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Oscillations of the hydrometeorological characteristics in the region of Lake Chapala for intervals of days to decades

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RESUMEN

Se presenta el análisis espectral para las principales características hidrometeorológicas en la región del lago de Chapala: temperatura del aire, precipitación, evaporación, presión atmosférica, viento, nivel del lago y volumen del flujo de los ríos. Las series de tiempo se agruparon con una igual discretización y duración. Usando métodos lineales y no lineales del análisis espectral (máxima entropía y máxima verosimilitud) se identificaron los principales periodos en el rango de días a décadas, obteniendo estimaciones de las amplitudes medias cuadráticas. Se discuten las causas físicas de las oscilaciones, así como las relaciones internas entre las fluctuaciones de diferentes parámetros hidrometeorológicos. Se discuten las causas de las grandes variaciones en el nivel del lago y en los brotes periódicos del lirio acuático.

PALABRAS CLAVE: Lago de Chapala, características hidrometeorológicas, oscilaciones.

ABSTRACT

A spectral analysis is presented for the principal hydrometeorological characteristics in the region of Lake Chapala: air temperature, precipitation, evaporation, atmospheric pressure, wind, level of the lake and volume of flow of the rivers. The time series were grouped with equal discretization and duration. Using linear and nonlinear methods of spectral analysis (maximum entropy and maximum likelihood) the main periods were identified in the range of days to decades, obtaining estimates of the mean square amplitudes. The physical causes of the oscillations are discussed as are the internal relationships between the fluctuations of the different hydrometeorological parameters. The causes of the long-term variations in the level of the lake as well as the periodic outbreaks of water lilies are discussed.

KEY WORDS: Lake Chapala, hydrometeorological characteristics, oscillations.

INTRODUCTION

Researchers from Mexico and other countries have made great strides in the study of Lake Chapala, the largest lake in Mexico. A review up to 1987 includes a list of 120 publications (Guzmán and Morelos, 1992). Furthermore, during the past few years, scientists from the Instituto Mexicano de Tecnología del Agua (IMTA) and from the Instituto de Limnología of the Universidad de Guadalajara (CUCBA, UdG) have conducted extensive studies of the concentration of pollutants and water lilies in the lake (IMTA, 1994).

A group of U.S. and Mexican biologists have studied the factors that control the production of phytoplankton in the lake for several years (Owen *et al.*, 1992). Studies have also been published on water circulation and on the dynamics of pollution in the lake (Escalante, 1992; Hansen, 1994; Leon, 1994; Curiel, 1995). However, there are no references on the variability of the hydrometeorological characteristics of the area of Lake Chapala. Biologists, geographers, ecologists and others generally use mean climatic characteristics such as temperature, precipitation, wind velocity, etc., though a large deviation in the mean magnitudes can be a determining factor.

The variability of the hydrometeorological regime of the lake should be useful in order to construct a complete hydrodynamic circulation model which responds to the variability of the atmospheric processes in a wide range of time scales, including processes with synoptic and climatic periods. First we should study the hydrological regime of the lake and of the rivers that drain into it, the geomorphologic processes along its shore and the structure of the bottom sediments. The goal is to discover the physical significance of internal relations between all the processes that form the hydroclimate of the lake.

In this paper we discuss the variability of the hydrometeorological characteristics in a region of Lake Chapala in a range of scales going from synoptic to climatic, using spectral analysis methods.

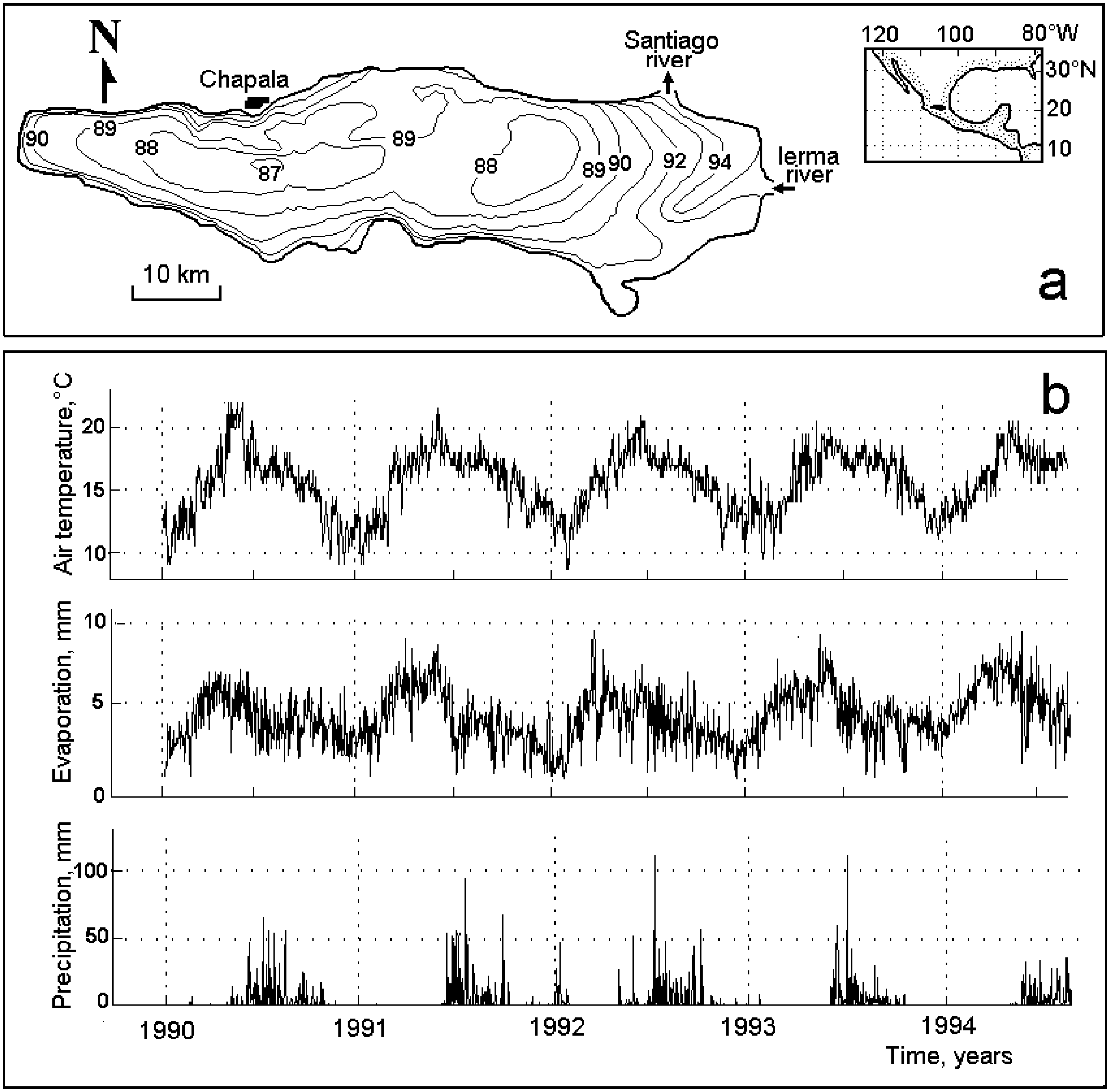

Fig. 1a. Map of Lake Chapala; (b), see the next caption.

