THE LONG-TERM FLUCTUATIONS OF LAKE PEIPSI (TCHUDSKOYE) WATER LEVEL AND THE CONNECTION WITH A GLOBAL ATMOSPHERIC CIRCULATION AND WITH A SOLAR ACTIVITY.

(The Second International Conference on Climate and Water, Espoo, Finland,1998)

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Abstract

The relationship between solar activity and the water volumes of lakes is searched here by means of correlational and spectral analysis methods. The level of two lakes, Pactzcuaro in Mexico and Tchudskyoe in Russia and Estonia, together with solar activity indexes are used for the analysis. It is found that the source of the oscillation mechanism of the level of those lakes is the solar activity cycle through his influence on the magnetosphere and the terrestrial atmosphere. The present study allows for the development of long-period prognostic of water volumes of big lakes.

I. Introduction.

The problem of a possible relationship between the seasonal and the long period variations of different atmospheric, hydrologic and geophysical processes with heliophysical and cosmophysical processes has been discussed very often in the literature. Since 1937 L.A.Chijzhevsky had argued about the primordial role of the sun within the group of phenomena and mechanisms which are now known as the field of Solar-Terrestrial relationships (e.g. [Chijzhevsky, 1976]). At present there is no doubt that the cause of perturbations of different nature in the terrestrial atmosphere and hydrosphere are connected with heliophysical processes [Zatopek et al., 1976; Halenka, 1986].

In particular, the atmospheric circulation, responsible of several hydrophysical processes, is subjected to the action of the cyclic variations of the solar activity [Zilhs et al.,1987]. Such variations also control the geomagnetic activity and the temporal variations of cosmic rays intensity (e.g. [Dorman et al.,1987a; Ariel et al.,1986; Xanthakis et al.,1981; Feynman,1982, Chertkov, 1985]). Consequently, it is expected a complex intercorrelation of solar activity with all those mentioned phenomena [Dorman et al.,1987b; Novikov et al., 1984] including the processes which determine the water volumes of lakes (e.g. [Jaani, 1973; Reap,1981, 1986}]).

The goal of the present work is the search of correlational relationships with stationary and quasi-stationary dependencies between different hydrological, meteorological and cosmoheliophysical processes in order to be able of subsequent forecasts, as for instance, the average characteristics of the behavior of hydrological parameters [Janni,1973]. The existence of such relations are deduced from the mere comparison of the temporal variations of solar activity with: the volume of lakes [Jaani, 1973], the wind velocity in energetically active zones [Dorman et al.,1987a,b] and the intensity of cosmic rays at the level of the earth surface [Xanthakis et al.,1981; Dorman et al., 1987b; Novikov et al.,1984]. One of the processes that reflects the general state of the atmosphere, and hence the helioactivity behavior, is the cyclic variations of the volume of lakes [Jaani,1973]. The index to describe such a connection is the lake mean level in a determined period, preferentially in large lakes without leakage. In the search of the mentioned intercorrelations, we use in the present work the annual mean values of: the sunspots surface **(S)**, the level of Lake Tchudskyoe **(H)** in the period 1885-1987, the frequency **(P)** of strong winds in the Baltic Sea [Dorman et al.,1987a], the geomagnetic index **(K_P)**, and the cosmic ray intensity **(I)** at the station Kiel. The present study is based on methods of spectral and correlational analysis with recurrent filtration of data [Key and Marpl,1981].

II. Description of Lakes Pactzcuaro and Tchudskyoe

The lake Pactzcuaro is located between 19.5^{O} 32' - 19.5^{O} 34' of north latitude and 101.5^{O} 30' - 101.5^{O} 45' of west longitude, corresponding to the north-center of the state of Michoacan, in Mexico. The origin of the lake is connected to the transversal volcanic system that has been affected by a series of faults and sinks. The drainage pattern of this area is not integrated to any hydrological region, since the leakages are often canalized or infiltrated in the land. However, it may be consider that it has a centripetal-radial drainage, becausee most of leakages converge toward the timber-roof depression; though the lake vessel is placed very near to the hydrological region No.12 (Lerma-Chapala-Santiago) it is isolated from the large hydrological systems of the country. This situation provokes that the recollection area of the lake, which has been subjected during long periods of time to erosive processes rebounds in important obstruct processes in the lake vessel. The climate in the region is subhumid, with rains in summer, temperate, with an annual mean temperature oscillating between 16^{O} and 18.5^{O}C, annual mean precipitation between 700 and 800 mm and average leakage to the lake of 100-200 mm.

