INVESTIGATION SEASONAL AND INTERANNUAL VARIABILITY OF THE CASPIAN SEA DYNAMICS BASED ON SATELLITE ALTIMETRY DATA

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ABSTRACT

The investigation is devoted to the study of the variability of the dynamics of the Caspian Sea based on TOPEX/Poseidon and Jason-1/2 satellites altimetry data. The technique of calculating the synoptic dynamic topography (DT) as a superposition of the mean sea climate DT calculated by thermohydrodynamic models and field of sea level anomalies calculated by satellite altimetry data is considered. An analysis of the geostrophic currents vorticity confirmed the predominance of cyclonic circulation in the Northern and Middle Caspian and anticyclonic in the Southern. Analysis of variation of average velocity and vorticity shows that the average velocity is inversely proportional to the vorticity. Since 1993 to 2007. vorticity rose at a rate of $-0{,}17\pm0{,}02\cdot10^{-7}$ per year, and average velocity has increased at rate of $+0{,}11\pm0{,}06$ cm/year. After 2008 the situation has changed to the opposite. The vorticity has increased at a rate $+0{,}75\pm0{,}12\cdot10^{-7}$ per year, average velocity rose at rate of $-0{,}47\pm0{,}19$ cm/year.

1. INTRODUCTION

The Caspian Sea is the world's largest isolated water reservoir, with only isolation being its significant dissimilarity from the open seas. The other features of the Caspian Sea including its size, depth, chemical properties, peculiarities of the thermohaline structure and water circulation enable to classify it as a deep inland sea. At present time its level is at -27 m (with respect to the Baltic altitude system) measured against the World Sea Level. The sea occupies an area of 392,600 km^2, with mean and maximum depths being 208 m and 1 025 m, respectively (Fig. 1). The Caspian's longitudinal extent is three times larger than its latitudinal one (1,000 km vs. 200−400 km), resulting in great variability of climatic conditions over the sea. The isolation of the Caspian Sea from the ocean and its inland position are responsible for a great importance of the outer thermohydrodynamic factors, specifically, the heat and water fluxes through the sea surface, and river discharge for the sea level variability, formation of its 3D thermohaline structure and water circulation [1].

Investigation of the Caspian Sea dynamics began simultaneity with the emergence of interest to this reservoir. Only after the creation of the modern instrument base (1950−1960) was possible to conduct research on the statistical regularities of the sea currents fields. The instrumental observations available on the Caspian Sea currents are mostly concentrated in its shelf zone. All the series were very shortterm and can characterize only the synoptic and higher frequency ranges of the water dynamics [2].

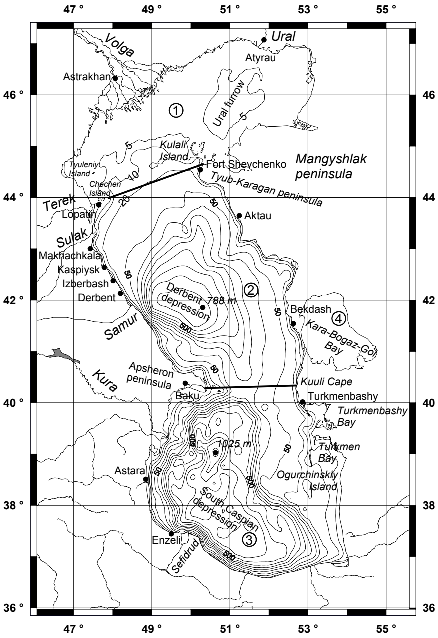


Figure 1. The Caspian Sea. Main parts of the Caspian Sea: 1 – the North Caspian; 2 – the Middle Caspian; 3 – the South Caspian; 4 – the Kara-Bogaz-Gol Bay. Isobaths are shown in meters

Knowledge of the general water circulation in the Caspian Sea has therefore been based on diagnostic simulations by numerical hydrodynamic models using the temperature and salinity fields [3−11].

