lake, as well as the fluctuations in water temperature, currents and lake level. The main purpose of this study is to gain more understanding of the thermal and dynamic patterns of the Lake Chapala during the dry and wet seasons.

2. Measurements and data sets

One major impediment in the data collection across the study area is a great number of fishing nets deployed in the Lake Chapala. Hundreds of people are engaged in the fishing industry, which is a major source of income for them. Therefore, working there, we always rely on good luck, but do not always succeed. On some occasions, partial losses of the instruments and equipment were inevitable.

This study is based on the analysis of the temperature, currents and lake-level data collected in 2005–2014 using the following oceanographic instruments: CTD SBE19-plus, SBE-39, SBE-26, HOBO V2 and a ADCP RDI 600 kHz, ADP SONTEK 1000 kHz. During that time period, the measurements were not taken regularly as they pursued different goals. The sampling strategies varied with the experiment (we used different sets of instruments) and will be described in the corresponding sections.

Most measurements were taken in the deeper northern part of the lake. The meteorological data were collected from the network of seven automatic meteorological stations deployed around the lake and in its center. The spatial structure of the temperature field and currents for the dry and wet seasons were sampled by towed temperature recorders arranged in the antenna pattern and ADCP.

3. Results

3.1. Long-term fluctuations in the lake level

In last century, Lake Chapala has suffered two catastrophic declines of its level. From 1945 to 1955, the level fell by nearly 4 m and then in the next 4 years was increased by 5m. In 1977, again a decrease began and by 1989 was down nearly 5 m. Then, for the year 1995, the level rose by 2 m and currently undergoes a period lake-level decline, but still lack about 0.5 m to reach the level of 91.9 m maximum reduction achieved in 1955 (**Figure 2**).

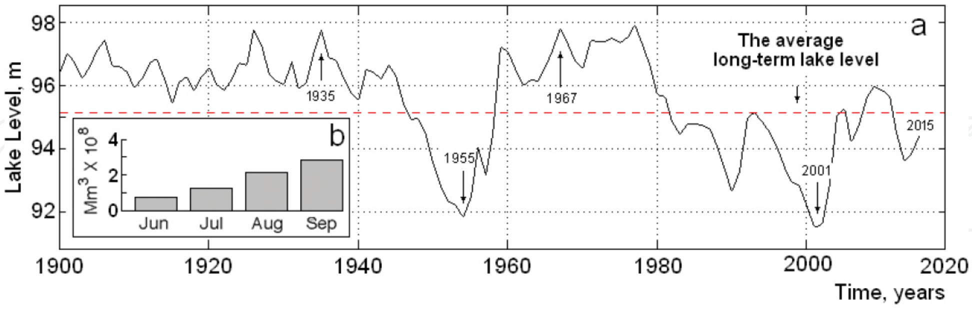

Figure 2. (a) Historical average annual water levels in Lake Chapala (Data from Water National Council of Mexico). Monthly mean Lerma River discharge in Chapala Lake (in millions cubic meters) during rain season from 2001. to 2007 (b).

The level oscillations with periods of 20–50 years are presented in all lakes in the world [7]. The cause of this is the climate oscillation in the territory of the basin, caused by the cyclical variation in solar activity and the succession of epochs of atmospheric circulation. Within each cycle phase, plenty of water (transgressive) is changed to that of low water (reverse). The increase or decreases in the water level in the lakes observed in these phases are the result of cyclical fluctuations in the intensity of rainfall.

The study of Filonov [8] also shows that the hydrometeorological regimen of Chapala Lake is influenced by El Niño episodes. The El Niño 1997–1998 event was the strongest of this century [10, 13]. This event registered unusually high air temperatures and consequently a very intense dry season in the west central of Mexico. In Guadalajara, Jalisco the monthly average air temperature from March to May 1998 was 3–4°C higher than the climatological mean for this same season. The atmospheric relative afternoon humidity decreased from 6 to 8% [14]. Due to the intense dry season, the lake lost more than 1 m of its water level due to evaporation and the excess of water pumped to satisfy water demand from the local industry and population [8].

3.2. Level fluctuations caused by free long gravity waves (seiches)

Cross analysis with wind and atmospheric pressure fluctuations has shown that sharply amplified seiches always after pressure increases that are caused by synoptic processes. A pulse of pressure acting on Lake Chapala obviously causes an inclination of its level on one of its parts (because of the large linear size of the lake) and then these pulses generate long free gravitational waves causing horizontal currents and level fluctuations [3, 9]. Undoubtedly, the lake breeze also causes fluctuations of lake level with daily periodicity, causing a “wind tide” on the coast in the afternoon and at its center in the night. The Lake acquires this energy, which eventually results in free lake-level fluctuation, with periods near of 6 hours and forced fluctuations with periods of 24 hours.

Basic equations describing seiches can be written in the following form [15]:

$$\frac{\partial u}{\partial t} - fv = -c^2 \frac{\partial \eta}{\partial x} + \tau_x \tag{1}$$

$$\frac{\partial v}{\partial t} + fu = +c^2 \frac{\partial \eta}{\partial y} + \tau_y \tag{2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{dy} + \frac{\partial \eta}{\partial t} = 0. \tag{3}$$

where x and y are the horizontal coordinates, u and v are the corresponding components of the vertically integrated current, t is a time, $\eta(x,y)$ is the free surface perturbation, f is the Coriolis parameter, $c=\sqrt{gH}$ is the speed of propagation of long gravity waves, g is the gravitation constant, H is the average depth of water, and τ_x,τ_y are the horizontal components of the force that causes seiches.