INFORMATION USED AND PROCESSING METHOD

We used practically all time series of the fluctuations of the hydrometeorological characteristics found in records of the Comisión Nacional del Agua (CNA), consisting of observations at the hydrometeorological station at Chapala. The time series on qualitative observations of water lilies in the lake was taken from IMTA (1994).

Mean annual anomalies of air temperature and rainfall in Guadalajara were obtained from the meteorological station of the Instituto de Astronomía y Meteorología of the University of Guadalajara. All time series analyzed were subjected to a critical control. Using a special program, the minimum and maximum values of the data were controlled and the maximum possible difference of two neighboring data was controlled. All segments of unreliable information in time series were replaced by a cubic spline interpolation.

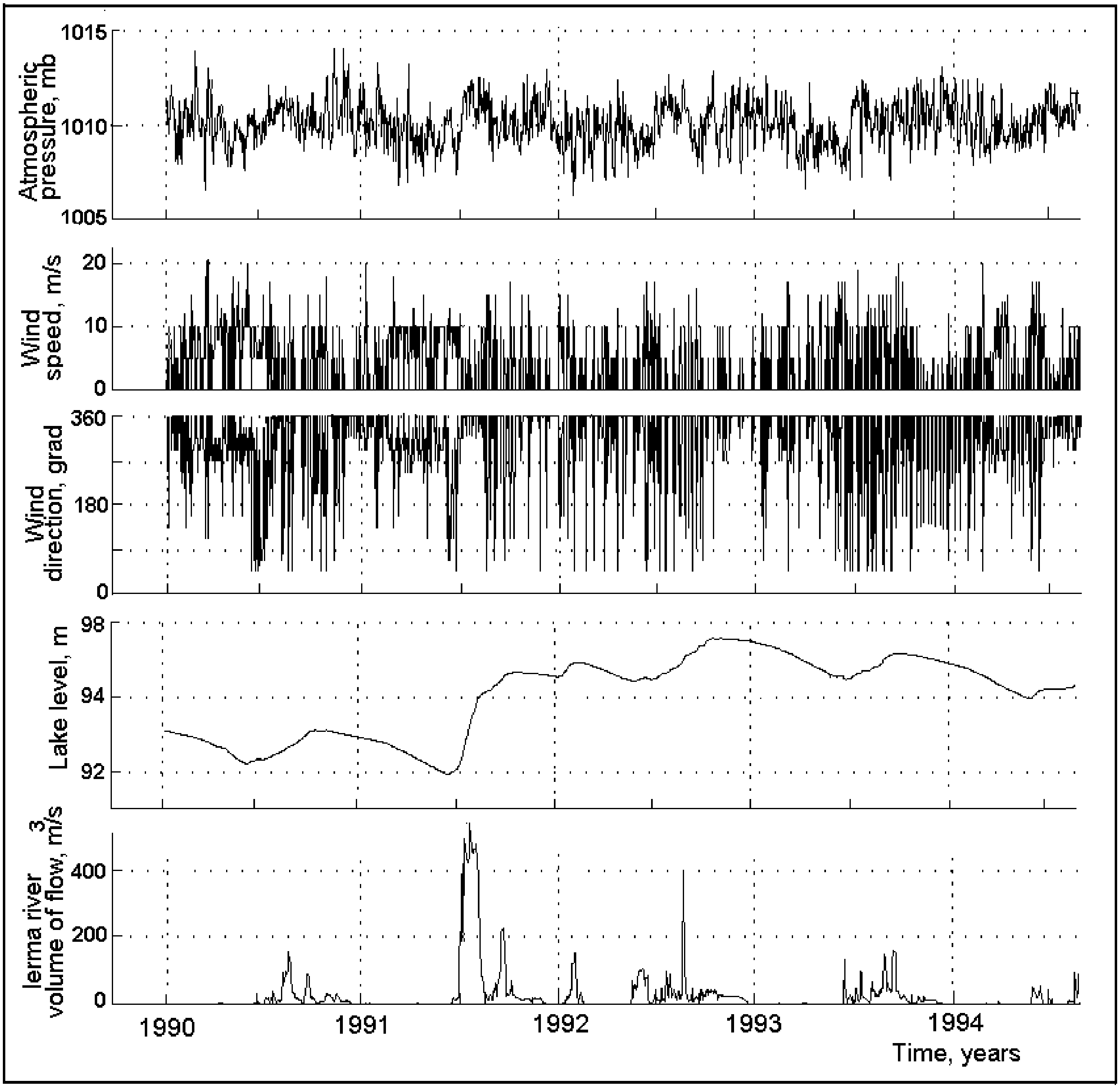

Fig. 1b. Hourly time series of the hydrometeorological characteristics, based on the data from the meteorological station at Chapala from 1990-1994 (group I).

The time series used in the study are summarized in Table 1. Depending on the data intervals the time series were grouped into three sections marked by Roman numerals in Table 1. The spectra of the amplitudes were estimated for each group of time series (Bendat and Piersol, 1967; Jenkins and Watts, 1969; Konyaev, 1990):

$$C_x(\omega) = \int_0^T x(t) \cdot \exp - i2\pi\omega t dt, \tag{1}$$

where $x(t)$ is the time series; T is the total length of the series; and ω is the frequency. Autoperiodogram $S_{xx}(\omega)$ and cross-periodogram $S_{xy}(\omega)$ were defined as

$$S_{xx}(\omega) = \frac{1}{T} C_x(\omega) \cdot C_x^*(\omega), \tag{2}$$

$$S_{xy}(\omega) = \frac{1}{T} C_x(\omega) \cdot C_y^*(\omega) = P_{xy}(\omega) - iQ_{xy}(\omega). \tag{3}$$

Here $P_{xy}(\omega)$, $Q_{xy}(\omega)$ are the true and imaginary parts of

Table 1

Characteristics 1/1/1990 of the time series used

Series Group	Discretization	Hydrometeorological Characteristic	Dimension	Data Star date	Data Stop date	Number of data
I	1 day	Air temperature	ºC	1/1/1990	8/31/1994	1703
		Evaporation	mm	1/1/1990	8/31/1994	1703
		Precipitation	mm	1/1/1990	8/31/1994	1703
		Atmospheric pressure	mb	1/1/1990	8/31/1994	1703
		Wind module	m/s	1/1/1990	8/31/1994	1703
		Wind direction	grad.	1/1/1990	8/31/1994	1703
		Level of the lake	m	1/1/1990	8/31/1994	1703
		Lerma river volume of flow	m^3/s	1/1/1990	8/31/1994	1703
II	1 month	Air temperature	ºC	1/1/1971	8/31/1995	286
		Evaporation	mm	1/1/1971	8/31/1995	286
		Precipitation	mm	1/1/1971	8/31/1995	286
		Atmospheric pressure	mb	1/1/1971	8/31/1995	286
		Wind module	m/s	1/1/1971	6/31/1991	204*
		Wind direction	grad.	1/1/1971	6/31/1991	204*
		Level of the lake	m	1/1/1971	8/31/1995	286
		Lerma river volume of flow	m^3/s	1/1/1983	8/31/1991	140
		Santiago river volume of flow	m^3/s	1/1/1971	8/31/1991	140
		Aqueduct volume of flow	m^3/s	1/1/1971	8/31/1991	140
III	1 year	Air temperature anomaly		1900	1989	90
		Precipitation anomaly	ºC	1900	1989	90
		Lake level anomaly	mm	1900	1995	96
		Presence of water lilies	m	1913	1995	82