The development of satellite altimetry [12] possible to study the dynamics of the Caspian Sea at a new standard [13−15].

2. DATA

To analyze Caspian Sea hydrodynamic variations, measurements from both the T/P and J1 satellites were

Proc. 'Living Planet Symposium 2016', Prague, Czech Republic, 9–13 May 2016 (ESA SP-740, August 2016)

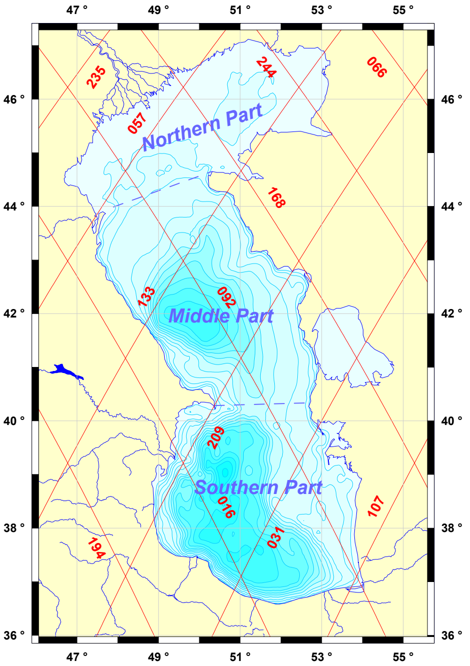


Figure 2. The position of the T/P and J1/2 ground tracks.

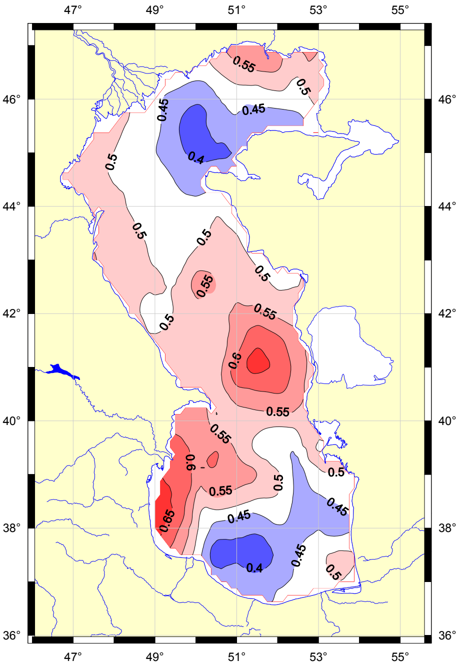


Figure 3. Normalized rates of the Caspian Sea level change based on the T/P and J1/2 satellite altimetry data from January 1993 till December 2012.

used for the following reasons. The precision of sea surface height (SSH) measurements by TOPEX/ Poseidon (T/P) and Jason-1/2 (J1/2) to the relative reference ellipsoid is 1.7 cm, which is higher than other altimetry missions. At the same time, accuracy of sea level measurements is at ~4 cm that allows adequate accuracy for studies to be conducted. The position of T/P and J1/2 ground tracks (Fig. 2) is optimal for analysis of sea hydrodynamic an level variations in the Caspian Sea [13−16]. The orbital repeat period (~10 days) enables analysis of interannual and seasonal variability of the sea hydrodynamic and level [13−16]. The T/P data represent the longest time-series of satellite altimetric measurements (September 1992 − August 2002 or 1−364 cycles) with the possibility of the data being extended by J1 data (August 2002 − January 2009 or 1−259 cycles) and J2 data (August 2008 or from 1 cycle to the present time) along the same tracks.