Solving Eqs. (1)–(3) can be accomplished only by numerical methods because their solution depends on the lake form. Let us make some estimates on the seiches without fully solving the given system of the equations. In long, narrow and shallow lakes ($H/L \ll 1$, L is the length of the lake), such Lake Chapala, it is possible to neglect geostrophic effects and vertical acceleration. Then, the solution for the current speed u (v - the cross component is very small), the free surface perturbation, and period of the seiches can be approximated under the following formulas [9, 16]:

$$u = u_{\max} \sin(n\pi x / L) \sin(2\pi t / \tau_s), \tag{4}$$

$$\eta = A_s \cos(n\pi x / L) \cos(2\pi t / \tau_s), \tag{5}$$

$$\tau_s = 2L / (n\sqrt{gH}). \tag{6}$$

u_{max} is the maximal current through a nodal line; A_s is the seiche amplitude at the edges of the lake; n is the number of seiches nodes. An Eq. (6) is known in the literature by the name of "Merian formula" [15].

Figure 3 shows an example of such oscillations; measured near the shore on the hydro meteorological station Chapala in 1997 (**Figure 1**). It was the first measurement of this kind on the lake. Let us estimate some parameters of the seiches in Lake Chapala, using the almost pure harmonic fluctuations (**Figure 3d**) having an average height (the double amplitude) of 15 mm and a period about 6.0 hours. These fluctuations should undoubtedly cause one-nodal seiches. Seiches period by the Eq. (6) gives a value of 5.8 hours, though this value is slightly less than the one described above by spectrum analysis. However, it can be used to calculate the data below.

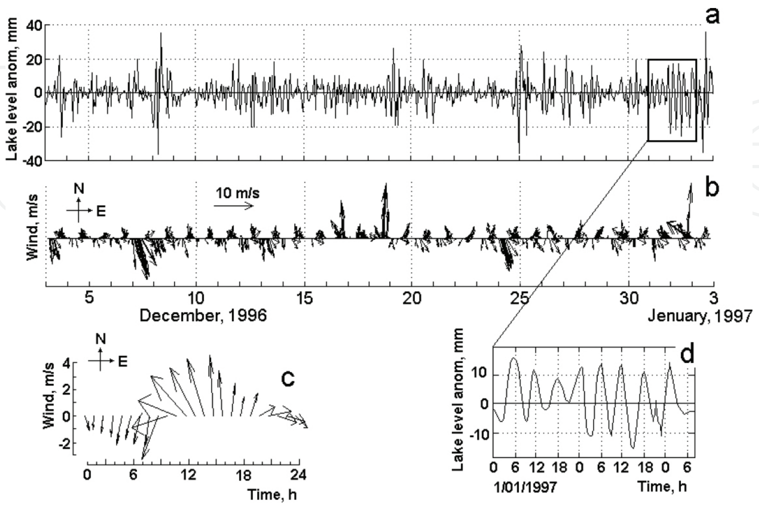

Figure 3. The fluctuations of the lake level anomalies (a). The panels (b) show the hourly course of the wind and daily average wind for 1. month (c). Almost pure sines fluctuations in lake level are described in (d).

3.3. Fluctuations in the level and the temperature at a fixed point of the lake

The main power source of the lake breeze circulation is the diurnal temperature cycle caused by the daily variations of (a) incoming solar radiation and (b) heating of the underlying surface and to atmosphere. The interaction between the land, lake and atmosphere is a very complex system with many feedbacks. The area around the Lake Chapala is mountainous, with valleys of various spatial orientations. The thermal energy pulsates with daily periodicity but does not remain at a fixed frequency. It is redistributed at different frequencies in a complex way in the form of fluctuations [17].

The principal dynamic process that occurs in the lake is the lake breeze circulation. Daytime breeze speed does not usually exceed 4 m/s. Beyond any doubt, the lake breeze causes the increase in the evaporation from the lake's surface. Lake Breeze, together with atmospheric pressure variations, generates free seiches waves.

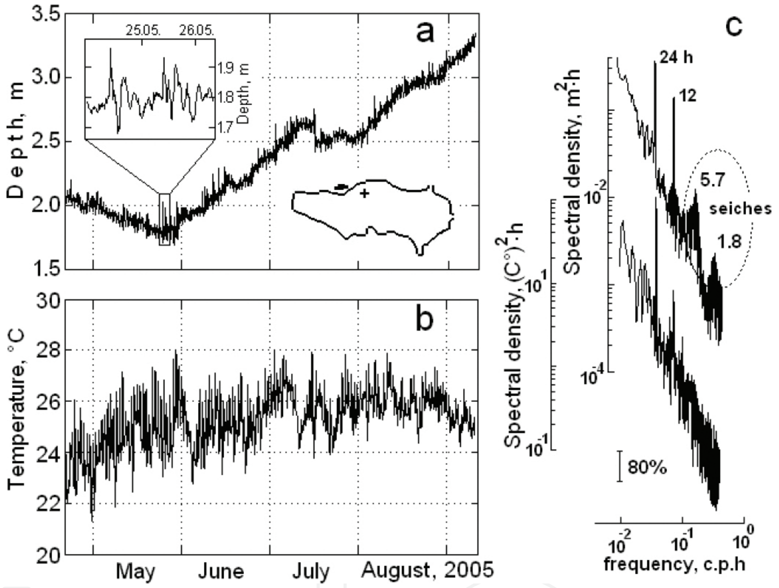

Figure 4. Hourly fluctuations of the lake level (a) and temperature fluctuations (b) at the mooring site during the summer 2005. experiment. Frequency spectra of the lake level and temperature fluctuations (c). The numbers designate the periods of the main peaks in the spectra. The vertical line designates the 80% confidence interval.

For a detailed study of the level and temperature variations at a fixed point of the lake, we made a special experiment. The measurements were taken from 20 April to 12 September 2005 (153 days). The lake level and temperature data were sampled every 5 min by a SBE-26 temperature-depth recorder (the accuracy is 0.002°C for temperature and 1 mm for depth). The device was deployed on the mooring in the northern part of the lake, at the water depth of 2 m. **Figure 4a** shows that the seasonal-level fluctuations in 2005 strongly depend on the evaporation and precipitation over the lake and its watershed. In April and May, the level dropped at a rate of about 30 cm/month, and then, until the middle of September, it raised more rapidly, about 50 cm/month. In July, the level remained almost unchanged because of the reduced rainfall during this time of the year, which usually occurs over the territory of Central Mexico and is called “canicula” [3, 10].