* There is no information for the series of wind speed and direction 1/1/1976 to 6/1/1979.

the crossed periodogram; (*) is the complex conjugate. The spectral estimate was obtained by smoothing the frequencies of the periodograms.

$$\hat{S}_{xx}(\omega) = \int_{-\infty}^{\infty} S_{xx}(\omega')Z(\omega-\omega')d\omega' , \tag{4}$$

where $Z(\omega)$ is a smoothing function.

The estimates of the coherence function were also calculated for pairs of time series at the limits of a group:

$$C^2_{o_{xy}}(\omega) = \frac{\left|\hat{S}_{xy}(\omega)\right|^2}{\hat{S}_{xx}(\omega)\cdot\hat{S}_{yy}(\omega)} \tag{5}$$

and the phase difference

$$\Delta\varphi_{xy}(\omega) = arctg\left(\hat{Q}_{xy}(\omega)/\hat{P}_{xy}(\omega)\right) . \tag{6}$$

In group III of the mean annual data series, nonlinear methods of maximum entropy (ME) and maximum likelihood (ML) for relatively short series, together with the traditional method of spectral analysis, were used to find the energy peaks of the spectra (Burg, 1967, 1972; Akaike, 1969; Konyaev, 1990). The spectral estimates for the maximum entropy method were obtained as

$$\hat{S}(\omega) = \sigma^2_M \cdot \Delta t \Big/ \left|A_{ME}(\omega)\right|^2 , \tag{7}$$

where σ^2_M is the variance and Δt, the interval of the time series data. The white filter $A_{ME}(\omega)$ was obtained as

$$A_{ME}(\omega) = \sum_{n=0}^{M-1} a_n \exp - i2\pi\omega\cdot n\Delta t , \quad a_0 = 1 , \tag{8}$$

and the filter coefficients a_n were calculated from the solution of the matrix equation:

$$\begin{bmatrix} B(0) & B(1) & \dots & B(M-1) \\ B(1) & B(0) & \dots & B(M-2) \\ \dots & \dots & \dots & \dots \\ B(M-1) & B(M-2) & \dots & B(0) \end{bmatrix} \begin{Bmatrix} 1 \\ a_1 \\ \vdots \\ a_{M-1} \end{Bmatrix} = \begin{Bmatrix} \sigma_M^2 \\ 0 \\ \vdots \\ 0 \end{Bmatrix} \quad (9)$$

Here $M \le N$, M is the order of the white filter; N is the number of data points in the time series; $B(0)$, $B(1)$…., $B(M-1)$ are the data of the correlation function of the time series analyzed.

The spectral estimates from the maximum likelihood method were calculated with

$$\hat{S}(\omega) = \Delta t / \left| A_{ML}(\omega) \right|^2 \quad , \quad (10)$$

where the averaging filter was found from

$$A_{ML}(\omega) = \sum_{k,j}^{N} a_{k,j} \exp - i2\pi\omega(k-j)\Delta t, \quad (11)$$

and the $a_{k,j}$ coefficients were obtained from the inverse of the initial correlation matrix of the time series:

$$\begin{bmatrix} B(0) & B(1) & \dots & B(N-1) \\ B(1) & B(0) & \dots & B(N-2) \\ \dots & \dots & \dots & \dots \\ B(N-1) & B(N-2) & \dots & B(0) \end{bmatrix} = \begin{Bmatrix} a_{11} & a_{12} & \dots & a_{1N} \\ a_{21} & a_{22} & \dots & a_{2N} \\ \dots & \dots & \dots & \dots \\ a_{N1} & a_{N2} & \dots & a_{NN} \end{Bmatrix} \quad (12)$$

From the values of the spectral density, the mean square amplitudes of the harmonics of the dominant peaks in the spectra were found. For the structure of the time series of the wind velocity and direction of group I, the method of rotary components (Gonella, 1972; Mooers, 1973) was used. To this end we find the estimates of the "clockwise" spectra,

$$S_{-}(\omega) = \frac{1}{8}\left[S_{uu}(\omega) + S_{vv}(\omega) - 2Q_{uv}(\omega)\right] \quad (13)$$

and "anticlockwise" spectra

$$S_{+}(\omega) = \frac{1}{8}\left[S_{uu}(\omega) + S_{vv}(\omega) - 2Q_{uv}(\omega)\right] \quad (14)$$

where $S_{uu}(\omega)$, $S_{vv}(\omega)$ are the autospectra, and $Q_{uv}(\omega)$ is the spectral square of the zonal and meridional components $u(t)$ and $v(t)$ of the wind velocity vector. The orientation of the major axes of the elliptic hodographs

$$\Theta(\omega) = arctg\left\{2P_{uv}(\omega) / \left(S_{uu}(\omega) - S_{vv}(\omega)\right)\right\} \quad (15)$$

and their stability

$$E^2(\omega) = \frac{(S_{uu}(\omega) + S_{vv}(\omega))^2 - 4(S_{uu}(\omega) \cdot S_{vv}(\omega) - P_{uv}^2(\omega))}{(S_{uu}(\omega) + S_{vv}(\omega))^2 - 4Q_{uv}^2(\omega)} \quad (16)$$

were also calculated, where $P_{uv}(\omega)$ is the co-spectrum of $u(t)$ and $v(t)$.

The confidence intervals were calculated at each level for all spectral estimates, from standard algorithms described in the literature (Jenkins and Watts, 1969; Konyaev, 1990). The number of degrees of freedom v, was found as $v = 2\alpha$ $(2F+1)$; where α is the number of independent segments of realization, in which the spectral estimates were averaged and F is the half-width of the filter that is used to average the periodograms.

Since the hydrometeorological observations of the region of Lake Chapala have not been discussed in the literature, we also present graphs of all time series of the spectral characteristics calculated here.

SYNOPTIC VARIABILITY

In the tropics, synoptic oscillations of the weather are weaker than at moderate latitudes (with the exception of tropical cyclones). Some significant deviations in the daily behaviour of almost all meteorological characteristics are difficult to explain from local causes. Synoptic-scale circulation systems present variable forms, intensities and durations. According to Riehl (1979), they present a characteristic longitude of L=3000 km, occurring on the average once every five days, and a transfer velocity of C=600 km/day (close to 7 m/s). Synoptic oscillations in the tropics are often easily located on weather maps. They can take on the form of a vortex (cyclones, anticyclones), wave perturbations (easterly waves) or linear systems in which the vortex or divergence has a tendency to concentrate along one line whose longitude is much longer than its width (Riehl,1979).