3. METHODOLOGY

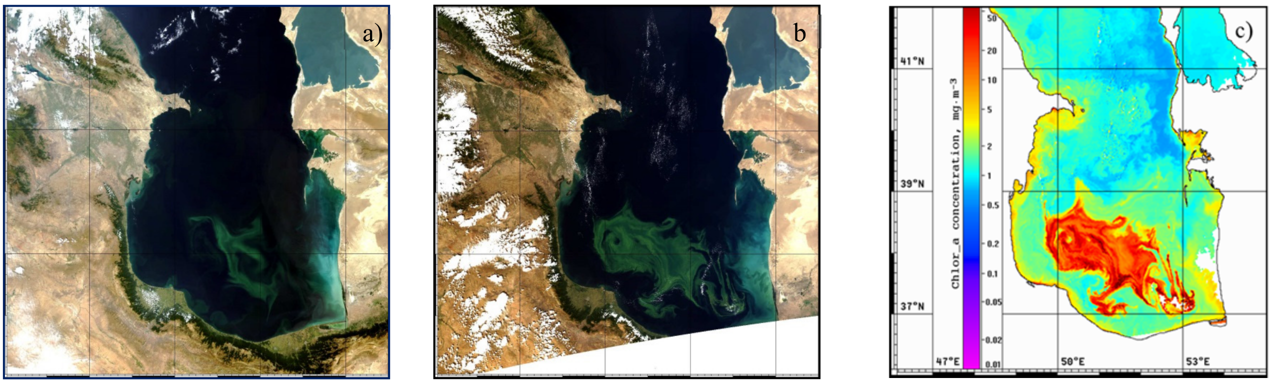
Data processing methods and analysis as well as obtained results on the Caspian Sea level, wind speed, and wave height variations were described in detail in [13−14, 16]. All necessary corrections from satellite altimetry data-base: microwave radiometer wet tropospheric, smoothed dual-frequency ionosphere and sea state bias are used in the data processing. Maximal tide height for the Caspian Sea is 2 cm in coastal zone so this correction isn't used in the data processing.

Regional mean sea surface (MSS) height model of the Caspian Sea (GCRAS12 MSS) was calculated according to the following scheme. For satellite altimetry data processing dry tropospheric correction was calculated on atmospheric pressure from nearest weather stations located along the Caspian Sea costal line. From the T/P and J1/2 satellite altimetry data, the SSH synoptic and seasonal variations for all passes of each repeat cycle were eliminated. In last phase, the GCRAS12 MSS was constructed as a SSH function of latitude, longitude, and time with correction on climatic dynamic topography. For specified time interval SSH was interpolated on grid by radial basis function method [17−18]. This MSS model considers the spatial inhomogeneity of the interannual variability in the Caspian Sea level (Fig. 3).

Dynamic topography (DT) was constructed on the basis of the superposition of the SLA (calculated relative to the GSRAS12 MSS model) distribution over the climatic dynamic topography (or hydrodynamic level), which was calculated on the base of a three-dimensional baroclinic model [9].

Verification synoptic DT fields constructed from satellite altimetry data conducted by other sea surface parameters (sea surface temperature, the concentration of suspended matter, chlorophyll content, and others.), calculated according to remote sending data, which are natural tracers, reflecting the features of mesoscale dynamics of water.

Consider the case anomalous algal bloom *Cyanobacteria Nodularia* in the Iranian coast in the Southern Caspian in 2005 [19]. It began to develop in the second decade of August and continued until the end September and cover an area of 20,000 km^2.