The Lake Tchudskyoe is one of the largest lakes in Europe, occupying the fifth place in water mirror surface (3,600 km) and the tenth place in Russia. The total surface of recollection including the lake, is 47,800 km^2. The collectible zone extends in the meridional direction almost 370 km, from 56^{O} 10' up to 59^{O} 30' of north latitude, with a mean width of 160 km (see, The Lake Tchudskyoe-Pskovskoe, 1983). The lake itself extends in the meridional direction almost 140 km, and is located in the quadrant of 57^{O} 5'- 59^{O} 01' of north latitude and 26^{O} 57'- 28^{O} 10' of east longitude. The lake consists of three different parts, whose differences are of morphometric nature in their respective regimens, although they form a sole water body [Jaani, 1987]. According to the mean lake level assumed in this work, 30 m in the Baltic system, the lake surface is 3,555 km^2 with a volume of 25.07 km^3 (see The Lake Tchudskyoe-Pskovskoe, 1983). This is a shallow lake, which mean depth is 7.1 m.

A detailed analysis of the cyclic oscillations of Lake Tchudskyoe was carried out by Jaani [1973], Welner [1929], Velner [1940], Eypre [1964, 1971]. Using the series of annual mean levels of the lake since 1885, and those of Lake Ladoga since 1859 (the holes in the data of this River were fulfilled by A. Jaani): it was found intersecular cycles with periods of 19 - 34 years (close to the so called Brikner cycles), and short period cycles with a mean extension of 5.1 years approximately. Furthermore, this author emitted the assumption about a relationship between the level of lakes and the 22 years cycle of the solar activity, and remarked a secular tendency to the reduction of such levels beginning from the years 20's. Quasibiannual cycles were not found in that study. As an intermediate mechanism A.Jaani analyzed the long period oscillations of the general atmospheric circulation (circulation of the Girs type) and found a similarity between the behavior of the level of Lake Tchudskyoe and the index of the Atlantic circulation of Vitels; a certain tetra-compass activity in the level curve is explained by the influence of several phenomena of the solar activity on the atmospheric circulation processes. Reap [1981] carried out the spectral analysis of the same series, detaching cycles (in years) of 6.1 - 6.4, 10 - 11 and 80 - 90, whereas in the series of floods of the Neva river detache cycles of 5.1 years (not very well defined), 6.1-6.3, 10.5-11 and 29.3 years. This author emphasizes (based on the work of Smirnov [1975] that in the case of the floods of the rivers of the north-east zone of the european territory of Russia, the minimum of the 10-11 years cycles is observed 1 to 3 years after the maximum of solar activity, while the maximum of the river floods occur 2 to 4 years before the maximum of solar activity.

Analogous dephasages of different processes are observed in the study of correlations between meteorological phenomena and solar activity, with different shift magnitudes in different periods of the solar cycle; according to Gulinsky et al. [1988] such a magnitude is higher in the descending period of solar activity. The study of the dephasage between the atmospheric properties and the solar activity shows a magnitude of 1 to 4 years for different cycles of solar activity [Dorman et al., 1987a]. It is worth to mention the fact that both phenomena are in opposite phases [Dorman et al., 1987b; Novikov et al., 1984; Reap, 1986; Jaani, 1973]. The determination of the hydrologic dephasage relative to solar activity, and the determination of the laws of variation of such shift leads to the development of quantitative long period prognostic of the water volumes of big lakes.

