# Solar-Terrestrial interaction: case study of Caspian Sea level changes

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**Abstract.** The results of the analysis of the average annual values concerning the Caspian Sea level, obtained according to the ground and satellite observations, and also the corresponding characteristics of solar activity, earth's magnetic field and a length of day are presented. Spectra of the indicated processes are investigated and their approximation models are also built. Previously assumed statistical dependence between space-geophysical processes and Caspian Sea level (CSL) changes is confirmed. Close connection is revealed in the low-frequency models of the solar and geomagnetic activity change with the sea level. Prediction to the next decades shows the high probability of an increase in CSL and decrease of the compared space-geophysical parameters.

**Key words:** solar activity, Caspian Sea level, Sun-Climate relationship, Forbush-effect, Lenght of Day

## 1. Introduction

The problem of the search for the causally investigation connections of changes in the Caspian Sea level and space-geophysical characteristics has long-standing history. Many researchers noticed correlations between different outer factors of extra-terrestrial origin and the nature of the Caspian Sea Level (CSL) changes. Assumptions about the connections of terrestrial processes with the solar activity were expressed by Russian researcher A.L. Chizhevskiy in the first half of last century (Tchijevsky A.L., 1938). For the first time Berg (1934) focused attention to the connection of CSL changes with the solar activity. In the second half of the XX century the connection of climate changes with the rotational regime of the Earth was first paid attention to. Active studies in this direction are carried out by N.S. Sidorenkov (1978).

The instrumental data about the height of CSL cover a time interval almost during two centuries. Prior to the beginning of the 90's the behavioral inquiry of Caspian Sea was accomplished according to the observational data at the tide gauges. These data were used for the analysis of the connections concerning CSL changes together with the geophysical factors. The most complete results of this study are represented in the Solovyeva's work (Solovyeva N., 2004).

The need for multi-disciplinary approach to the behavioral inquiry of the Caspian Sea Level (CSL) for long time intervals is noted, particularly, by Naderi Beni A. et al. (2013).

Today instrumental data time series is supplemented substantially due to the satellite altimetry measurements. In Fig.1 the number of the yearly mean values of CSL are represented.

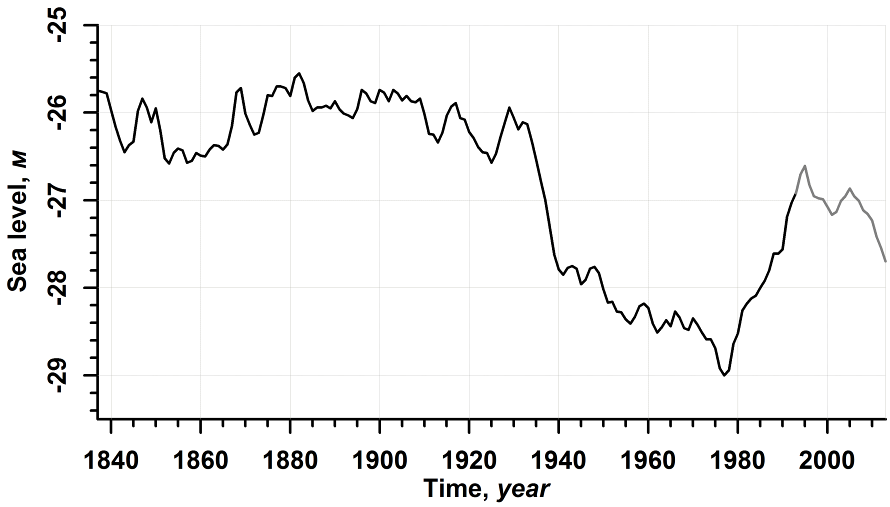


**Fig. 1.** The yearly mean values changes of CSL. The tide gauge data are shown black, gray - observations of satellite altimetry.

Since the end of 1970's prior to the beginning of 90th CSL experienced catastrophic rise with a more than decimeter per year. This led to an intensive water-tables elevation of the coastal territories, where active building took place during the previous decades. From the quick ascent of the level many cities suffered. The reliable prediction of the behavior of CSL was an actual problem at the beginning of the 90ies. To the problems of study the Caspian Sea and its politico-economic status the special International conference was dedicated "The Caspian Sea-95" Caspian Sea: the economy, ecology, mineral resources, Moscow, 20 June 23, 1995.

At the conference, in particular, the models and forecasts of the tendencies of changes in the level of the Caspian Sea were discussed. The smallest number of researchers assumed a beginning of a decline level period in the near future after the rapid increase of 1977-1995. This scenario came true for the following year after conducting the conference.