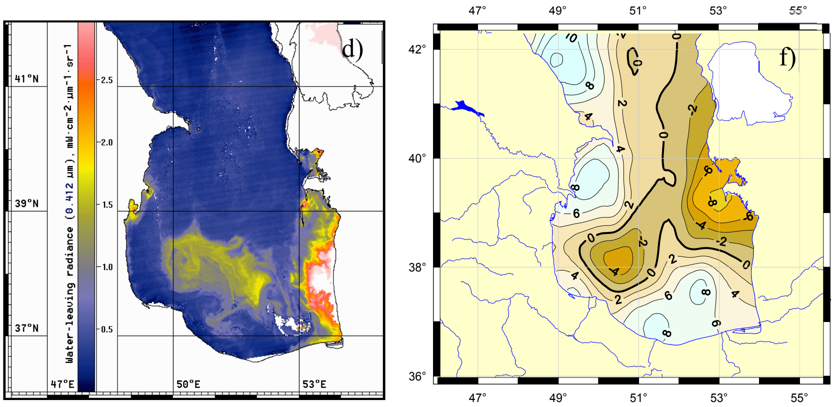


Figure 4. The anomalous algal bloom Cyanobacteria Nodularia according spectroradiometer MODIS data of satellite Aqua (a) on 17 August 2005, (b) September 1, 2005 ; (c) map of chlorophyll concentration (mg/m^3); (d) the upwelling radiation of sea water on wavelength of 412 nm (mW/cm^2) as of September 1, 2005; and (d) of the synoptic dynamic topography (cm) for August 2005 calculated according to the altimetric measurements of satellite J1.

The anomalous algal blooms have been reported according to the spectroradiometer MODIS of satellite Aqua on August 12 and peaked September 1, 2005 (Fig. 4a-b). Analysis of satellite images the same season in the previous 5 years, did not confirm the presence of algal blooms this scale existed ever before.

Analysis of chlorophyll concentration maps and upwelling radiation of sea water (wavelength 412 nm) of 1 September 2005, the spectroradiometer MODIS data of satellite Aqua shows the presence of a strong anticyclonic eddy in the Southern Caspian, whose center has the coordinates 50°28' E and 38°09' N. This eddy is observed in the monthly synoptic dynamic topography field based on altimetric measurements of Jason−1 satellite in August 2005. However, the shape of the eddy from these data smoother than with maps, calculated by spectroradiometer MODIS data. This fact can be explained by the spatial resolution of the data. For the chlorophyll concentration and the upwelling radiation of sea water (wavelength 412 nm), calculated by the spectroradiometer MODIS data have the spatial resolution of 250 m, and monthly synoptic dynamic topography field − 0,125° or 12.5 km.

Thus it is shown that the field of synoptic dynamic topography fields calculated by altimetric measurements according to the algorithm well reflect the feature of the mesoscale dynamics of the Caspian Sea.

4. RESULTS AND DISCUSSION

Analysis of monthly dynamic topography fields shows that in February (Fig. 5a) cyclonic eddy, located in the northern part of the Middle Caspian, is more powerful declined to the climatic position (Fig. 5e), and insignificantly shifted towards the west coast. In the Southern Caspian and there is a strengthening of cyclonic circulation in the center. In the Middle Caspian along the coast of Dagestan from Agrakhan Peninsula to Derbent in southern Caspian on coast of the Turkmenistan Bay and to the south there is an intensification of coastal currents.

In the spring (April) (Fig. 5b) cyclonic eddy in the northern part of the Middle Caspian subsided. To the north of Apsheron Threshold anticyclonic eddy is formed. Cyclonic gyre in the center the South Caspian also declined in comparison with the climatic position (Fig. 8a). Intensification of coastal currents observed in the Northern Caspian Sea from the eastern part of the Volga River delta to Makhachkala.

In the summer (August) (Fig. 5c) cyclonic eddy in the northern part of the Middle Caspian is declined, and the anticyclone was formed in the spring increases and occupies almost the entire south-western part. In the Southern Caspian cyclonic gyre declined and in this part of the sea is dominated by anticyclonic circulation. Still in the North Caspian Sea from the eastern part of the Volga River delta to the border with the Middle Caspian Sea there strong coastal currents.