Lake Chapala is located in the southwestern part of the Mexican Plateau, at an average elevation of 1500 m above sea level. The central and southern part of the plateau is under the influence of an anticyclonic circulation with small gradients in the baric field and average pressure oscillations from 1008-1020 hPa (Riehl, 1979). However, due to non-periodic irruptions of cold air from North America and the movements of atmospheric fronts, the variability of the temperature and pressure near the earth's surface shows a synoptic periodicity of 5-9 days (Mosiño and García, 1973). For this reason the weather is predominately dry with low humidity in winter.

For the synoptic variations, it was only possible to estimate their time scales and mean square amplitudes based on daily data at Chapala meteorological station during almost 5 years (group I). A high-frequency filter was applied to the time series with a cosine filter at a pass width of 30 days. The initial series of the module and wind direction were transformed to components $u(t)$ and $v(t)$.

Using the filtered series of the hydrometeorological characteristics, the frequency-time spectra $S(\omega,t)$ were calculated. A time sequence of segments was formed for each series, some in front and some behind, overlapping by 50% (Rozhskov, 1979; Pourahmadi and Saleni, 1984). This procedure allowed us to study the seasonal dependency of the oscillation on the synoptic range of frequencies. An appropriate length of the segments of realization and the magnitude of their coverage were chosen experimentally. When an excessive length of the segments of realization was obtained because the process was not stationary, the estimates of the frequency-time spectra $S(\omega,t)$ fitted poorly in time. Too short a segment worsened the ability of the analysis to fit, due to the frequency. The tests suggest two months (60 data points) as an optimum segment length, for a 1-month coverage. The periodogram of each segment was smoothed with three data points.

Spectral estimates $S(\omega,t)$ of the synoptic range of frequencies of the hydrometeorological characteristics analyzed are shown in Figure 2. Table 2 shows the periods of the spec-

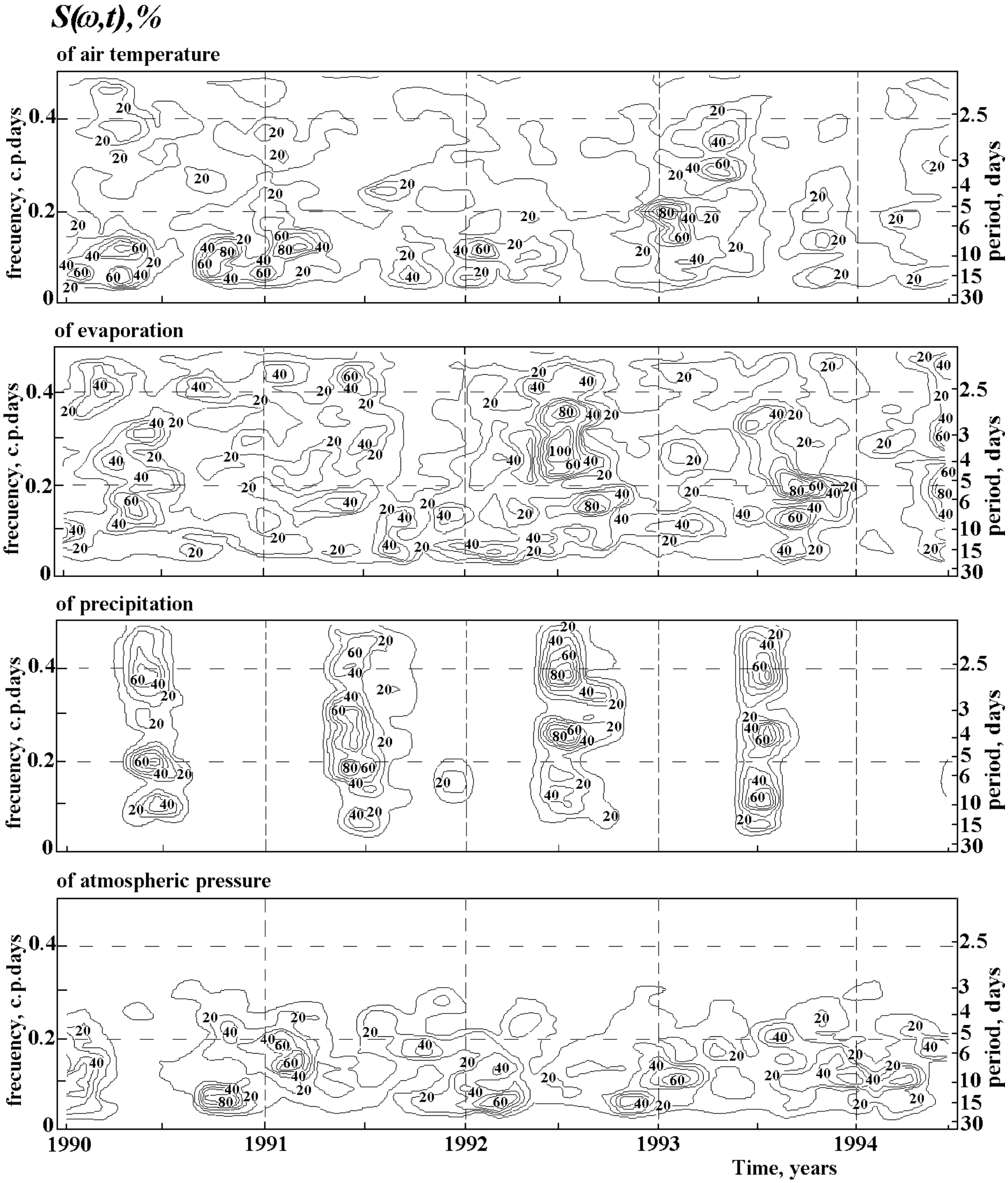

Fig. 2. Time-space spectra of the synoptic oscillations, based on the data from the group I time series. The relief in the spectral density is shown as a percentage of the maximum value.