III. The Basic Formulation for the Spectral Analysis

For the determination of the dephasages, the precision of their magnitudes and the study of the general cyclicities in the data of water volumes of lakes and solar activity, we have employed the traditional methods of spectral analysis, assuming a quasi-stationary status of the processes under consideration.

The spectral methods have been widely described by Key and Marpl [1981]; here, we will limit us to a brief description of the basic formulae of our concern. To search for general cycles in data series we use the Blackman-Tiuki method, based on the Fourier transform of the correlation function of the original process $\{x(n)\}$.

To obtain the cross estimations (i.e., for the determination of common cycles to all the processes) we employed the methods of cross spectral analysis [Key and Marpl, 1981], which allows the estimation of the cross spectral amplitude **(A)**, the phase spectrum **(F)** characterizing the shift between the analyzed processes at different frequencies and the coherence spectrum **(K)** determining the correlation degree of the series at different frequencies.

The reliability of the obtained results was controlled by means of the simultaneous application of different spectral analysis methods and special procedures: data filtering, widening of the spectral windows, and others, as well as the calculation of the maximum value of the cross correlation coefficient with respect to the shift used to obtain the estimations of dephasage between the processes $\{x(n)\}$ and $\{y(n)\}$ [Key and Marpl, 1981].

Furthermore, the reliability of the obtained estimations was controlled by applying the spectral analysis methods to the test data, in particular to the velocity of the wind in the Baltic Sea and to the $\mathbf{K_P}$ index, corresponding to the same periods of analysis of the water volumes of Lake Tchudskyoe [Dorman et al., 1987a; 1987b].

IV. Procedure and Results of the Spectral Analysis

The analysis of the spectral characteristics was made with the series of the annual mean values of solar activity, water volume of Lake Tchudskyoe from 1885-1987; the $\mathbf{K_P}$ index from 1920-1984, atmospheric characteristics from 1934-1985 and the cosmic ray intensity from 1947-1987 (ionization chambers). The length of the studied series (with the possible exception of that of cosmic rays) allows with reliance to determine the quasibiannual [Gulinsky et al., 1988}] up to the secular [Jaani,1973] cycles; the application of the spectral methods permits to estimate not only the shift between the different processes but also among each one of the cyclic components of each particular process (with relation to S). From the mentioned statements a number of conclusions can be drawn that agree with the results obtained previously by Jaani [1973]: the cross correlation functions of the initial series present well defined cycles: one of 11 years and another of secular nature [Libin, 1997a,b]; a way to test the later is the extinction time of the series **H(t)** of these processes, which varies between 80 and 90 years; the correlation function of the water volume series H shows a clear cycle of 22 years, and has its reflection in the cross correlation functions of the filtered data by the Gauss technique: moving average of 7 years with coefficient of Gauss, the presence of a 11 years cycle can be seen clearly in the correlation functions of [Libin, 1997c], after the application of the First Differences filtration technique (smoothing the tendency); the maximum of the cross correlation function was obtained by shifting the series **H** relative to the series **S** in 2 and 3 years [Libin, 1997d].

The calculations of the cross correlation functions of **H** and **P** show a good agreement with the results of [Gulinsky et al., 1988]: the notorious dephasage between **H** and **P** agrees with similar results for the series of **P** and Wolf numbers **W** [Dorman et al.,1987a]. The calculations of the cross correlation functions between solar activity **(S)** and geomagnetic activity **(Kp)** shows a dephasage of about 1-2 years among them, in the course of time. Besides, the cross correlation analysis between **H** and **Kp** reveals a delay of the water volume in 1-2 years (the processes result in opposite phases), which agrees with the delay of **H** relative to **S.**

The calculation of the power spectrum of each one of the analyzed processes shows the presence of a complex structure, in particular in the zones of high frequency (periods of 2-6 years), as well as the existence of variations of 2-3 years, 11 years, 22 years and secular variations in both the water volume and solar activity data. The obtained results coincide quite well with the results of other analysis of different geophysical and heliophysical processes carried out in recent years [Ribin,1985; Dragan et al, 1984}; Olh et al, 1985}; Bazilievskaya et al, 1984]: the spectral analysis of the solar activity, the geomagnetic field, heliospheric pulsations and atmospheric pulsations reveal similar periods. The analysis of the cross spectra show that in the time series of the water volume of Lake Tchudskyoe, four cycles can be distinguished, that can be trustily related with solar activity and atmospheric processes:

The quasibiannual period, which is possibly related with the quasibiannual variations of the solar wind, as well as with the corresponding temporal variations of atmospheric pressure and temperature [Djzhaniashville et al., 1985]. It should be emphasized that though such interpretation of the quasibiannual variations of the water volume of Lake Tchudskyoe is of preliminar character, however, the correlational link ($r \sim 0.7$, $K^2 \sim 0.6$) make such explanation highly probable.

The 11 years cycle, related with solar activity (either with the surface of sunspots, **S**, or with the Wolf number, **W**) is also present in the water volume through analogous oscillations of the earth climate [Gulinsky et al.1988; Olh, 1985; Plakhotniuk, 1980; Vitinskiy et al., 1986}]. In fact, the comparison of the power spectra of the water volumes of Lake Tchudskyoe with analogous spectra of atmospheric parameters [Dragan et al., 1984] shows, not only a good coincidence of relevant peaks, but also a high degree of correlation among them: $\mathbf{r \sim 0.7}$ between **H** and **P** ($K^2 \sim 0.6$); $\mathbf{r \sim 0.9}$ between **H** and **S**; K(tau) ~ 0.9 ($K^2 \sim 0.8$).

The 22 years cycle, prevailing in the water volume variations and standing out in the power spectra [Perez-Peraza, 1997a] and in the correlation functions [Perez-Peraza, 1997b]. This cycle coincides with analogous cycles in climatic data. Rojzkov, [1988] presents the spectral analysis of a 1000 years series, corresponding to a index which describes the rate of the Deuterium content relative to Hydrogen in the annual rings of trees (the variation of this index is proportional to the variation of the atmospheric temperature). As a result, it was obtained a period of 22.36 pm 0.04 years, very close to the 22 years cycle of the solar activity related with the evolution of the general solar magnetic field. The closeness of both cycles in the water volumes, in the atmospheric characteristics and in the solar activity is an argument supporting their intercorrelation. It has been shown by Olh [1975] that the 11 years solar activity cycle, characterizing the evolution of sunspots has a weaker influence on meteorological and climatological processes than the 22 years cycle of inversion of solar magnetic field. Both the 11 and 22 years cycles show a high reliability: r ~ 0.7 between H and S; r ~ 0.75 between H and P (K(tau) ~ 0.5). It must be emphasized that the presence of the 22 years cycle of the solar activity on the earth climate has, as a general rule, a regional nature [Olh,1983], that is, the climate variations related with the cycle of 22 years have different amplitudes and opposite phases in different regions of the planet. It is interesting to note that the cross phase spectra between H and S for one side, and P and S by other side, give close results with little time variation, which seems to reveal the existence of a general mechanisms for the appearance of the 22 years variations in the water volumes and in the atmospheric parameters.

The secular cycle (80-90 years), which is observed in the power spectra in the form of a small amplitude peak in the zone of low frequencies [Libin,1997d] is discernible due to the attenuation of the correlation function of the water volumes H [item]. The calculation of the correlation coefficients for the secular variation of the water volumes confirm the statistical significance of the observed peak (K(tau) ~ 0.6; K(tau) ~ 0.4), although its determination by traditional methods has certain methodological difficulties.