In the autumn (November) (Fig. 5d) general circulation of the Caspian Sea is close to the climatological (Fig. 5e). From the equations of geostrophic balance, when the

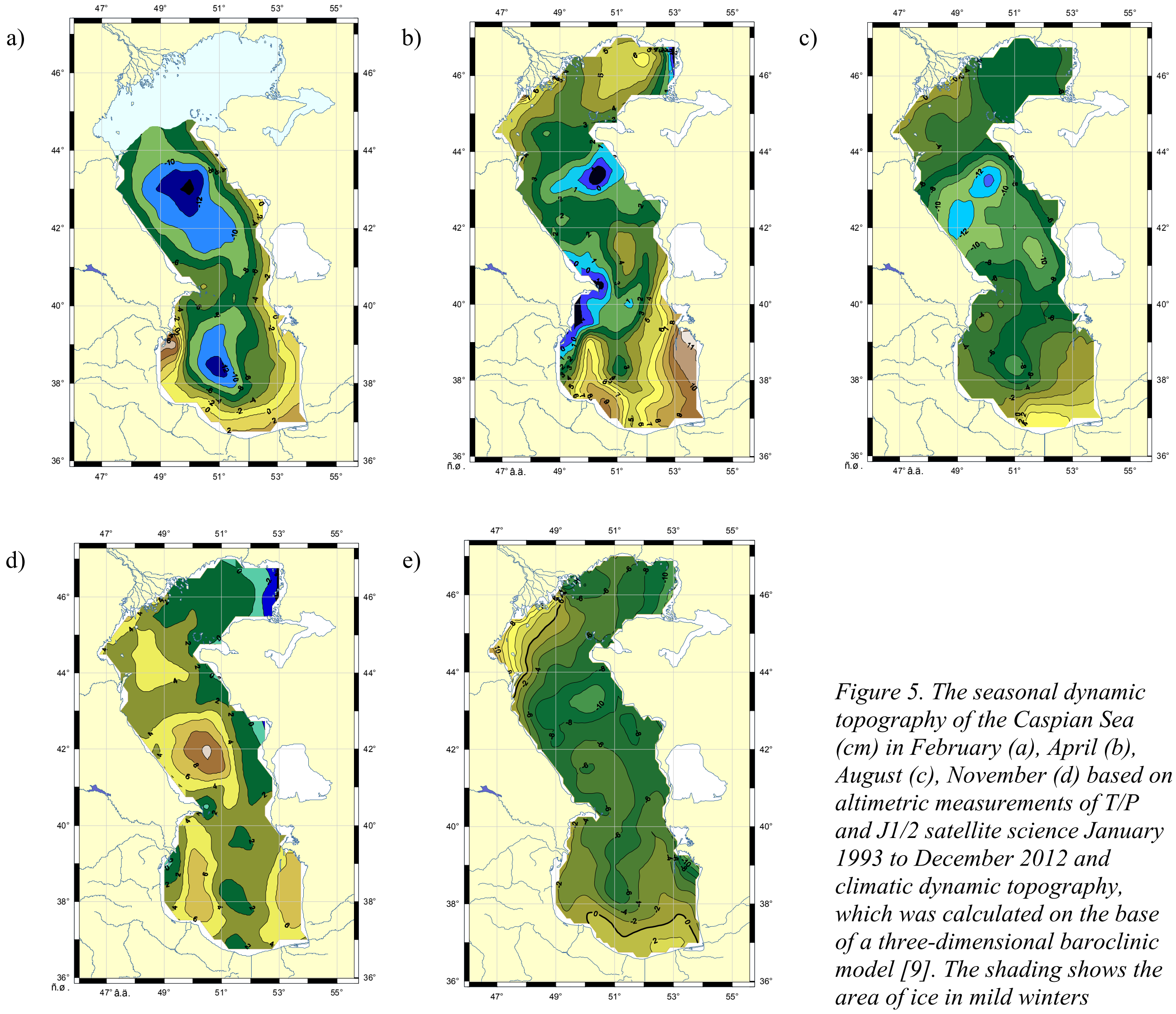


Figure 5. The seasonal dynamic topography of the Caspian Sea (cm) in February (a), April (b), August (c), November (d) based on altimetric measurements of T/P and J1/2 satellite science January 1993 to December 2012 and climatic dynamic topography, which was calculated on the base of a three-dimensional baroclinic model [9]. The shading shows the area of ice in mild winters

horizontal pressure gradient is compensated by the Coriolis force, the current velocities determines by the dynamic topography h_{dyn} gradients as:

$$U_g = -\frac{g}{f}\frac{\partial h_{dyn}}{\partial y} \qquad V_g = \frac{g}{f}\frac{\partial h_{dyn}}{\partial x}$$

where U_g and V_g is the surface geostrophic components of the current velocities of the axes; g=9.80665 m/s^2 is free fall acceleration; $f = 2\Omega \sin\varphi$ is Coriolis parameter defined by the angular velocity of the Earth's rotation $\Omega = 7.2921 \cdot 10^{-5}$ s^{-1} and φ is the latitude.