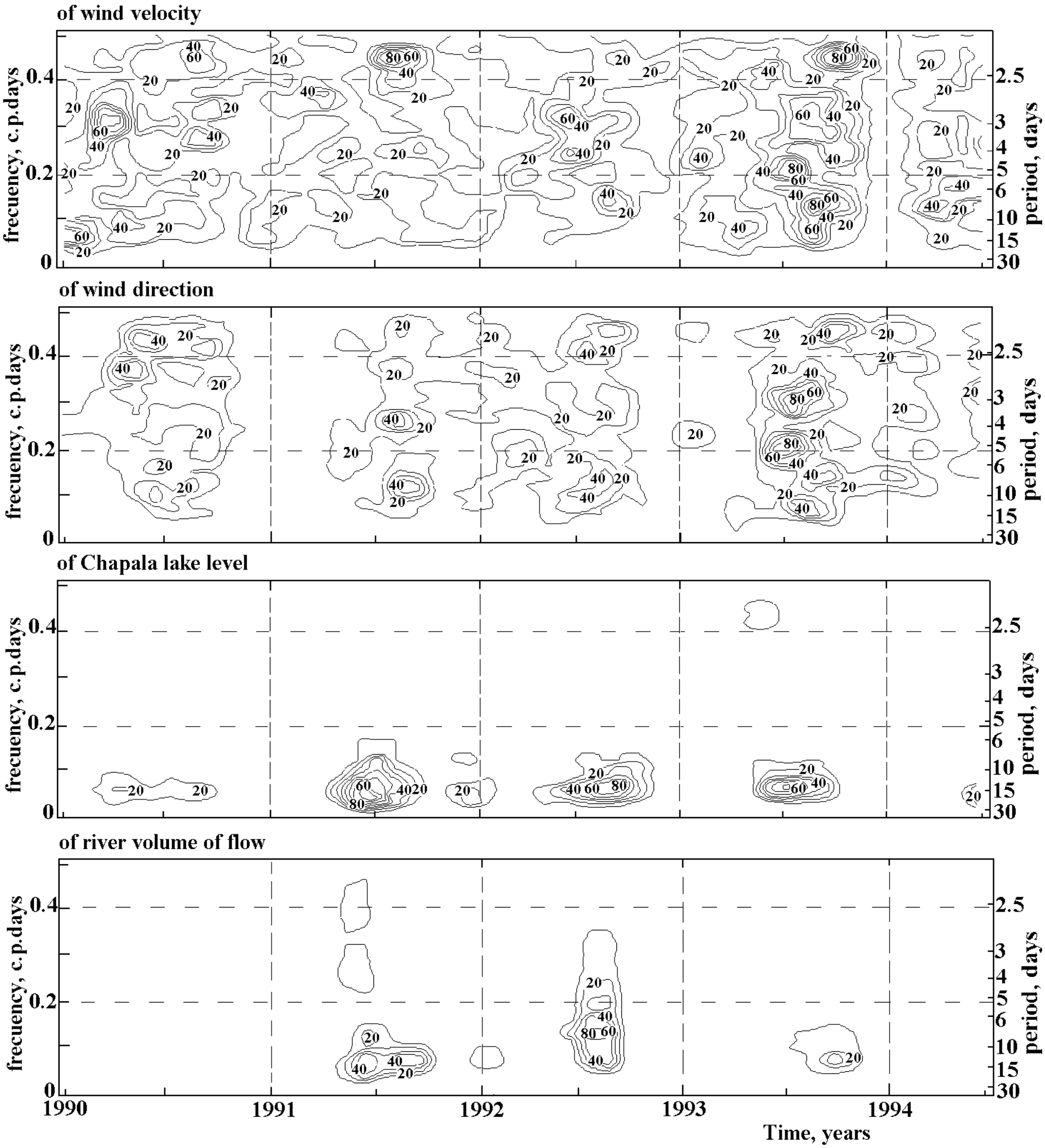

Fig. 2. Cont.

tral peaks and the mean-square amplitudes of the oscillations. A seasonal cyclicity in the intensity of the synoptic oscillations can be clearly observed in all frequency-time spectra; this is characteristic of correlated periodic random processes. The synoptic processes in the neighborhood of Lake Chapala present periods from 2 to 15 days, which agrees with previous results (Mosiño and García, 1973). Air temperature and atmospheric pressure fields increase during winter (dry season), and wind, evaporation, precipitation and volume of flow of the Lerma river increase in the rainy season.

We find considerable mean-square amplitudes of the synoptic oscillations in the neighborhood of Lake Chapala. They can reach 20-40% of the annual harmonic amplitude; the variation in precipitation can be even greater. The synoptic oscillations of all meteorological characteristics show a similar structure with regard to periodicity. In the flow of the

Table 2

Parameters of the synoptic variability in the area of Lake Chapala.

Hydrometeorological characteristics	amplitudes of the synoptic oscillations*	Months of greatest intensity
Air temperature	3.5(0.7), 5(0.9), 8(1.1), 10(0.9)	November-March
Evaporation	2.5(0.6), 4(0.8), 6(0.6), 9(0.7)	May-September
Precipitation	2.5(2.3), 4(9.5), 6(8.7), 9(7.8)	June-September
Atmospheric pressure	4.5(4), 6(5), 8(7), 10(6)	November-March
Wind module	2.5(56), 4(64), 6(48), 9(52)	May-September
Wind direction	2.5(56), 4(64), 6(48), 9(52)	May-September
Level of Lake Chapala	Nonexistent synoptic variability	
Lerma River volume of flow	9(51), 15(32)	June-September

* Mean square amplitudes of the oscillations of the corresponding periods are shown in parentheses and have the dimension of the initial time series.

Lerma river there are only two synoptic periods: 9 and 15 days. Apparently, synoptic processes of shorter periods could not be identified in the flow oscillations, since they are smoothed by the large area of the basin and by the time it takes for the river to rise. Frequently, short-period rain structures in the tropics provide more precipitation than the long-period section of the spectrum, which also confirms our results (see Table 2). This also explains the increase in flow of the Lerma river by a factor of almost one and a half in the 9-day period, compared to a 15-day period.

Table 3 shows the parameters of the synoptic variability of the wind oscillation obtained from the rotary component method (Gonella, 1972). For each peak in the spectral frequency, the direction of rotation of the velocity vector of the wind, the orientation of the major axis of the elliptical orbit and its stability were estimated. The velocity vector does not present an ordered rotational direction for the 2.5- to 4-day periods. The counter-clockwise rotation of the velocity vector dominates in the range of the 5- to 9-day periods. For all but two synoptic peaks, the stability of the orbital movements exceeds 95% of the confidence interval and the orientation of the major axes of the elliptical orbits are close to the axial line of the lake. Thus the spatial orientation of the synoptic pulsation of the wind in the region of Lake Chapala is due largely to the topography. The mountain chain that bounds the lake from north to south directs the synoptic air flows in a west-east direction.

Cross-spectral analysis for pairs of meteorological characteristics were also conducted for the synoptic periods: temperature-atmospheric pressure in the winter period and the other characteristics in the summer (see Table 1). All estimates of coherence were greater than the confidence. The phase displacement for pairs of characteristics varied little in all periods. Thus we may assume that the phase lag in the synoptic processes in the region of Lake Chapala originates from the same physical regularities that are characteristics of its microclimate and from the physical-geographical position of the lake.

SEASONAL VARIABILITY

The amplitude of seasonal variability, and its influence on the hydrometeorological parameters will allow us to understand the climatological peculiarities of the study area. In Figure 3, the monthly mean time series of the hydrometeorological characteristics of group II can be observed. They were used to identify of the seasonal variability in the region of Lake Chapala. Not all series have the same quality and quantity of data. The nonqualitative observations of the wind and atmospheric pressure series are particularly “contaminated”; there are segments with constant pressure and wind values throughout an entire year. However, this was all that was available. An estimate of the influence of the “contaminated” parts of the records was made beforehand for the estimates obtained from the spectra. The spectra of the segments that covered a length of 10 years were analyzed plus another interval of 5 years. It was found that segments with a great amount of non-qualitative data did not distort signifi-

Tabla 3

Parameters of the synoptic variability in the region of Lake Chapala, obtained from the rotary components method (Gonella, 1972).