Y. Autorregresive Analysis to Improve the Reliability of the Results

It must be remarked that the calculations associated with the oscillations of Lake Tchudskyoe [Libin,1989] need a very extensive computer time. For this reason, in the process of comparing the spectral and temporal characteristics of the oscillations of both lakes, when the results of the spectral analysis (Blackman-Tiuki type) coincide the calculation was not repeated for the level oscillations of Lake Pactzcuaro. Besides, it must be kept in mind that the cross power spectra give confident estimations of the intercorrelations among the observed processes, which allows to estimate the shift among them. However, the reliability of a series of relations is just in the limit of reliability of the obtained results, so that, to certain extent, it is the skill of the investigator that plays the main role in the selection of the analysis methods,. and the estimation of the truthfulness of the results. For this reason, in subsequent analysis we used the autoregressive spectral analysis (ARSA), described recently by Yudakhin et al. [1991] and Libin and Jaani [1989]. The main difference between the ARSA and the standard methods states on the possibility to apply the ARSA to quasi-stationary processes (as the series analyzed here), and on the possibility to estimate intercorrelations between the analyzed series, with a reliability of 100 % in the frequency space. However, it must be reminded that the amplitudinal estimations obtained with the ARSA are relatives, i.e., though their temporal behavior is absolutely comparable, however, it cannot be related to the initial series. In other words, even if it is not possible to relate the calculations of the amplitudinal spectra to the original data in an absolutely exact form, their temporal dynamics may be reproduced in univocal manner.

The analysis of the oscillations of the levels of Lake Pactzcuaro (in Mexico) and Lake Tchudskoe (in Russia), as well as the oscillations of solar activity were carried out on the basis of monthly and annual series: in particular, from december 1921 to january 1993 for Lake Tchudskyoe, and from january 1950 to january 1993 for Lake Pactzcuaro. The methodology for the calculation of spectra by means of autoregressive (AR) models leads to obtain the correlation functions, the cross correlation functions, the symmetric part of the correlation functions, and both the symmetric and asymmetric parts of the cross correlation functions, and on those basis to proceed to the determination of the order of the AR model for the analyzed series. Using the results obtained in this way, the residual dispersion of both series is determined, and finally, the definitive orders of the AR and MA (number of equations) of the models for each series is obtained.

The result of the calculation of the spectral characteristics of Lake Tchudskyoe by means of AR-MA models of order 5-7, for the period 1921-1932 shown is important to remark now, that results clearly reveal oscillations of Lake Tchudskyoe with periods of 1.5-2.0 and 9.06 years, all of them related with solar activity. Analogous measurements for the period 1932-1943, 1943-1953, 1953-1985 and 1986-1997, show similar results, that is, periodicities of 2 - 4 and 8 - 9 years, also related with solar activity.

To be convinced of the precision and reliability of the obtained estimations, it was decided to carry out the complete autoregressive analysis of the oscillations of the studied lakes, and the solar activity, in the following order: **1st.** AR-MA analysis of the oscillations of both lakes for the period 1950 -1997; **2nd.** AR-MA analysis of the oscillations of Lake Tchudskyoe and solar activity for the same period; **3rd.** AR-MA analysis of the oscillations of Lake Pactzcuaro and solar activity for the same period.

In **Figs. 1a,b** it is shown the behavior of the level of lakes in the period 1950-1997. At least two remarkable features stand out from both figures: the evidence of a variation of 22 years, and that the oscillations of the level of both lakes are in opposite phases. The calculation of the cross correlation functions between the two lakes support those conclusions: it can be seen in **Fig.2** a clear anticorrelation (~ 0.6), with a delay of 1 to 2 years in the annual series.

The autoregressive analysis of the variations of Lakes Pactzcuaro and Tchudskyoe in the annual means **(Figs.3)** reveals the presence of oscillations with periods about 4, 11 and 22 years in the course of all the analyzed period. A high resolution of spectra in the region of low frequencies led to separate the waves of 11 and 22 years, resulting with amplitudes completely comparable. On this basis, the periodicity of 22 years was artificially eliminated in subsequent calculations. The calculations shows the dephasage between the oscillations of both lakes and showing that the coherence of both processes is particularly high, of the order of 0.8 for the oscillations of 22 years, about 0.6 for the 4 years and about 0.3 for the 11 years oscillation. The comparison of the amplitudes shows a relative elevation, 2-3 times, in the oscillations of Lake Tchudskyoe with respect to the Lake Pactzcuaro.