The kinematic model, developed by V.I. Kaftan was one of the justified forecasts. It was presented as a report in the First international seminar: Stresses in the lithosphere (global, regional, and local). It was held in the Institute of geology and exploring of combustible minerals (IGIRGI, Moscow) in 1994 a year before the sharp reversal of changes in sea level (Kaftan V.I., 1994). Two versions of the models, whose extrapolation was qualitatively confirmed by the behavior of the level, are presented in Fig. 2. The model was a trigonometric polynom of order n, which consists of the sum of linear trend and of n sinusoidal components (harmonics). After comparing the forecast (Fig.2) with real data of Fig.1, it is possible to see the quality of the forecasts. Let us note that the model of 15th order showed even the short-term special features of level changes, registered later. The forecast was justified with respect to a change in the tendency level dynamics, but the absolute value of the level was predicted with an error more than 0.5 m.

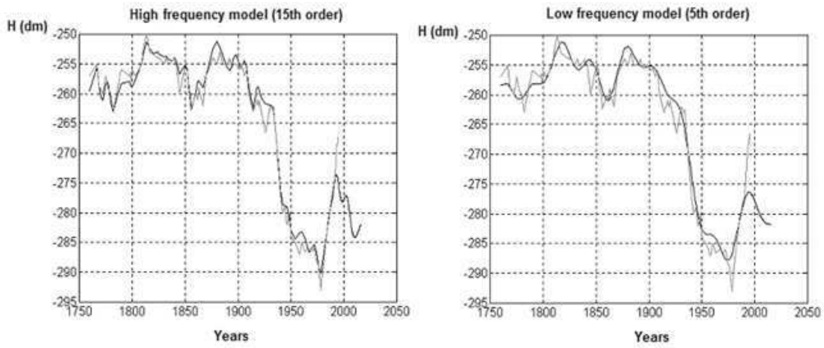


**Fig. 2.** Kinematic models of CSL changes - black line. Grey line shows the motion of the measured average annual values of level, obtained according to the observational data at the level posts.

The corresponding approximations of changes in the solar, geomagnetic activity, Earth rotation velocity and other geophysical characteristics were the additional demonstration for the degree of reliability of the obtained models concerning the CSL changes. It was shown that the solar and geomagnetic activity changes occur with close oscillatory periods, but in antiphase with CSL changes (Kaftan V. I., 1995, 1996; Kaftan V. I., Tatevian S. K., 1996). 11yr oscillations in the level changes were not detected.

Satellite missions ensured obtaining of new data in the subsequent decades (Cazenave A. et al, 1997; Lebedev & Kostianoy, 2004, 2006, 2008). Till now the satellite observations cover more than 10% of the total instrumental observations period. This provides the opportunity to approach the simulation of cumulative data at a qualitatively new level and to carry out their combined analysis. Furthermore, many space-geophysical characteristics compared with CSL during the recent decades were also obtained on the basis of the observations of space missions, higher than before by accuracy and details. The content of this publication is presented by the results of the analysis of historical and contemporary observation for the purpose of finding out the correlations between CSL changes and space-geophysical processes, by contemporary concepts about the reasons for CLS changes, as well as their simulation and prediction.

## 2. Observation data

In joint analysis some kinds of observational data, represented by the time series of corresponding average annual values, were used.

The yearly mean values of the normal heights of the average Caspian Sea level (CSL) have been calculated by a colleague from the State Institute