The SBE-26 time series also shows that the daily fluctuations of lake level are determined by diurnal and semidiurnal harmonics. At a single point, the level fluctuations occur at times of the amplification and easing of the breeze whose speed was measured at the weather station Chapala [18]. The breeze forcing is the main source of energy for all kinds of motion in the lake. With a well-defined diurnal cycle, this breeze varies from virtually calm at night and morning to steady northerly winds up to 6 m/s (gusting up to 10–12 m/s) in the afternoon. The lake-breeze circulation is important on the processes of vertical and horizontal mixing, since it is active throughout the year [6].

The analysis shows that the start of wind intensification lags the time of the downturn of the lake level by less than 2 hours. The rise and drop of the level are asymmetrical. The trough lasts longer than the peak, which is apparently caused by the asymmetric impact of the wind on the water surface.

As seen from the data (**Figure 4b**), the amplitude of the daily temperature fluctuations at the mooring site are 2–3°C at the 2 m level and decrease to 1–1.5°C as the instrument depth increases due to the higher lake level during the summer months.

Figure 4c shows the spectra computed from the time series of lake level and temperature variations. The level spectrum reveals the presence of free seiches waves with 5.7- and 2.8-hour period in the lake. Their mean square amplitudes are 15.4 and 8.1 mm, respectively. The lake is shaped like an ellipse whose axes vary in size; therefore, the oscillations with a period of 5.7 hours likely correspond to the seiches propagating along the greater axis of the ellipse (west-east). The other oscillation mode is related to the seiches propagating along its smaller axis (north-south).

We used the Merian equation (Eq. (6)) to evaluate the theoretical periods of the two principal waves, taking that the maximum length of the lake is 75 km, maximum width of 22 km and the average depth is 5 m [18]. Thus, the periods of the first and second modes of horizontal oscillation are 5.87 and 2.7 hours, respectively. These results closely match those obtained from our measurements. The seiches oscillation periods in Lake Chapala depend mainly on the mean depth of the lake, as the length along the major axis of the lake is almost unchanged. Interannual fluctuations of the Lake Chapala can reach 6 m, for example, in 1955–1960 [11], and therefore, in extreme years, the seiches periods may vary (increase or decrease) from 3 to 8 hours.

Our earlier study [18] reports almost similar results, except that there is no well-defined mode with the 2.8-hour period due to the weak amplitude. The seiches generate periodic currents, which peak at 1 cm/s in nodal line areas [18].

3.4. The diurnal variation of the lake temperature profile

Until now, no scientific work has addressed the issue of daily variations of water temperature in the Lake Chapala from in the entire water column. Many believe that in such a shallow lake the water temperature is uniform within a water column due to wind mixing [19]. Our research has shown that it is not true.

To study the variability of a vertical temperature profile, high-frequency measurements of water temperature in the entire water column were taken on 7–8 June 2005 from a boat anchored near the mooring. A boat-mounted meteorological station HOBO-logged wind speed and direction with a 10-min sampling rate. The water depth in this experiment was about 2 m. Water temperature was measured by a CTD 19-plus (Sea-Bird Electronics profiler) with temperature depth and accuracies of 0.005°C and 4 cm, respectively. The CTD profiler with a 0.25-s sampling rate was manually dropped and raised every 5 min with a speed of 0.1 m/s.

Chapala is a freshwater lake, and hence, the vertical change in water density is completely determined by temperature. To estimate the variability of the vertical stratification in the vicinity of the mooring, the buoyancy frequency was calculated: $N(z)=[(g/\rho)\cdot(\partial\rho/\partial z)]^{1/2}$, where z is the depth, $\rho=\rho(z)$ is the density of lake water, which was calculated under the formula: $\rho=\rho_o\,(1–1.96\times 10^{-6}(T–289)(T–4^2)/(T+68.1)\times 10^3)$, which is usually used for shallow lakes [20].

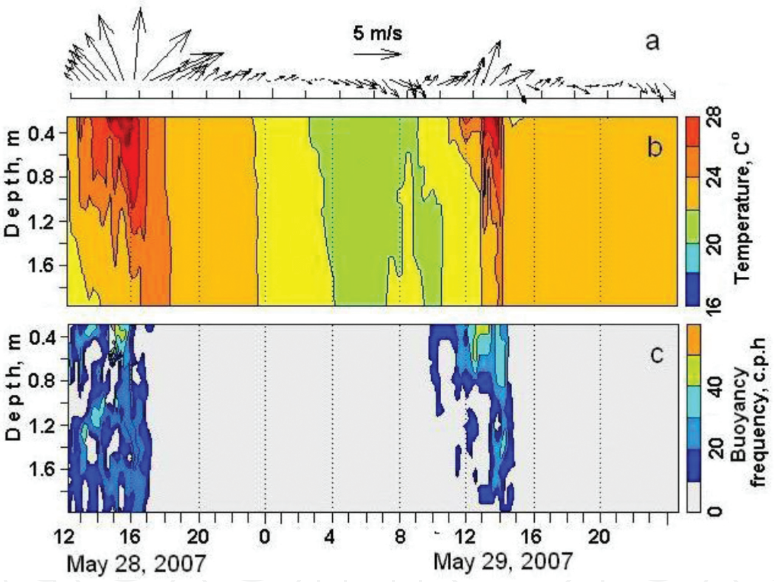

Figure 5. Variation of wind (a), temperature (b) and buoyancy frequency (c) in the vicinity of the mooring. The vertical casts were made every 10. min with a CTD-SBE-19 plus, which was manually dropped from an anchored boat with an up cast and down cast speed of about 0.1 m/s and a 0.25 s sampling rate.