The AR-MA analysis of the levels of the lakes and solar activity allows to draw a number of important conclusions, for further calculations. In [Libin,1997a-d] it is presented the results of the AR-MA spectra of amplitudes of solar activity in the period 1950-1985 and 1950-1996. The comparison of these spectra with those of the lakes reveals an absolute coincidence in the presence of the oscillations, mainly for those with periods of 4 years. The cross amplitudinal spectra of the levels of both lakes and the solar activity, the coherence spectra, as well as the phase spectra confirm the mentioned conclusions about the behavior of both lakes, and in addition they confirm, in an univocal form, the solar origin of the 9-11 years oscillations (in agreement with the solar activity cycle) and the 4 years oscillation, all this with a coherence coefficient of about 1.

VI. Conclusions

The obtained results show good coincidence with the results of similar calculations for essentially distinct correlational windows (as those of Barttlet, of Jinchin and of Berg) by using recursive filters of Battervort, which have spectral properties that are also significantly distinct. As a matter of fact, the employment of recursive filters gives good results for the estimation of power spectra by means of autoregressive models. However, that is out of the scope of the present work and shoul be studied by an independent analysis.

Hence, the correlational and spectral analysis of the data of the level of Lake Tchudskyoe have confirmed: the proposed relation between water volumes and solar activity [Jaani, 1973; Reap, 1981], the existence of water volume variations of Lake Tchudskyoe of statistical significance with periods of **2.6, 11.2, 22** and **80-90 years** and the dephasage of **H** relative to **S** oscillates from 1 up to 3 sim 4 years, depending on the solar activity cycle. For the odd cycles, the maximum of the water volume delays in two years relative to the minimum of solar activity. For the even cycles, the delay is around 3 years. It must be remarked that the structure of water volume histograms for even and odd cycles is different, which also supports the thesis of a prevailing 22 years periodicity in the atmospheric and hydrologic processes.

The employment of all the spectral mathematical formalisms existing up to date, and the confrontation of results of different calculations show that the source of the oscillation mechanism of the level of closed lakes (of the type of the Lake Pactzcuaro in Mexico, Lake Tchudskyoe (Peipsi) in Russia and Estonia, the Caspio sea in Russia, or the Great Lakes in United States of America) is the solar activity cycle, through his influence on the earth magnetosphere and atmosphere. The obtained results lead (in an autoconsistent manner) to the development of an autoregressive model to forecast the oscillations of lakes [Dorman, 1987a,b; Perez-Peraza, 1997].

It is possible that in the future, some ecological disasters (as those of the Caspio sea in the years 80's, and Lake Tchudskoe in 1924) may be avoided on basis to scientific prognosis. However, it is necessary to take into account that no scientific prognostic can substitute the good common sense of people and governments; otherwise, in spite of excellent forecasting models, new ecological catastrophes may occur as that of the Aral Sea in Turkmenia and Uzbekistan.