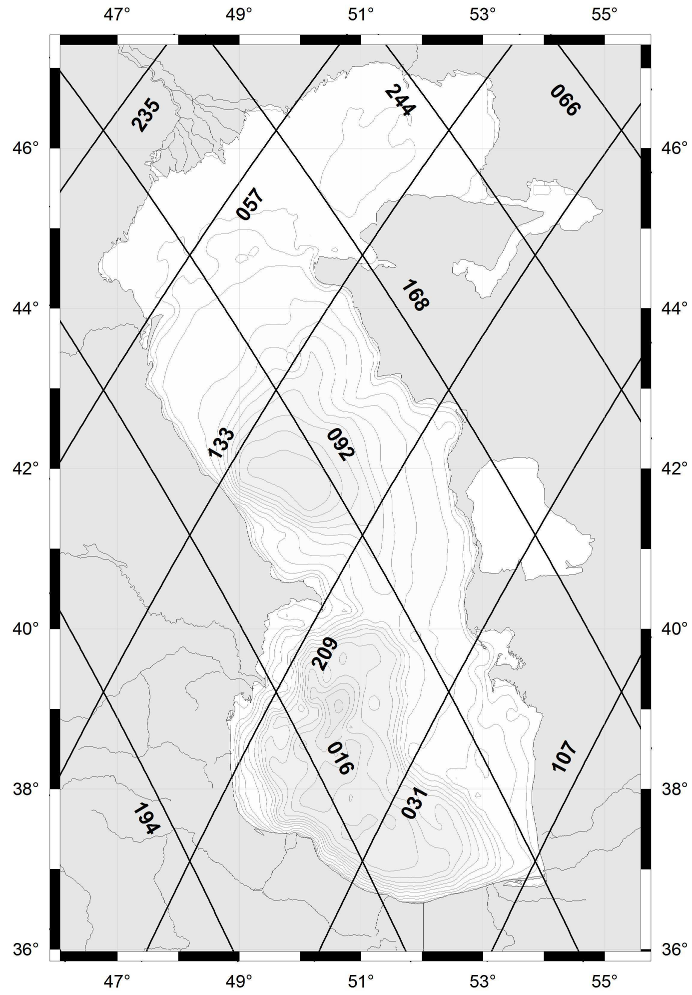


**Fig. 3.** Trajectory of the satellites of the missions TOPEX/Poseidon, Jasson-1 and Jasson-2 missions, which are used in the analysis (black heavy lines).

of Oceanography of the Russian Federal Service on Hydrometeorology and Environmental Control (Rosgidromet) - S.V. Pobedonostsev, employing the author's procedure (see Pobedonostsev S.V., 1987). The yearly mean CSL values, obtained on the base of the tide gauge observations, covered the interval of 1837-1994. The geodetic heights average CSL according to the observations of satellite altimetry were obtained employing the procedure (Lebedev S. A., 2012) for the interval of 1992-2013. In the analysis, observational data of the TOPEX/Poseidon, Jasson-1 and Jasson-2 satellite missions were used. The tracks of the satellites are shown in Fig. 3.

Two types of factors were taken into consideration in the study: 1) External space factors - solar activity and the connected with it changes of geomagnetic activity; 2) Geodynamic factor - the influence of the Earth rotation regime over the redistribution of the ground-based and underground water masses.

The first group of factors was represented by: 1) the annual Wolf's number values (SSN). They were taken from the Solar Influence Data Center (SIDC) database WDC-SILSO, Royal Observatory of Belgium, Brussels http://sidc.oma.be/silso/datafiles; 2) The Group sunspots numbers (Hoyt D.V. & Schatten K.H., 1998) from the NOAA National Geophysical Data Center http://www.ngdc.noaa.gov/stp/solar/ssndata.html;
3) The geomagnetic AA-indices- from NOAA National Geophysical Data Center
http://www.ngdc.noaa.gov/stp/geomag/aastar.html.

The Earth rotation velocity variations were represented by the values of the excess of the length of the day (so called LOD-index), represented in the International Earth of Rotation and Reference Systems Service, service bulletins (EOP C01 1846-now) http://www.iers.org/nn_10968/IERS/EN/DataProducts/EarthOrientationData/eop.html.

The lengths of time series used in the analysis were limited to the intervals, indicated in the table.

**Table 1.** Used data series

| No | Characteristic | Time interval |
|---|---|---|
| 1 | Caspian Sea level heights | 1837-2012 |
| 2 | Wolf numbers (Ri) | 1700-2013 |
| 3 | Group sunspot numbers (RG) | 1730-2000 |
| 4 | Geomagnetic AA-indeces | 1868-2011 |
| 5 | Length of day excess (LOD) | 1837-2013 |

## 3. Used time-series analyses techniques

For primary diagnostic analysis of the spectral structure of the obtained time series a standard Wavelet analysis was used. As a mother function a complex Morlet wavelet with parameter $\omega_0 = 6$ was applied. The evaluation was executed by the use of Matlab routines based on the special software freely available by C. Torrence and G.P. Compo (Torrence, C. and Compo, G.P., 1998) at http://paos.colorado.edu/research/wavelets/.

To investigate in more detail the determined periodic oscillations, especially in the low frequency range, and to build the models under investigation of physical processes two procedures were used. These are: the

TR-periodogram analysis of B.P. Komitov and Sequencing analysis of the dominated harmonics (Dominant-analysis) of V.I. Kaftan.

TR-periodogram analysis makes it possible to select approximating function for the time series $F(t)$ as a superposition of periodic component of the type

$$\varphi(t) = A_0 + a\cos(2\pi t/T) + b\sin(2\pi t/T),$$

where $t = 0, 1, 2...$ - corresponding moments of time, $A_0$ the average value in the time series, $a$ and $b$-parameters of fluctuation which are obtained on the base of least square procedure for every fixed value of $T$. The last one is varying from $T_0$ to $T_{max}$ with a step $\varDelta T$. For each of the derived functions $\varphi(t)$ the correlation coefficient $R$ with respect to the time series $F(t)$ is calculated. The local maxima of $R$ are indicated for the possible existence of periodical sinusoidal components by durations equal to corresponding periods $T$. Statistical significance of the cycles is estimated by using the formula

$$\sigma_R = (1 - R^2)/\sqrt{N}$$

where $N$ is the number of terms of time series.