The collected data sets are presented in **Figure 5**, which illustrates the connection between temperature fluctuations and strengthening (weakening) of the stratification caused by the breeze. The thermocline is formed around midday in the 1 m subsurface layer, in which the vertical temperature gradients reach 0.5°C/m and decrease to zero at the bottom. The cooling of the surface layer started at 20:00 and peaked at about 6:00, causing the cold water to sink to the bottom. Below the 0.4-m depth, the water temperature was almost homogeneous because of the intensive stirring. At daytime, the buoyancy frequency in the surface layer exceeded 50–60 c/hour (about a 1-min period).

The intensive subsurface thermocline serves as a “hard cap” and prevents the daytime heat and momentum exchange at the surface from penetrating into the deeper layers of the lake. Moreover, a similar stratification whereby a narrow surface waveguide for short internal wavelengths is generated was previously observed in the experiment in the eastern part of the lake [18]. In that experiment, it was shown that the short waves have periods of 10 min, amplitudes of 1 m and phase speeds of 0.15 m/s.

Thus, the daily variability of temperature stratification in the Lake Chapala prevents the water masses from mixing and contributes to the accumulation of heat in the surface layer during the daylight hours. Conversely, the cooling process results in negative vertical temperature gradients, which in turn cause the intense vertical flow. The latter powers the ascent of nutrients to the surface, which contributes to the high biological productivity of the lake.

3.5. North-south temperature cross section of the lake

The spatial distribution of surface temperature across the Lake Chapala was previously discussed in reference [2, 3], based on extensive satellite data sets with high spatial resolution. In that study, it was shown that the northern part of the lake is warmer than its central and southern parts, which is caused by the specific features of its circulation.

To confirm this finding and shed light on other processes that occur in the lake, north-south temperature cross sections were carried out in February, April, July and October 2006. Each survey included 60 equidistant bottom casts, 250 m apart. The SBE19-plus CTD profiler with 0.17-s sampling rate was manually dropped from the boat with a speed of about 0.1 m/s. The global position system (GPS) fixed the coordinates of the casts.

The measurements were taken in the morning (from 7:00 to 9:00 am), so that the temperature along the cross section was not biased. The cross section extends from the northern coast (near the town of Chapala) to the south side of the lake. The spatial distribution of temperature at the cross section is shown in **Figure 6**.

It is observed that the *in situ* measurements confirm the previous finding, namely that in all seasons the temperature in the central and northern parts of the lake is higher than in the southern part. This holds true not only for the surface but also for the bottom layer. In all four seasons, vertically averaged temperatures at the north and south ends of the cross section differ by 2–3°C. The vertical distributions of temperature on the sections are uneven.

The northern part of the section shows the penetration of warm water from the anticyclonic gyre which is stationary in the study area at morning time. In April, July and October, the water columns in the central and southern parts of the lake were poorly stratified, which was probably caused by vertical mixing at nighttime. These results shed new light on the thermal structure of the lake obtained and discussed in previous studies [2, 3, 18, 19, 21]. They should be taken into account in the design of future experiments in the study area and 3D model simulations.

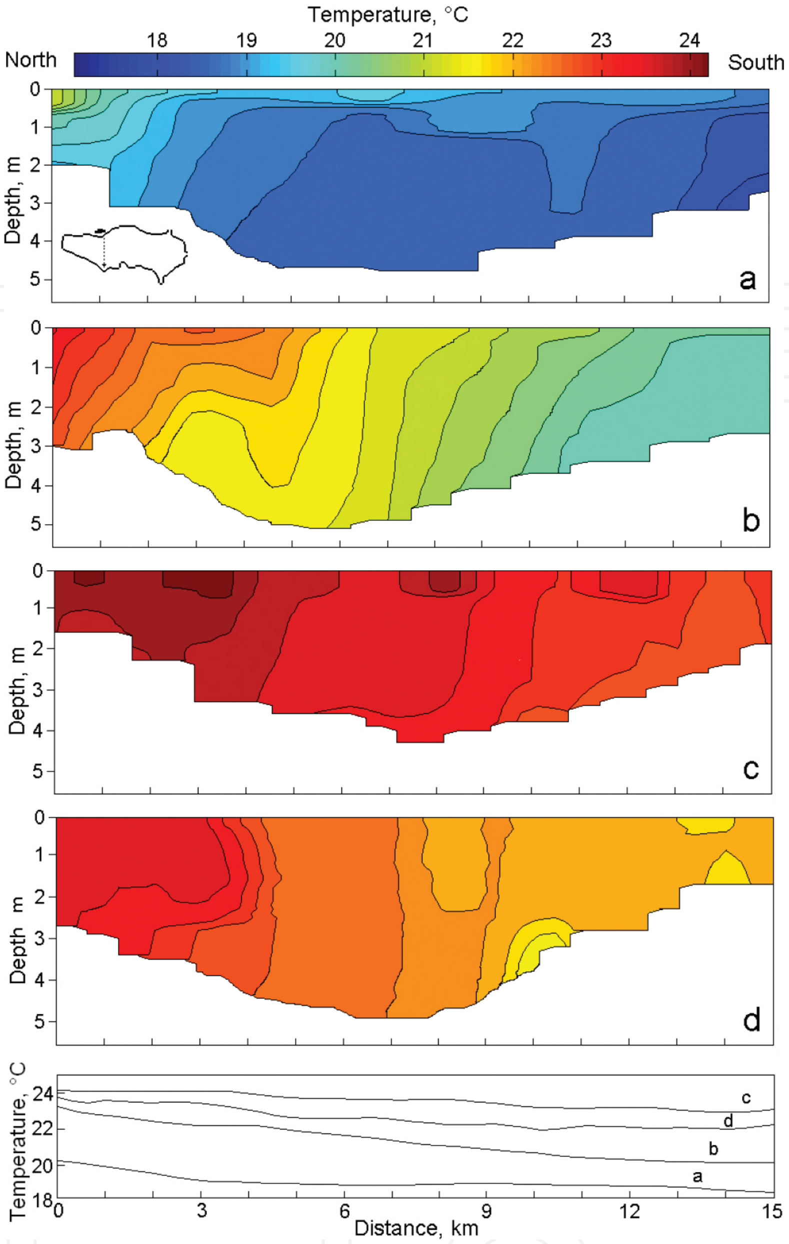

Figure 6. Vertical temperature cross sections in February (a), April (b), July (c) and October 2006. (d). The bottom panel shows the vertically averaged temperatures at the corresponding cross sections.