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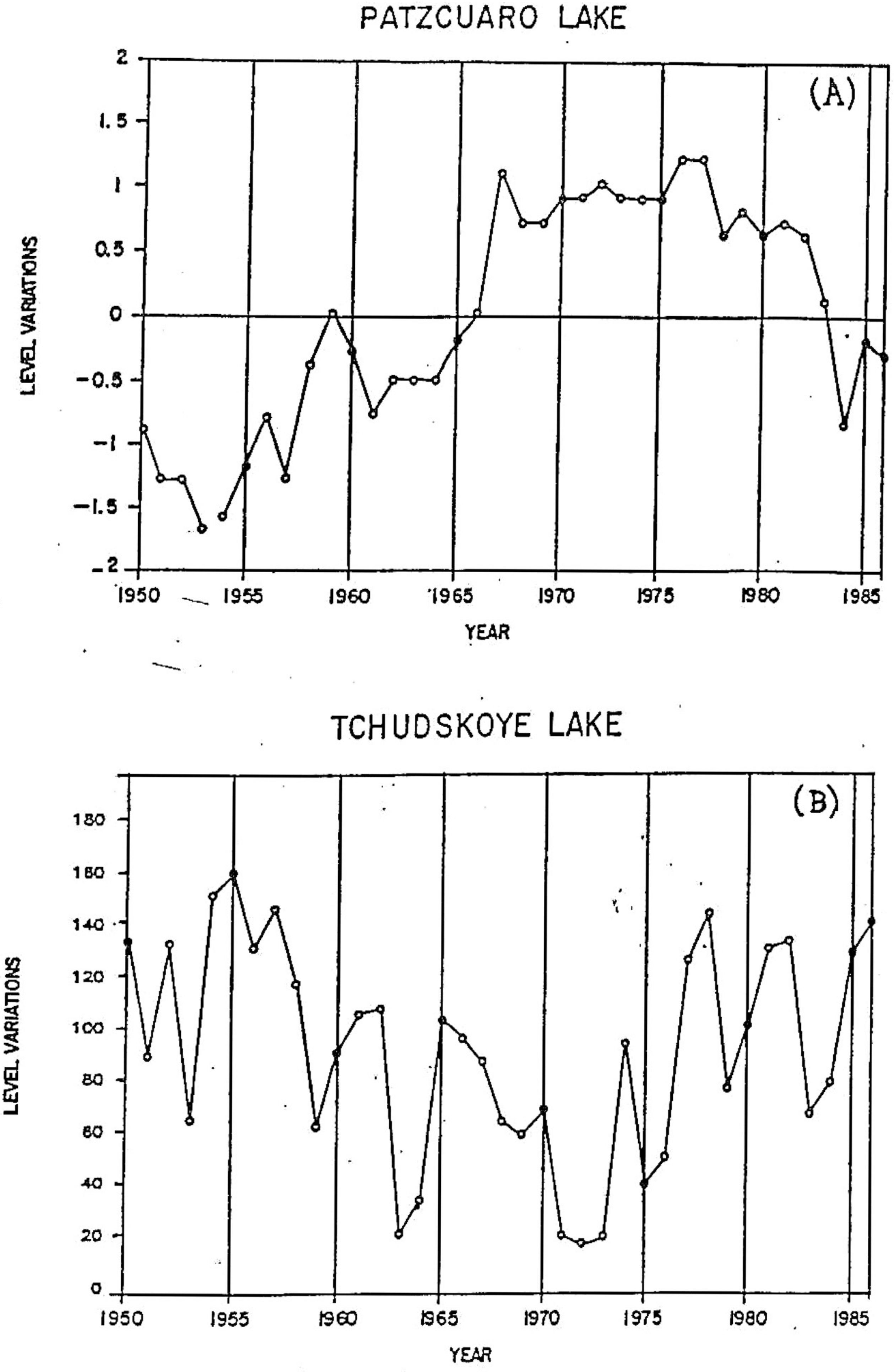

Figure 1. Mean annual water level of lakes: (A)

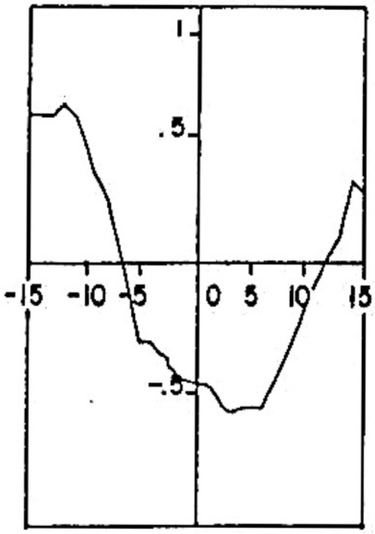

Figure 2. Correlation function between mean annual level of Lake Pátzcuaro and that of Lake Tchudskyoe.