The TR-periodograms technique is detailed in (Komitov B., 1986) and (Komitov B., 1997).

The Dominant-analysis technique is based on step by step approximation of studied time series $y(t)$ through trigonometric polynomial function

$$y(t) = \sum_{j=1}^{n} \left(M_j + A_j \sin(\omega_j t + \phi_j)\right), \tag{1}$$

where $M_j$ is the ordinate of an oscillation axis of the $j^{th}$ harmonic, and $A_j$, $\omega_j$, and $\phi_j$ denote the amplitude, the angular frequency, and angular phase of the $j^{th}$ harmonic, respectively. These four coefficients of a harmonic are determined by the iteration least square method. The method allows to determine the root mean square errors for every harmonic coefficient separately. A description of the technique is provided in (Kaftan V., 2012).

## 4. Results and interpretation

### 4.1 Wavelet diagnostic

For the investigated time series wavelet-skeylograms and global spectra of the power of the desired fluctuations were obtained and compared. The results are represented in Figs. 4-5. The upper number of images in figures 4-5 contain skeylogramms of the studied processes; the lower number demonstrates the global spectra of the signal power.

The results of the comparison testify about the presence of close periods in the behavior of both the Caspian Sea and solar activity in the low-frequency part of the spectra. There are peaks of power spectra in the range of approximately 100 and 200-year cycles of fluctuations. It is remarkable,

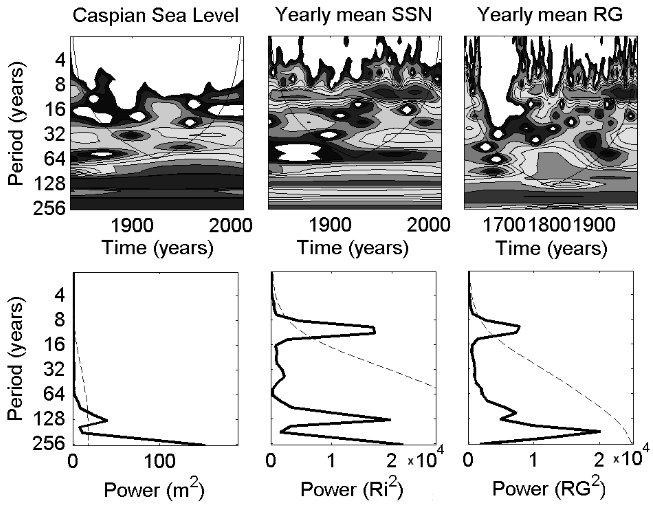


**Fig. 4.** Comparison of the results of the wavelet-analysis of the solar activity series (second and third columns) and CSL (first column).

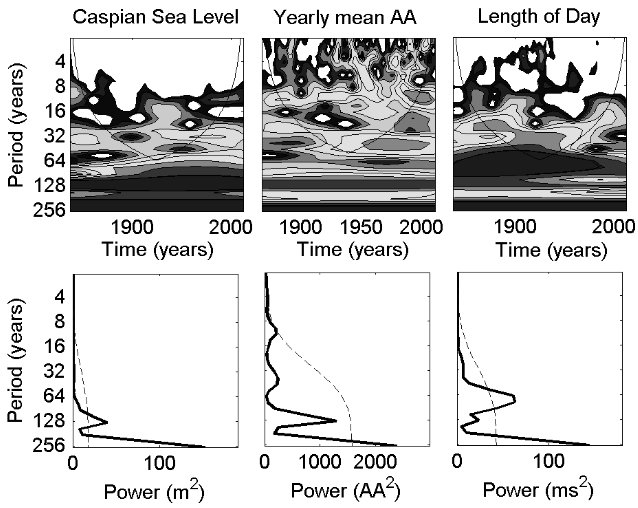


**Fig. 5.** Comparison of the results of the wavelet-analysis of the data about changes in the geomagnetic field changes (AA-index) and LOD (second and third columns, respectively) and Caspian Sea levels (first column).

that an activity of high-amplitude fluctuations is not discovered in Caspian Sea level in the range around the main 11-year solar cycle.

The geomagnetic activity, just as the solar one, manifests proximity with the behavior of CSL in the region of centurial and super-centurial cycles as well as 11yr cycle. LOD also has shown quasi-centurial cycles in its spectral structure, but it has demonstrated independent oscillation of $\sim$ 60yr too.