3.6. Current simulations in the lake for the dry and wet seasons

The results of numerical simulations of the Lake Chapala circulations are reported in some publications [3, 18, 21–26], but none of them is based on the experimental and observational wind data sets collected in the study area during different seasons. Therefore, we carry out this study.

The HAMSOM model (Hamburg Shelf Ocean Model) was used to model the horizontal currents resulting from wind circulation over the lake. The model is written in a finite difference scheme, using the Arakawa-C grid [27]. The HAMSOM model is vertically averaged, bi-dimensional, non-linear, semi-implicit, written in finite differences and represents the simultaneous solution to the Navier-Stokes and a continuity equations. The model was previously applied to the Gulf of California [28, 29]; the Santa Maria del Oro Volcanic Lake [30] and Lake Alchichica [31] and in the North Sea [32, 33].

To study the circulation patterns throughout the dry and wet periods, a simulation was conducted with the HAMSOM model forced by the wind field obtained from the network weather stations. The current simulation was carried out for the dry and wet season. The bathymetric grid had a 97 × 270 mesh: $= \Delta y = 300$ m and $\Delta t = 30$ s. The simulations started from a condition of no movement and were run for 30 days before obtaining a stable initial condition. The model was initialized with wind fields from the network of weather stations in the Lake Chapala area collected in 2006–2007 (**Figure 7**). The river runoff data were obtained from CONAGUA (Mexico's National Water Council). The wet-season average of the inflow from the Lerma River was set to 600cubic meters per second, the outflow through the Santiago River —120 cubic meters per second.

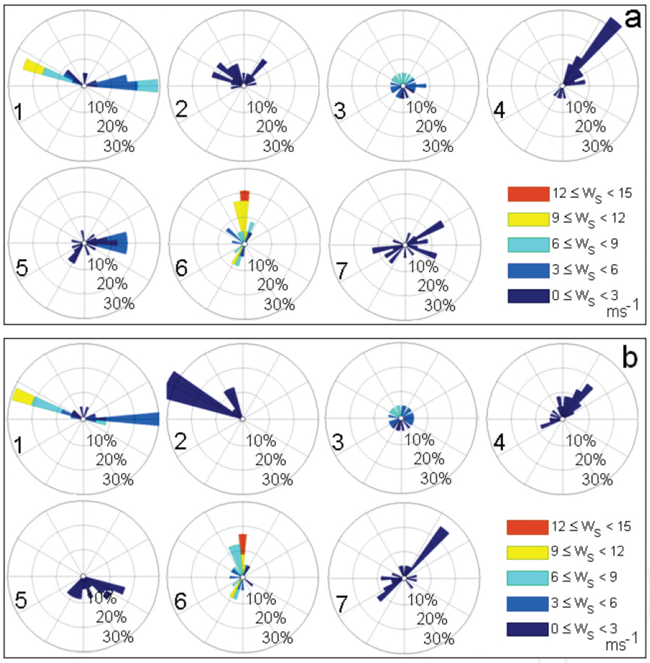

Figure 7. Annual wind rose at the weather stations around the lake: (a) the dry season; (b) the wet season. The data were averaged over the years 2006–2007.

The model results are shown in **Figure 8** as vector plots of current fields at 4-hour interval. The breeze-induced circulation pattern in the lake is represented by two gyres. One of them is cyclonic (counterclockwise rotation) and located in the east-central part of the lake. The other gyre is anticyclonic (clockwise rotation) and located in the west-central part. The model results exhibit a very complex dynamics, whose small-scale features are difficult to interpret. Nevertheless, similar gyres were identified near the east and west coast.

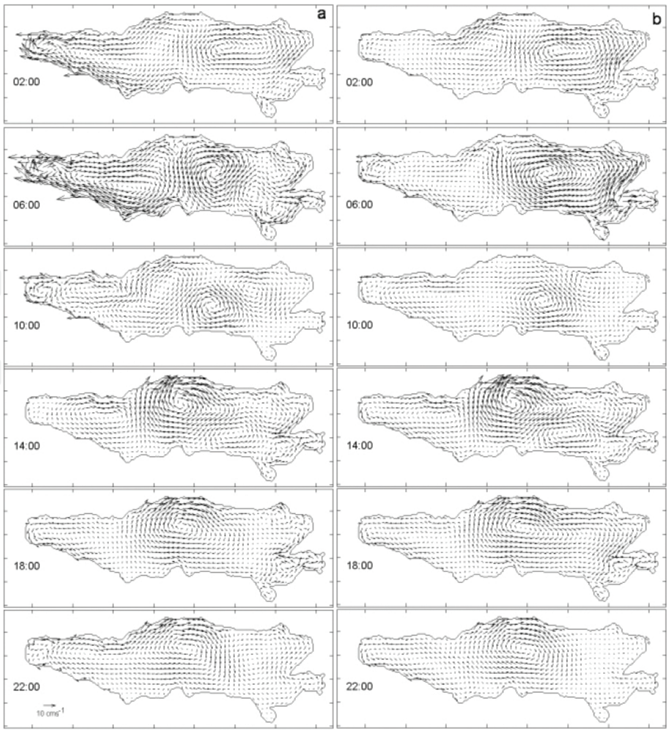

Figure 8. Model simulations of the wind-generated: (a) the dry season; (b) the wet season. The data were averaged over the years 2006–2007.