Spectral peak period, days	Peak number in the spectrum	Normalized spectral density of the components $S_+(\omega)$	$S_-(\omega)$	Rotary vector of the velocity vector	Θ(ω), degrees	$E^2(\omega)$
2.5	0	48	34	+	128-308	0.58
	0	22	38	-	75-255	0.78
	3	38	24	+	117-297	0.71
	4	100	58	+	96-276	0.70
	5	24	28	-	110-290	0.84
	6	55	60	-	86-266	0.77
	7	54	45	+	102-282	0.95
3-4	1	37	30	+	114-294	0.63
	2	54	45	+	141-321	0.22
	3	23	46	-	70-250	0.64
	4	29	52	-	78-258	0.53
	5	19	68	-	114-294	0.55
	6	49	51	-	164-344	0.29
5-9	1	35	27	+	76-256	0.54
	2	36	24	+	83-263	0.79
	3	38	25	+	62-242	0.69
	4	32	34	-	97-277	0.55
	5	43	23	+	60-240	0.77
	6	100	47	+	103-283	0.89
	7	50	25	+	110-290	0.58

* The stability of the elliptic orbits that surpass the 95% confidence interval are identified with darker numbers.

cantly the spectral density in the frequencies of seasonal variability, but there was some important deformation in the high and low frequencies.

Figure 3 a, b shows the spectra of the time series analyzed. Note that the seasonal variability of the meteorological characteristics of the lake region is completely determined by two overlapping harmonics: annual and semiannual, as well as by the contribution of the low-frequency tendency and the random noise of the high frequency. The contribution of higher intra-annual harmonics with periods of 4, 3, etc. months, is almost two orders of magnitude smaller than the main harmonic, even though these oscillations are clearly separated in almost all the spectra. Thus, the low-frequency behavior of temperature, for example, in the lake region can be presented in the form of the model:

$$T(t) = T_0+A_0t +A_1 \sin[2\pi(\omega_1 t +\varphi_1)]+A_2 \sin[2\pi(\omega_2 t +\varphi_2)]+\gamma\,, \quad (17)$$

where T_0 is the mean multi-annual air temperature in the lake region; A_0 is the angular coefficient of the linear tendency; A_1, A_2, ω_1, ω_2, φ_1, φ_2 are the amplitudes, frequencies, and initial phases of the annual and semiannual harmonic; and γ is the high-frequency random component. The unknown mag-

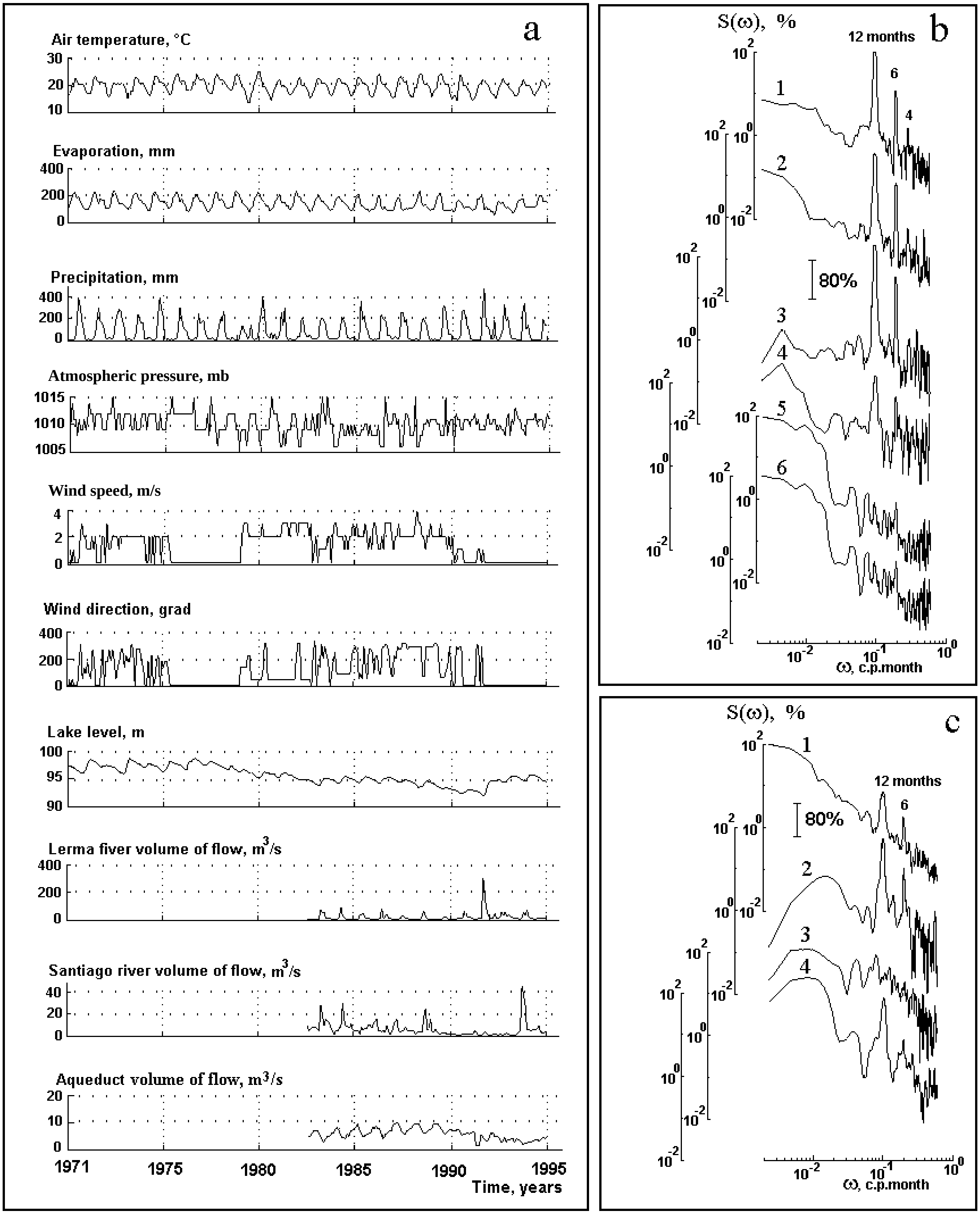

Fig. 3. (a) Time series of the average monthly hydrometeorological characteristics of the observations at the Chapala station during 1971-1995 (group II). (b) Normalized energy spectra of the meteorological characteristics: (1) air temperature; (2) evaporation; (3) precipitation; (4) atmospheric pressure; (5) zonal component of the wind speed; (6) southern component of the wind speed. (c) Normalized energy spectra of the hydrological characteristics: (1) oscillation of the level of the lake; (2) volume of flow from the Lerma river; (3) volume of flow from the Santiago river; (4) volume of flow from the Chapala-Guadalajara aqueduct.