## 4.2 Hidden periodicity revealed by the use of Dominant and TR-periodograms analysis techniques

In what follows the methods for detecting of hidden periodicity we will call for convenience method 1 and method 2, for Dominant and TR-periodograms analysis, respectively.

By using these methods the spectra of physical processes were investigated and compared. The mutual compatibility of the obtained spectra is demonstrated in Fig. 6-7. In the figures the continuous correlation coefficients spectra of method 2 is represented by continuous dotted line. The rectangular boxes present the discrete amplitude spectra of the most probable value areas for the spectral components, obtained by the method 1. The center of rectangle fixes the most probable value of the period (x-axis) and the amplitude (y-axis). The boundaries of the rectangular ranges fix the confidence intervals of $\pm 2\sigma$. It is obvious that the low-frequency cycles possess the greatest uncertainty. The comparison of the spectra shows their essential similarity, especially, in the high-frequency range. In the low-frequencies differences are observed. This is especially noticeable in the range of periods with the duration from 100 to 200 years and more. Such are the divergences for LOD-index too (Fig. 6, a, b, c).

The absence of clearly expressed 11-year cycles, which have high amplitude in sunspot and geomagnetic activity, is a remarkable feature of the CSL and LOD series. This special feature is known by researchers in the field of solar- climatic relationships and it has been noted, for example in Ogurtsov et al, (2002), Solovyeva N. (2004).

In view of the fact that the high-frequency fluctuations of solar and geomagnetic activity are not expressed in CSL data series, the subsequent analysis was carried out taking into account this special feature.

By comparison of the spectra, obtained by methods 1 and 2, noticeable differences for harmonics of the lowest frequencies (the centurial and super-centurial variations) were discovered.

## 4.3 Model simulations

Approximating models were built to find the hidden periodicities by using of methods 1 and 2. The models were the trigonometric polynomials of form 1 for method 1. A special feature of the approximating model 2 is the use of a united common ordinate $A_0$ for all members of polynomial, whereas in model 1 a similar characteristic of $M_j$ for each of the periodic components is taken. At the present moment it is difficult to judge the better or worth validity of each of the approaches.

The experience of the application of method 1 shows that not in all, but in most cases, $M_j$ become statistically insignificant beginning from the second component of the model.

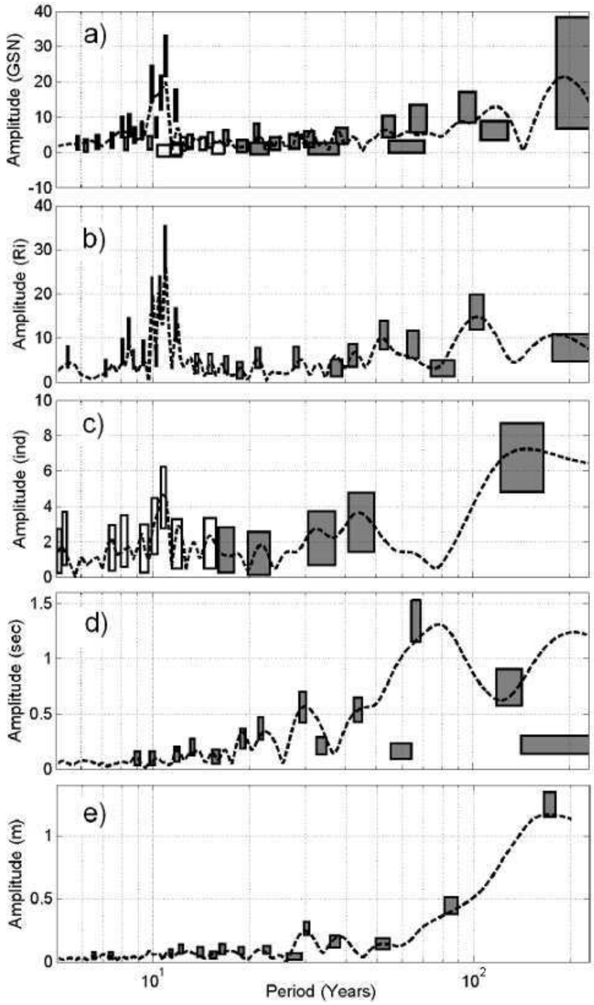


**Fig. 6.** Spectra of the yearly mean Group Sunspot Number RG (a), Wolf numbers Ri (b), the geomagnetic activity of AA-indices (c), LOD (d) and CSL(e). The rectangular areas present the discrete interval amplitude spectra by method 1, dotted line – continuous spectra of the correlation coefficients by method 2.