The core of the anticyclonic gyre, which was generated in the west part of the lake, propagates to the northwest and continues to develop during the most part of the simulation period. Conversely, the cyclonic gyre originally located in the east-central part moves to the southwest part of the lake. Subsequently, it vanishes due to the bottom friction and its remainder merges into the returning flow of the anticyclonic gyre. The model simulations show that the currents near the south and north coast reach 12 cm/s. These and other model results require the comparisons with current meter data. Therefore, two special experiments were carried out in January 2007 and June 2014.

3.6.1. *Temperature and currents variability within two lake polygons*

In order to quantitatively describe the spatial-temporal variability of temperature and circulation in the Lake Chapala, two special experiments were conducted: (i) on January 10, 2007 (the Alacranes polygon, **Figure 9a**, center-left) and (ii) on June 1, 2014 (the Mezcala polygon, **Figure 9a**, center). Both experiments were conducted with the use of a vertical array of temperature recorders and a boat-mounted ADCP.

The array contained 15 temperature recorders (13 HOBO Pro v2, one HOBO-LEVEL sensor and one SBE-39), evenly placed from the surface to 7.2 m depth. The boat towed the array. A down-looking ADCP RDI 600 kHz set up in bottom-track mode was mounted on the starboard side of the boat. The bin size was set to 15 cm (the total of 13 bins), and the ensemble interval was 15 s.

The instruments were protected from fishing nets by a specially designed triangular metal case shaped to fit the recorders so that the fishing gear caused no damage. The designated depth of the array was controlled by HOBO-LEVEL and SBE-39 pressure sensors and weights (**Figure 9b**). The sampling rate of temperature and pressure sensors was 1 min. The towing speed of about 2 m/s allowed the acquisition of temperature and currents data with the horizontal spatial resolutions of 120 and 30 m, respectively.

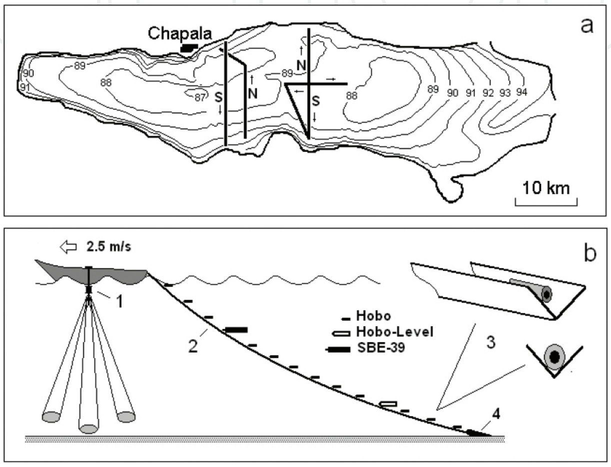

Figure 9. (a) The schematic of the experiments in the Lake Chapala conducted on January 10, 2007. (polygon Alacranes: center-left) and June 1, 2014 (polygon Mezcala: center of the figure). (b) The schematic of the towed array of recorders. 1. 600 kHz RDI ADCP, 2. angular metal case for the protection of the recorders, 3. the recorder mount and 4. weights for lowering of the recorders.

Current profiler data is calibrated according to [34], and bad data removed following the procedure explained in Ref. [35].

3.6.2. The Alacranes polygon

The spatial distribution of temperature along the transect ***S*** (carried out from 12:00 to 14:30, the boat sailed southward) is shown in **Figure 10a**. The transect ***N*** (on which the boat sailed from south to north) was carried out from 16:40 to 17:50 and the corresponding temperature field is shown in **Figure 10b**. On both transects, the meteorological conditions were recorded. During the transect ***S***, the average air temperature was 14.5°C; the wind was blowing onshore, and its speed was 12 m/s. Later, during the transect ***N*,** the average air temperature was higher and reached 20.9°C; the wind was blowing offshore, which is a typical breeze circulation in the Lake Chapala [18].

It is seen from these transects that the heat fluxes were directed toward the surface layer of the water column, whereby the vertical gradient reached 2.5°C per the top meter of the column. During the cross section ***S***, all temperature fluctuations were confined between 17 and 18.5°C. Few hours later, the rapid development of a thermocline was observed on transect *b* (**Figure 10**) with temperatures ranging between 17 and 20°C. At the end of the ***N*** transect, the coastal water began to mix due to the lake breeze effect. Furthermore, at the north end of the transect*S* the water was warmer than at the south by 1°C (**Figure 10**).