Another characteristic is the vorticity of the velocity field, which is a quantitative measure of the velocity rotor

$$\zeta = \frac{\partial V_g}{\partial x} - \frac{\partial U_g}{\partial y}.$$

Plus value ζ the predominance of cyclonic circulation, negative – anticyclonic.

Analysis of the monthly geostrophic current velocities at the surface shows, than the most maximum monthly rate of (7.5±0.5 cm/s) are observed in the Northern Caspian and the minimum (4.6±0.1 cm/s) in the South Caspian. In the Middle Caspian and in the sea as a whole the average monthly rate almost identical [16].

Seasonal course current velocities in the Northern and Middle Caspian are in opposition. When in April in the northern part of the sea there is a maximum 8.1 cm/s, in the middle part it is about 4.3 cm/s. In July, the situation is reversed. In the Middle Caspian there is a maximum 4.8 cm/s, in the North – about 6.9 cm/s. The following maximum current velocities in the Northern Caspian 8.2 cm/s is observed in November, and at least in the middle 4.5 cm/s – in September [16].

Analysis of the seasonal variability of the vorticity field shows that in Northern and Middle Caspian has general cyclonic circulation predominates, while in the southern part of the sea – anticyclonic circulation. Seasonal variability of vorticity field Northern and Middle Caspian are in opposition. The maximum cyclonic vorticity in the northern part of the sea observed in the summer, in July, corresponds to the minimum vorticity in the middle of the sea. In the Southern Caspian is dominated by anticyclonic vorticity throughout the year. At least it comes in the summer, and the maximum – in winter [16].

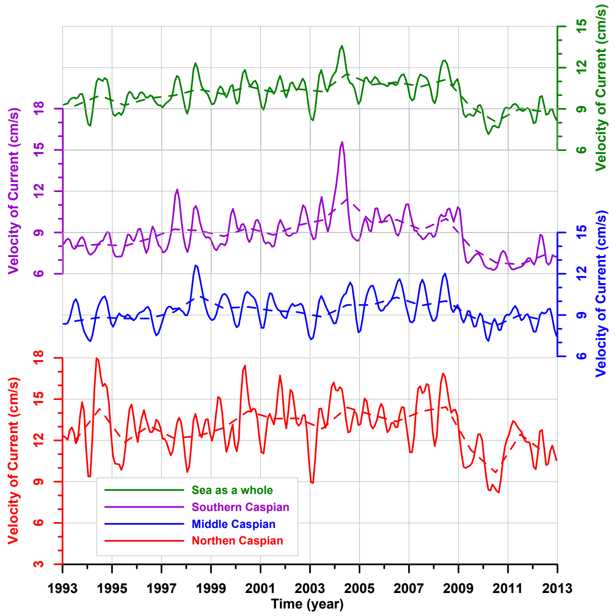


Figure 6. The interannual variability of monthly geostrophic current velocities (m/s) base on altimetric measurements of T/P and the J1/2 satellite since September 1992 to December 2012. The dashed lines show average annual values