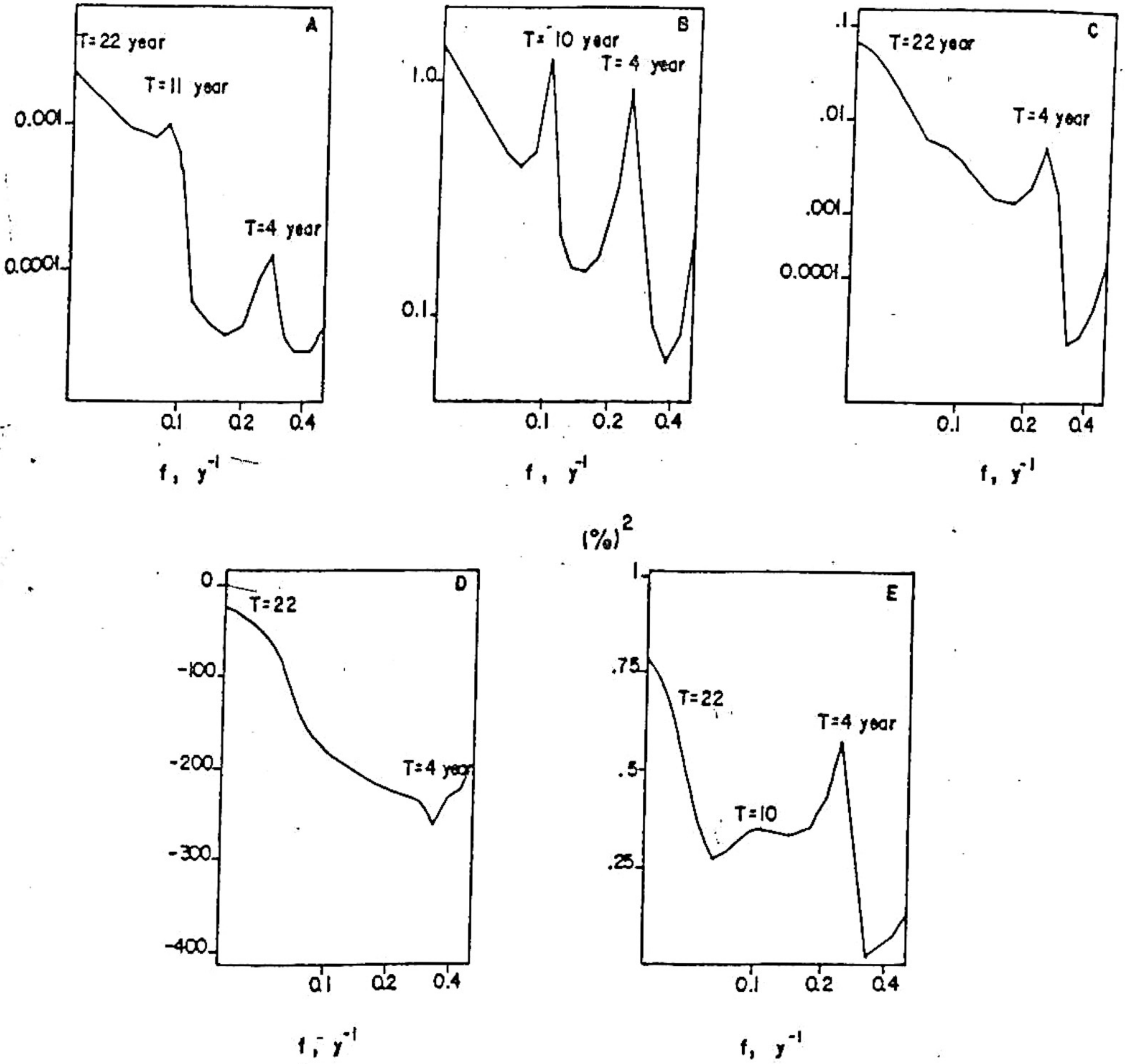

Figure 3. Autoregressive analysis of the mean annual level of both lakes: (A) the amplitude spectrum of Lake Patzcuaro; (B) the amplitude spectrum of Lake Tchudskyoe; (C) the cross amplitude spectrum: (D) the cross phase spectrum; (E) the cross coherence spectrum.