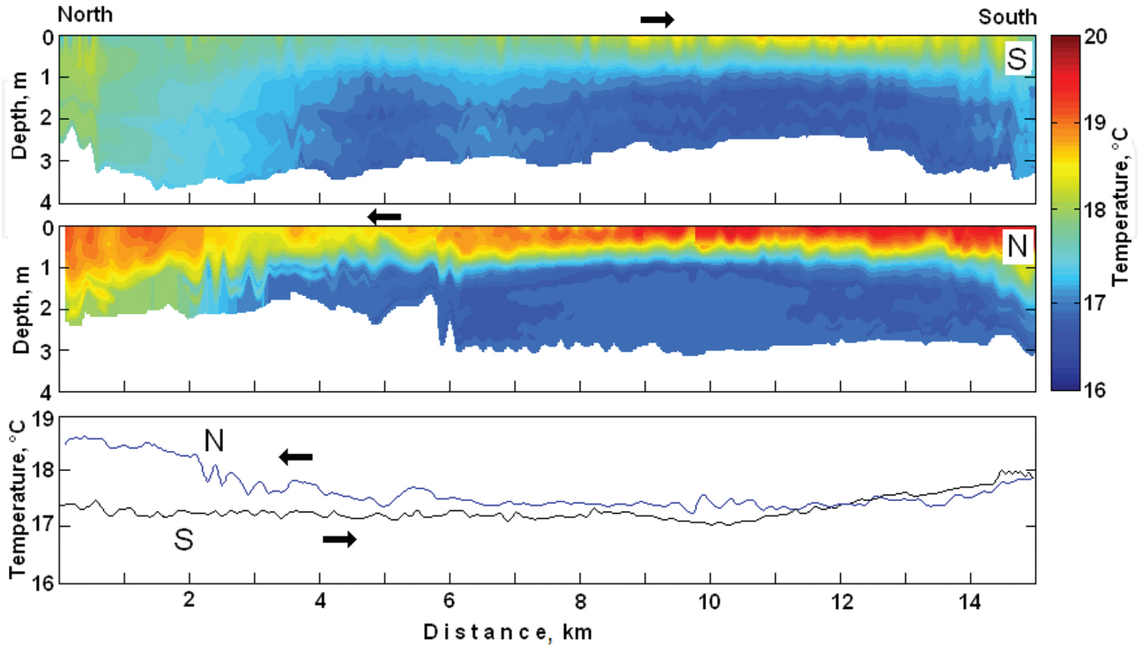

Figure 10. Vertical temperature cross sections of the lake carried out from north to south (S) and from south to north (N) obtained from the arrays of recorders on January 10, 2007, in the Lake Chapala. The bottom panel shows the vertically averaged temperatures at both cross sections.

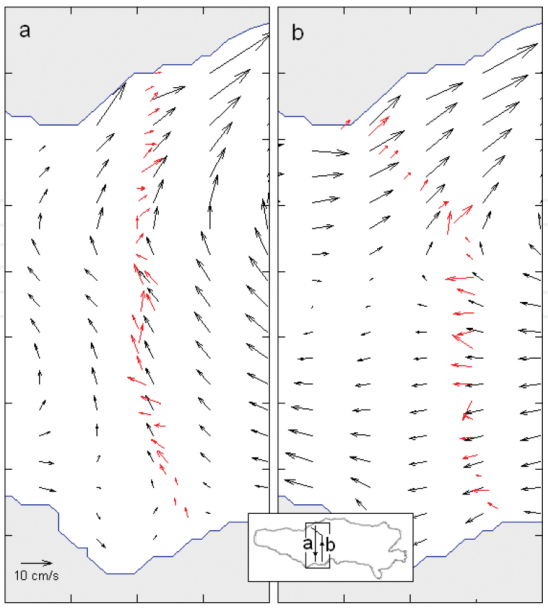

Figure 11. (a) Modeled (black) and observed (red) currents in the vicinities of the *S* and *N* transects. The experiment was conducted on January 10, 2007; the simulations are shown for 12:30. and 19:00, respectively.

The wind field is believed to be the main mechanism that continually sustains the circulation in the Lake Chapala, including the gyres. **Figure 11** presents the vector plots of vertically averaged currents measured by the towed ADCP and simulated by the HAMSOM model. In general, the modeled and observed data are in good agreement.

The transect ***S*** was carried out from 12:00 to 14:30, while the boat was sailing from north to south. The speed of the northeastward flow along the cross section peaked at 10 cm/s. The flow was presumably generated by the prevailing onshore wind dubbed "the Mexican" by local fishermen [22]. The 13:00 model simulations are in good agreement with the data collected in the northern part of the lake (**Figure 8a**). At the same time, the south part is characterized with a significant difference between the modeled and observed data, in terms of both the currents and temperature field.

Nevertheless, the transect ***N*** data collected between 16:30 and 18:00 show fairly good agreement with the southern part of the 18:00 model field, with velocities reaching 15 cm/s. It was found that in the southern part of the lake, the direction of the flow could change from west to south in only 2 hours. The wind speed of 12 m/s was recorded by the Chapala city weather station at the same time when transect ***S*** displayed southeastward flow. In just 2 hours upon the completion of transect ***N***, the flow changed its direction to southeastward and gained speed of 10 cm/s. These results suggest that the model successfully simulates the effect of the morning breeze circulation.

3.6.3. The Mezcala polygon

The model simulations show the presence of a steady anticyclonic gyre of 10–12 km diameter in the central part of the lake, across from the town of Mezcala, during both seasons (**Figure 8**). To confirm these numerical calculations, we carried out the Mezcala polygon survey. The temperature and currents within the gyre where observed with the use of towed temperature recorders and ADCP. The cross-shaped polygon of about 6 km length was situated in the deepest part of the lake, inside the gyre. Continuous measurements along the three directions (**Figure 9a**) were taken on July 1, 2014 from 8:30 to 19:00, whereby the boat was sailing back and forth.

As shown in **Figure 12**, the temperature is distributed along the two transects: the transect ***S***, which was carried out from 8:30 to 10:20, while the boat was sailing south and the transect ***N***, which were carried out from 17:00 to 19:00. The meteorological conditions during the experiment were typical for this time of the year: the morning was calm followed by a moderate breeze in the afternoon. The towing speed was higher than on the Alacranes polygon; therefore, the deepest recorder was only at a 2.2 m depth. Nevertheless, the collected data shed a new light on the horizontal and vertical structure of the temperature field on the polygon in the presence of the anticyclonic gyre.

As seen from **Figure 12**, in the morning (cross section *S*), at the time when the boat was sailing south (from 9:15 to 10:22 AM), the stratification of the lake was moderate. The average temperature near the southern shore of the lake was steady at 23.4°C (lower panel at the **Figure 12**). During the reverse leg along the transect (from the south to the north), the measurements were taken only in the afternoon (from 17:00 to 19:00), when the wind and temperature conditions over the lake were quite different from the morning. The simulated currents are reasonably comparable with the observed data and suggest that in the second half of the day the gyre was well developed. The gyre exerts a strong impact on the spatial temperature distribution in the study area.