Table 4

Values of the square function of the coherence of the phase differences and the mean square amplitudes of the annual harmonic of the hydrometeorological characteristics of the region of Lake Chapala. (Time series from group II) * The values of the phase differences in parentheses are given in months.

Evaporation	0.76	0.99		69(2.3)	37 (1.2)	40	Lerma river volume of flow	0.68	0.73		---	---	14.8
Precipitation	0.88	0.96	0.65		324 (10.8)	89	Santiago river volume of flow	0.26	0.56	0.14		---	3.5
Atmospheric pressure	0.84	0.69	0.93	0.55		2.1	Chapala-Guadalajara aqueduct volume of flow	0.01	0.10	0.03	0.14		2.1
* The values of the phasse differences in parentheses are given in months.													

nitudes in the equation are easily obtained from the amplitude and energy spectra of the time series. It is clear that not all the time series can be satisfactorily described with this model; however, for most cases, the approximation is reasonable.

Figure 3b shows (except for the spectrum of the flow of the Santiago river), two principal seasonal harmonics. The high-frequency levels are substantially less than for the spectra of the meteorological elements. The hydrological characteristics are more conservative and react weakly with the intra-annual pulsations of the atmospheric processes. Table 4 gives the values of the square coherence, the phase differences and the mean square amplitudes for pairs of hydrological and meteorological elements, with the exception of the air components. The variation of the annual harmonic amplitude of the meteorological elements presents coherences that almost always exceed the confidence level. For example, the seasonal oscillation of water withdrawal from the lake by the Chapala-Guadalajara aqueduct is incoherent with other characteristics, even though its spectrum presents statistically reliable peaks at the frequencies of the principal seasonal harmonics. This lack of coherence can be explained by the fact that the spectral estimate is very sensitive to phase change in the time series (Jenkins and Watts, 1969; Konyaev, 1990). The extraction of water is anthropogenic and depends on the needs of the national economy. It presents seasonal variations with displacements of hidden phases from year to year, which explains its incoherence with natural oscillations.

The pulsations of the coherence estimates between the flow of Santiago river and the other characteristics may be explained by the hydrological regime of this river that flows out of the lake. The mean-square seasonal oscillations in the level of the lake are small (21 cm for the annual harmonic), and cannot change significantly the transverse section of the river. There may be other non-periodic factors that produce irregular variations in the flow from this river. From Figure 3, unlike the spectra of the other hydrological parameters, the spectral variation in the flow of the Santiago river does not have energy peaks in the frequencies of the principal seasonal harmonics, but it does present peaks in the periods close to 2.5 and 1.5 years.

The phase differences given in Table 4 for the principal seasonal harmonics have a clear physical significance and reflect the inertial peculiarities of the reactions of the different hydrometeorological characteristics in the seasonal energy balance to the surface of the land.

INTERANNUAL VARIABILITY. OUTBREAKS OF AQUATIC WEEDS IN THE LAKE

During the present century, Lake Chapala has suffered two nearly catastrophic decreases in its level. Starting in 1945, the mean annual level fell almost four meters in ten years; in 1955 and the four years that followed, it rose almost five meters. From 1977 to 1998 the level decreased again by almost five meters. If the first catastrophic decrease was caused by secular variations in the climate, the second one, in part, was produced from the rapid increase in the extraction of water through the Chapala-Guadalajara and Calderón aqueducts and the Atequiza canal. The climatic oscillations of the level of the lake are a complex process with inverse relations of different signs, with which nature regulates the level of the lake, as has been confirmed during a history of centuries. Evidently, the extraction of water for agriculture and other uses has not exceeded the critical levels. In some way, the lake and its watershed are still in a compensation mode from these losses.

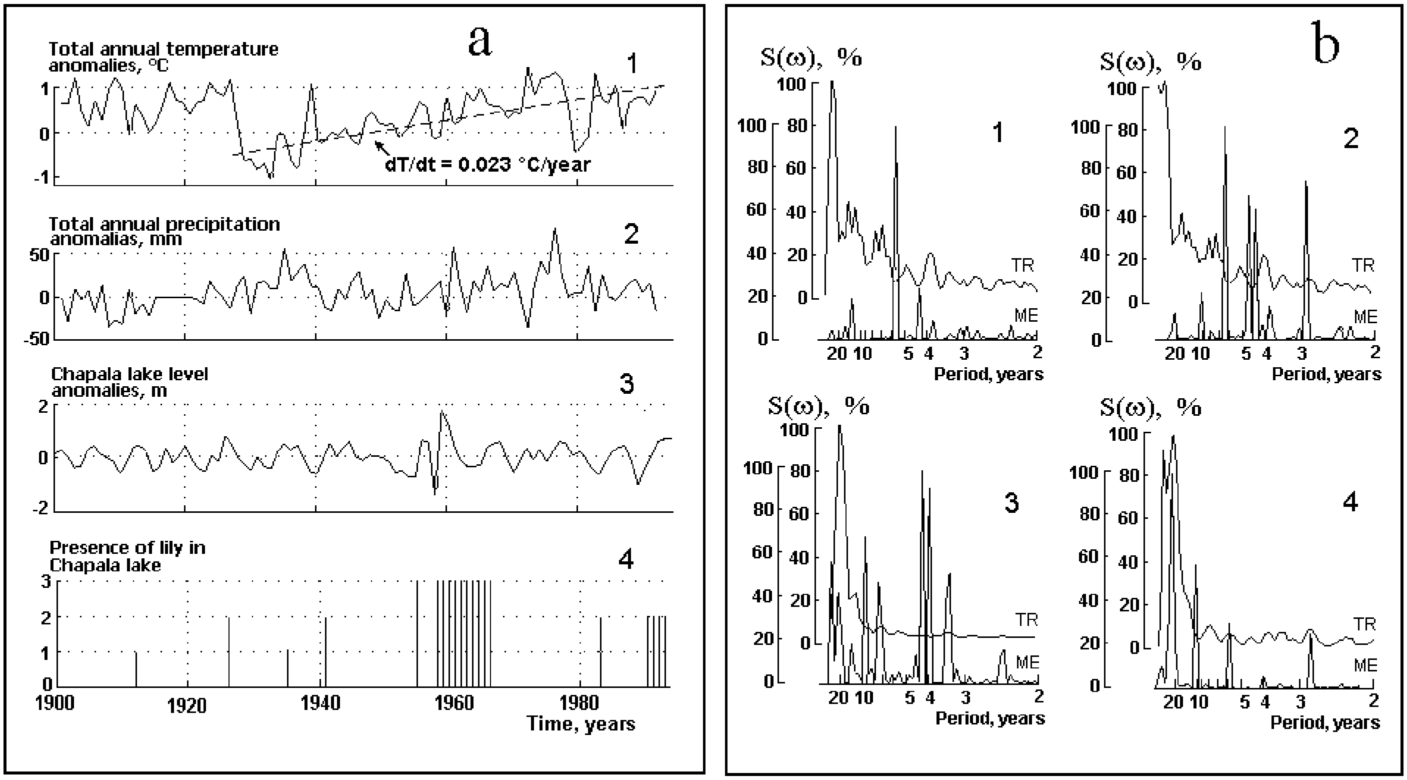

Fig. 4. (a) Time series of the average annual anomalies in (1) air temperature in degrees centigrade; (2) anomalies in precipitation in Guadalajara in millimeters; (3) anomalies in the level of Lake Chapala in meters; (4) time series that qualitatively characterize the presence of water lilies in the lake under the conditions: 1 - little, 2 - much, 3 - too much. (b) Normalized traditional estimate (linear) of the spectrum (TR) and estimate using Maximum Entropy (ME).