As it was noted above, the high-frequency fluctuations were not included in approximating polynomial functions in the simulation of solar and geomagnetic activity behavior. In these cases the cycles with periods $T > 16$ yr were used in the approximation.

The models of the behavior of the Caspian Sea Level (CSL) and space-geophysical parameters are represented in Fig.7.

Fig. 7 makes it possible to estimate visually the proximity of the obtained models and the observational data. It is also possible to see that models 1

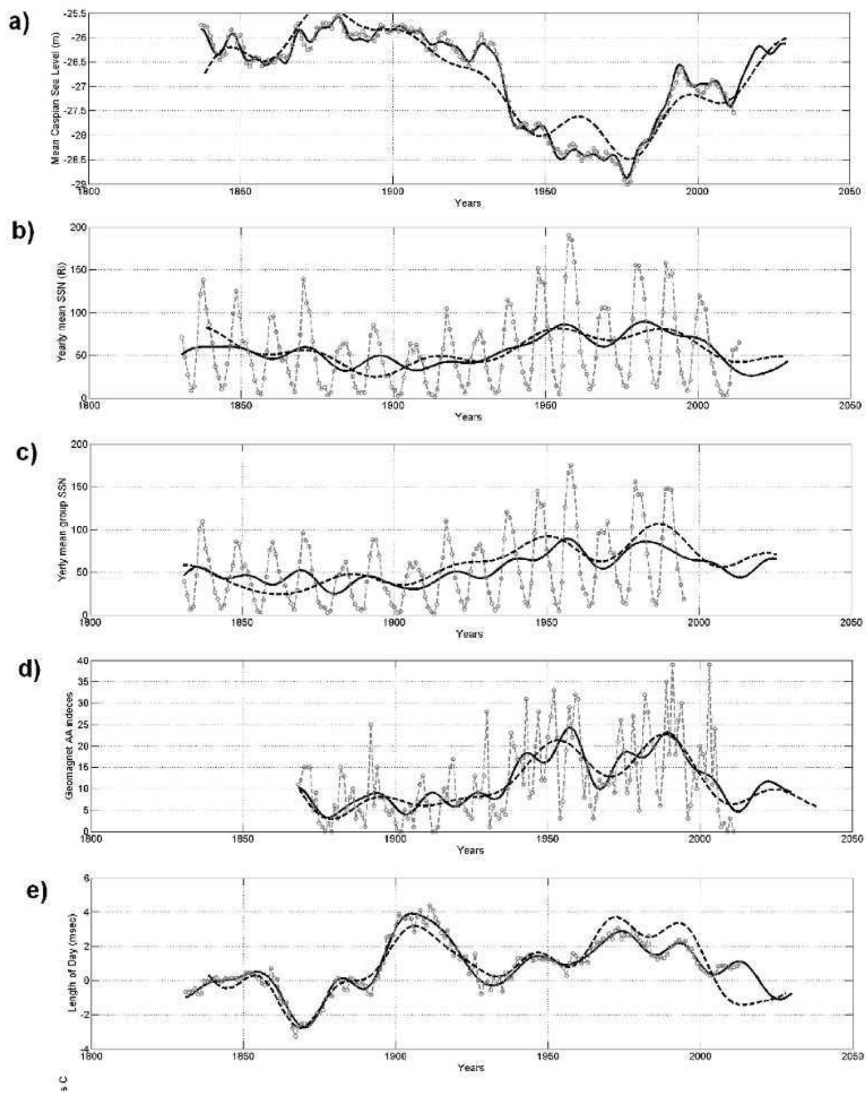

**Fig. 7.** Investigated space-geophysical characteristics (gray dotted line) and their approximating models (black lines) of CSL (a), Wolf numbers Ri (b), the Group sunspot number RG (c), the geomagnetic AA-indices (d), LOD (e). Continuous blacks line - model 1, broken black line - model 2.

and 2 agree with each other in a varying degree, reflecting the running of space-geophysical processes in their low-frequency part in general. Let us note that only statistically significant harmonic components are used in the models. For the models of solar and geomagnetic activity oscillating components with periods less than 16 years were not used.

For predicting the future changes of investigated parameters an extrapolation until 2030 was realized. Depending on the observation data series the extrapolation intervals were different. Thus, by using of the models a forecast for the development for the processes is possible.

On the base of the main stated problem, let us focus attention on the nature of the extrapolation curve of CSL changes in the future. As is shown in Fig. 8 (a) it reverses the sign, already beginning from the present time, and the forecasted values of the level begin sufficiently intensively to grow at a rate of more than 10 cm per year. Predictions for an intensive increase in CSL during the period until 2030 are published also in the work Solovyeva (2004), where contemporary data of satellite altimetry were not used, as well as in Roshan et al. (2012). The Internet site of the Ministry of ecology and natural resources of Republic Azerbaijan http://www.eco.gov.az/en/x-seviyye.php also demonstrates a forecast for a CSL increase in the future decade.