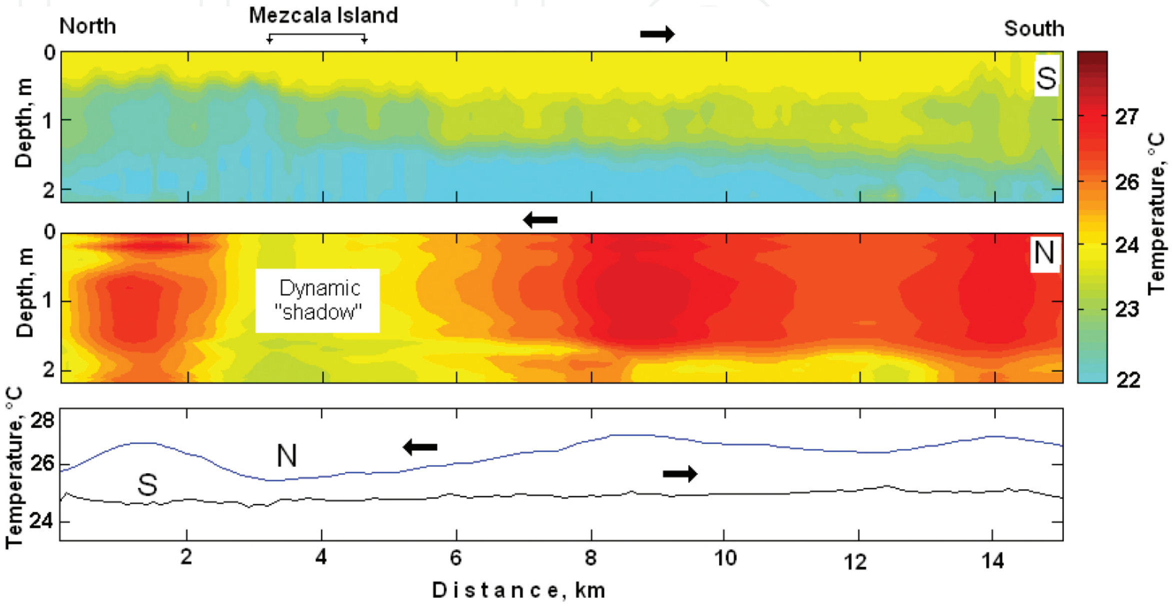

Figure 12. Vertical temperature cross sections: the north-to-south (*S*) and south-to-north (*N*) transects, obtained from the arrays of recorders on July 1, 2014. The vertically averaged temperature at both cross-sections is shown on the lower panel.

A zone of strong vertical mixing was discovered on the last leg, about 1 km east from the Mezcala Islands, when the array of the recorders was towed from the south to the north. These islands are about 1.5 km long. They are perpendicular to the flow of the gyre and create dynamic shadows. Within this area, the upwelling of cold-bottom water due to the Bernoulli effect resulted in its mixing with the warm surface water. Unfortunately, the spatial grid of the model (300 × 300 m) was too coarse to simulate this effect.

More detailed hydrographic surveys off the Mezcala Islands and the Alacranes polygon are planned for the future with the subsequent assimilation of the collected data into 3D numerical models. This will allow us to confirm the above-mentioned assumptions about the impact of the vortex on the vertical and horizontal mixing near the islands.

4. Conclusions

A great deal of results presented here are unique for the Lake Chapala. Although this study was carried out during different time periods, on average, it gives a fair account of the dynamic processes occurring in the lake and its surroundings. The main dynamic process occurring in the lake is the breeze circulation. The daytime breeze does not usually exceed 4 m/s. Beyond any doubt, the lake breeze results in the increased evaporation from the lake's surface and also generates free seiches waves.

The spectral analysis of the lake-level fluctuation measured by a high-precision HOBO-level recorder shows that there are two seiches modes in the lake with the periods of 5.7 and 2.8 hours, with the average amplitudes of 15.4 and 8.1 mm.

This study shows for the first time the main features of the diurnal variability of the stratification in the lake. The thermocline is formed around midday. It is very narrow and well defined. Within the top 30–40-cm layer, the vertical temperature gradient reaches 0.5°C/m and falls to zero at the bottom. The buoyancy frequency in the surface layer during the day hours exceeds 50–60 c/hour (a period of about 1 min). The well-defined stratification of the surface layer prevents the development of turbulence and mixing by wind and waves. In contrast, during the nighttime, negative temperature gradients of up to 3°C/m are formed due to the strong cooling of the surface layer. This serves to increase the intensive vertical mixing and results in a constant temperature within the entire water column of the lake.

The new data on the diurnal variations of the thermal structure of the lake are very important for the understanding of the migration behavior of biological organisms. The data are also important for the development of three-dimensional models of the dynamic processes in the lake.

The study shows that the northern part of the lake is warmer than its central and southern parts, which is essentially an important feature of the circulation. However, until now there were no detailed accounts of the horizontal and vertical structure of the temperature field in the lake in different seasons.

Our *in situ* measurements taken in February, April, July and October 2006 confirmed the previous finding that the temperature in the central and northern parts of the lake during different seasons is always higher than in the southern part, which holds true not only for the surface but also for the entire water column. In all four seasons, the average temperatures at the north and south coasts differ by 2–3°C. The vertical distribution of temperature along the cross sections was not homogeneous.

In this study, the simulation of currents was carried out by means of the HAMSOM 2D model for the dry and wet seasons. The model was initialized with the wind data from the network of weather stations in the Chapala Lake area collected in 2006–2007. The model results demonstrate very complex dynamics, in particular, the continuous presence of two gyres. One of them rotates counterclockwise (cyclonic rotation) and is located in the east-central part of the lake. The other one rotates clockwise (anticyclonic rotation) and is located in the west-central part.

In order to describe the spatial-temporal variability of temperature in the lake and compare the model simulations with the observed data, two special experiments were conducted in the Lake Chapala on January 10, 2007 (polygon Alacranes) and on June 1, 2014 (polygon Mezcala). In these experiments, a vertical array of temperature recorders aligned in the antenna-like pattern was towed along the cross sections by a boat with onboard ADCP. These high-frequency measurements on both polygons shed new light on the distribution of temperature and currents in these parts of the lake. The data collected on the Mezcala polygon confirm the presence of an anticyclonic gyre and show the influence of the islands on the dynamics of water masses and the temperature distribution in the lake.

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