A major ecological problem of Lake Chapala is the sporadic outbreak of water lilies and other aquatic weeds, which destroy other forms of life in the lake and decrease its attraction for tourism. The weeds can cover more than 20% of the surface, forming large islands that drift by local wind action. Observations of water lilies in the lake have been made from almost the beginning of the century, which makes it possible to analyze the available information with the help of spectral analysis.

From qualitative indices for the presence of water lilies, we generated a time series of the data: 0- no weeds; 1- some weeds; 2- large outbreak; 3- extreme outbreak. This series is shown in Figure 4a. Usually the outbreak of water lilies began as the level of the lake rose to maximum values. Non-periodic outbreaks of water lilies existed before the intense anthropogenic contamination of the lake; thus it can be assumed that it is related to multi-annual variations in the level of the lake and to the volume of flow from the rivers that empty into it. During the years when the level of the lake decreased, the shallows dried out and nutrients accumulated there. When the level began to rise again nutrients in the ground were incorporated into the lacustrine cycle causing the outbreak of the water lilies. The intensity and duration of an outbreak is proportional to the preceding decrease in the level of the lake. Thus, for example, the longest and most intense outbreak in this century lasted almost 10 years (with a short interruption), followed by a ten-year of decrease until reaching a catastrophic low. In this time, the dry area was close to 270 km^2 (Simons, 1984). The second largest outbreak began in 1991 and continues to date. The dry area exceeds 130 km^2. If our hypothesis is correct, the present outbreak will continue a few years until the level of the lake reaches the mean multi-annual mark and interrupts the entry of nutrients to the water. The multi-annual variations of the amount of anthropogenic nutrients also influence the abundance of weeds. Such nutrients reach the lake through the river and the eroding of its shores from rain. However, there is no information that confirms this dependency at present.

Figure 4b shows the spectral estimates for the time series from group III. Three types of spectral estimates were calculated: traditional, maximum entropy and maximum likelihood. Due to the size of the initial series, the spectral estimates with the ML method differed slightly from the

Table 5

Periods (in years) of the predominant peaks in the spectra of the multiannual time series of the hydrometeorological characteristics and presence of water lilies in Lake Chapala (time series from group III)

Spectrum of the air temperature anomaly in Guadalajara		Spectrum of the air precipitation anomaly in Guadalajara		Spectrum of the lake level anomaly in Chapala		Spectrum of the presence of water in Chapala	
Traditional	Maximum entropy	Traditional	Maximum entropy	Traditional	Maximum entropy	Traditional	Maximum entropy
22.2	16	23	11	20.1	22	22	22
16.7	5.6	16.2	6.3	13	11.1	7.8	11
7.1	4.3	7.1	4.8	7.1	7.2	6	5.8
5		5	4.5		4.2	2.8	2.8
3.8		4	2.9		3.9		2.9
					3.5		2.4

Table 6

Values of the square function of the coherence, phase differences and mean square amplitude of the harmonics of the hydrometeorological characteristics and of the qualitative characteristic of the presence of water lilies in the lake during periods of (a) 7 and (b) 4 years (time series from group III).

	a					**b**				
	Anomalies in temperature	Anomalies in precipitation	Anomalie in the level	Presence of water lilies	Mean square amplitude	Anomalies in temperature	Anomalies in precipitation	Anomalie in the level	Prescence of water lilies	Mean square temperature
Anomalies in temperature		----	----	226 (4.7)	0.26		----	----	----	0.18
Anomalies in precipitation	0.22		215 (4.5)	----	12	0.28		206 (2.0)	102 (1.0)	9
Anomalies in the level	0.25	0.44		43 (0.8)	21	0.17	0.77		96 (0.3)	12
Presence of water lilies	0.45	0.07	0.68		----	0.43	0.84	0.81		----

* The values of the phase differences in parentheses are given in years.

traditional ones and for this reason they are not presented. The estimates of the ME method were calculated for the maximum length of the white filter $P = 36$, with the relation: $P=2N \cdot \Delta t/\lg(2n \cdot \Delta t)$, where N is the length of the series and Δt is the discretization of the data (Konyaev, 1990). The graphs show that the ME estimate outlines the details of the spectral density better than the traditional estimate of the spectrum. Table 5 shows the periods of the peaks in the spectral variations analyzed, based on both estimates. The interannual variations of all parameters present a wide range of periods, from 2.8 to tens of years. The characteristics of the cross-spectra were calculated for oscillations with periods of 7 and 4 years, since all the spectra are present in them. These estimates are shown in Table 6. Neither harmonic of the temperature anomalies correlates with variations of rainfall or lake level, but they do have upper coherence with the confidence with variations in the amount of water lilies. As expected, the variations in the lake level and the amount of water lilies present a very high coherence in both periods. The differences in phase show that the outbreaks of water lilies precede the maximum lake level by 9.6 months in a period of 7 years and by 3.6 months in a period of 4 years.

CONCLUSIONS

The climatic processes in the region of Lake Chapala and neighboring areas are exceptionally complex and variable due to their space-time scales. Unfortunately, the lack of reliable data makes it impossible to study the variability of the processes related to diurnal meteorological processes. These processes have a local character and are very sensitive to the orographic peculiarities of the area. The classic mechanism of atmospheric circulation above the lake is destroyed by the combined effect of the fog and angled winds. For a detailed study of these processes it is necessary to meteorological data at many point along the shore of the lake and at its islands. This may be obtained in short-term field expeditions during different seasons of the year. It is important to study the character and interaction of the fog circulation with the angled winds at different parts of the lake, especially the depth of penetration when headed towards land or lake and how the fog winds influence the dynamics of the water mass. It is particularly interesting to study the local peculiarities of the mechanism of energy transfer from the main diurnal harmonic to the high-frequency oscillations, and the role of a nonlinear transformation of the energy.

The processes that cause the seasonal and interannual variations of the hydro- meteorological parameters are on a large spatial scale. Estimates of energy spectra, coherences, phase differences and mean square amplitudes can be used as characteristic magnitudes for a neighboring area of the lake.

Finally, our hypothesis on the relationship between outbreaks of aquatic weeds and the inter-annual variations of the river discharges and lake level can be tested in the future with a mathematical model. Since the existing data are insufficient for obtaining the precise quantitative estimates with a model, new field measurements are needed.

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