The mutual comparison of the obtained models concerning the changes of the space-geophysical parameters together with CSL changes represents the great interest for understanding of cause-effect relationships.

## 4.4 Estimation of interrelation of data and received models

The visual comparison of the obtained approximations (Fig. 7) testifies about the antiphase behavior of space-geophysical processes with respect to changes in CSL. Let us examine the agreement between each of the space-geophysical characteristics and the level of the Caspian Sea on the special graphs. In Fig. 8 the paired comparisons of CSL changes with the graphs of changes in the other processes are represented. The real graphs of space-geophysical processes changes are flipped vertically.

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The visual analysis of the graphs of the obtained models shows that the behavior of the characteristics of solar and geomagnetic activity sufficiently well agree with the models of CSL changes (Fig. 8 a-c.). In much smaller degree this is valid for the approximations of changes in LOD series (Fig. 8 d).

The cross-correlation function $r_{xy}(\tau)$ for each pair of numbers of $x_t$ (CSL changes) and $y_t$ (compared processes), moved towards each other on the time intervals $\tau$ was calculated for obtaining the quantitative assessments of the relationship of the CSL changes with the investigated space-geophysical parameters.

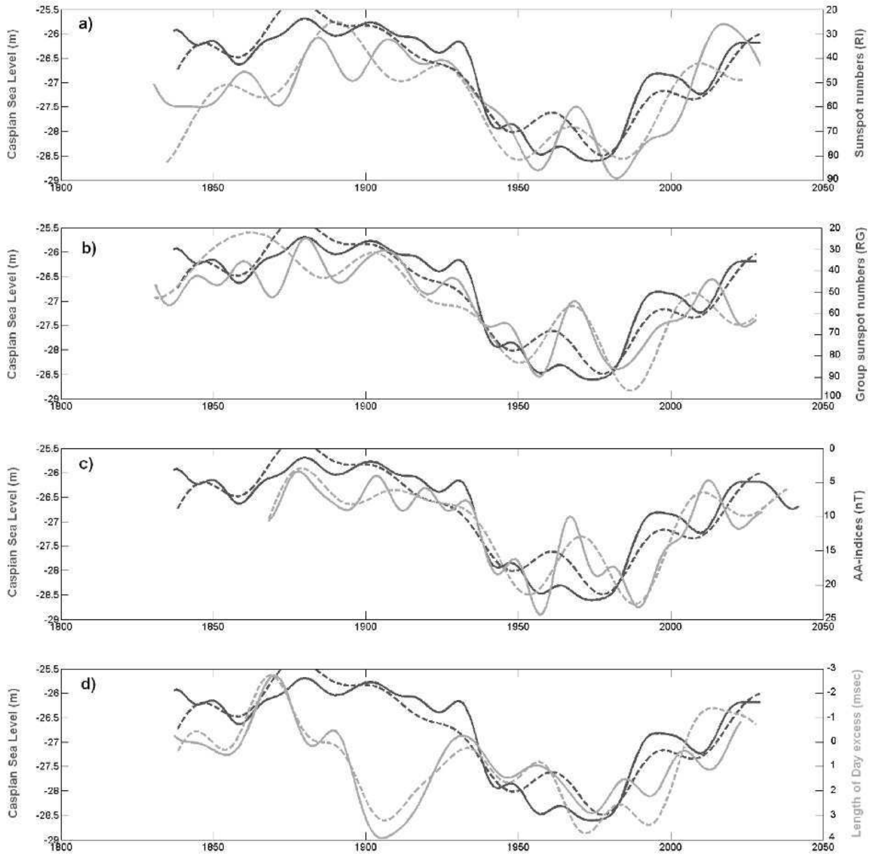


**Fig. 8.** Comparison of the approximating models of CSL changes with the inverted models for Wolf number(a), Group Sunspot number RG (b), the geomagnetic AA-index (s), LOD (d). Solid lines present model 1, dotted lines - model 2.

$$r_{xy}(\tau) = \frac{(n-\tau)\sum_{t=1}^{n-\tau} x_t y_{t+\tau} - \sum_{t=1}^{n-\tau} x_t \sum_{t=1}^{n-\tau} y_{t+\tau}}{\sqrt{\left[(n-\tau)\sum_{t=1}^{n-\tau} x_t^2 - (\sum_{t=1}^{n-\tau} x_t)^2\right]\left[(n-\tau)\sum_{t=1}^{n-\tau} y_t^2 - (\sum_{t=1}^{n-\tau} y_t)^2\right]}} \qquad (2)$$

The position of the function (2) extrema on the time (x) axis fixes the values of the time delays of one physical process with respect to other processes. Coefficient values (2) demonstrate the statistical significance of the relationship of the investigated processes. The results of cross-correlation analysis are represented in Table 2.

**Table 2.** Estimation of time lags and the statistical confidence of interconnection

| Data series | | | Modelled series | | |
|---|---|---|---|---|---|
| Predictor (CSL) | Correlation coefficients $r \pm \sigma_r$ | Phase shift (years) | Predictor (CSL) | Correlation coefficients $r \pm \sigma_r$ | Phase shift (years) |
| SSN (Ri) | $-0.36 \pm 0.07$ | 4 | SSN (Ri) | $-0.86 \pm 0.02$ | 10 |
| SSN (RG) | $-0.41 \pm 0.07$ | 5 | SSN (RG) | $-0.85 \pm 0.02$ | 4 |
| AA-indices | $-0.30 \pm 0.06$ | 6 | AA-indices | $-0.80 \pm 0.02$ | 6 |
| Length of Day | $-0.33 \pm 0.07$ | 0 | Length of Day | $-0.53 \pm 0.05$ | 0 |

The results of the evaluation of the cross-correlation of primary data (first three columns of table 2) testify about the statistically significant correlation dependence between CSL changes and compared space-geophysical parameters. The obtained correlation coefficient $R$ peaks more than three time exceed the corresponding standard deviations of the same ones. This can be estimated as an argument in favor of the existence of physical relationship between CSL and the examined processes. The obtained estimations of phase shifting between the processes testify the timing advance of solar and geomagnetic activity in respect to CSL changes about 4-6 years. On the other hand LOD acts synchronously with the behavior of the Caspian Sea level.

The analysis of cross-correlation between the approximating models series clearly demonstrated the considerable forcing of interdependence between the compared parameters. Especially this appeared in the comparison of CSL changes with long-period solar and geomagnetic activity ones.

The highest correlation coefficients $R$ reach to 0.8 - 0.86. Phase shifts are obtained in the range from 4 to 10 years. The modeled LOD changes preserved synchronous coordination with CSL.

## 5. Discussion and conclusion

The executed studies concerning the spectral structure of the average CSL values and the natural processes of planetary and space scales made it possible to construct their kinematic models and to obtain quantitative assessments of their statistical relationship.

The use of two different methods for development of hidden periodicity ensured the estimation of the level of probability of the tendencies concerning the behavior of the investigated processes.

The closeness of the cross-correlation connection between the time series and approximating models gives the basis to assume their real physical dependence and mutual hierarchy. The CSL fluctuations, unexpected according to some researchers, begin to acquire the proofs for reversibility and predictability.

The obtained estimations about significant statistical relationship concerning the behavior of solar and geomagnetic activity testify in support of Forbush effect hypothesis (Dergachev et al., 2012) about accumulation of atmospheric precipitations on the enormous territory of the Caspian Sea drainage basin.

The evidences for the presence of connection between the solar activity changes and climate are examined in the work (Ogurtsov et al. 2002). The relationship of changes in the Earth's magnetic field with the precipitation is critically discussed also in the work Knudsen & Riisager (2009). The less close statistical connection between CSL changes and LOD indicates the probability of the presence of connection between the atmosphere circulation regime and the Earth rotation parameters, assumed, for example, in Sidorenkov (1978, 2009), Sidorenkov & Wilson (2009). This feature can be explained for example by the influence of the Earth's rotation parameters on the accumulation of atmospheric precipitations dynamics. On the other side the changes in the sea level fluctuations and Earth's rotation velocity are connected also by a tidal mechanism. The presence of a relationship between the Earth's inner core nutation and the geomagnetic activity is also discussed by researchers (Malkin, 2013.). There are original hypotheses about the coupling of CSL oscillations to the tectonic stresses in the Earth's crust (Shilo N., 1989; Shilo and Krivoshey M.I., 1989).

These circumstances make possible to assume the multifactor nature of the Caspian level behavior with a different degree of contribution of each factor. It is very probable that the solar and geomagnetic factors play the predominant role, but also rotary mechanism ensures the contribution of close, although smaller, order.

With respect to the estimation of future tendencies, the results of the conducted investigations give arguments to suppose rapid increases in CSL during the next decades with a speed of more than 10 cm per year.

The significant inverse correlation with the Caspian Sea level in this case testifies about the high probability of future reduction in the solar and the geomagnetic activity (Komitov and Bonev, 2001; Komitov and Kaftan, 2003), and the decrease of the day length.

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