The interannual variability of monthly geostrophic velocity at the surface shows that the flow velocity in different parts of the Caspian Sea and in general does not have a pronounced seasonal pattern, as there are significant interannual differences (Fig. 6). So in the Northern Caspian in 1994, 2000, 2002, 2004, 2007 and 2008. observed maximum values of monthly current velocity (more than 15 cm/s) with respect to the average value (12.9±1.9 cm/s). In the Middle Caspian in 1998 alone there was an anomaly maximum value of the average monthly current velocity (more than 12 cm/s), but in the Southern Caspian Sea – in 1997 (more than 11 cm/s) and 2004 (more than 15 cm/s). Monthly mean climatological values of current velocities for these parts of the sea respectively 9.3±1.1 cm/s and 8.8±1.5 cm/s, which is close to the values for the whole of the sea as a whole 10.1±1.2 cm/s. Figure 6 clearly shows that in 1997 and 1998, and also in 2003, the time course of the average monthly velocities of all sea parts the most synchronous, that talk about the features of the sea circulation mode in these time interval. After 2009 there was a sharp drop in the average monthly velocities of all parts of the sea in the range of 1–2 cm/s, which appears to be associated with changes in the regime of atmospheric circulation in the region.

An analysis of the interannual variability of vorticity of geostrophic velocity field shows that in different parts of the Caspian Sea and in general it does not have a pronounced seasonal pattern, with the observed significant interannual differences (Fig. 7). Between the North and Middle Caspian Sea as well as in the season course, there has been a change in antiphase vorticity.

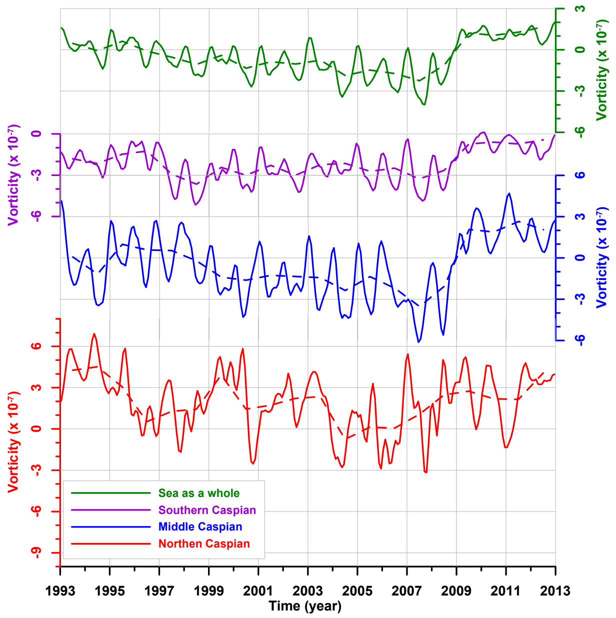


Figure 7. The interannual variability of vorticity of monthly geostrophic current velocity field base on altimetric measurements of T/P and the J1/2 satellite since September 1992 to December 2012. The dashed lines show average annual values

In the North Caspian in 1993–1995, 1999–2000, 2002–2003, 2007–2010 and 2012. observed maximum values of vorticity (more than $4\cdot10^{-7}$) relative to the average climate value ($2.02\cdot10^{-7}$). In the Middle Caspian in 1993 and 2009–2011 anomaly highs values of vorticity of geostrophic velocity field observed (more than $3\cdot10^{-7}$). Vorticity mean climatological value for this part of the sea was $-0.61\cdot10^{-7}$. In the Southern Caspian similar local maxima in the period 1993–2012 are not observed. Average climatic values of velocity current vorticity in this part of the sea was $-2.20\cdot10^{-7}$, indicating that the prevalence of anticyclonic circulation. To the sea in general, the value of the vorticity is $0.51\cdot10^{-7}$. Figure 7 shows that after 2008, the value of the vorticity in almost all parts of the sea with the exception of the northern part of the increase in the range of $1.5–3\cdot10^{-7}$. According to the analysis of the time course of the average monthly velocity (Fig. 6), at this time there was a drop in all parts of the sea. This once again confirms the change in atmospheric circulation mode in the region.

Also after 2008, the vorticity in all parts of the sea increased, indicating a regime change in atmospheric circulation over the water area of the Caspian Sea. Analysis of variation of average velocity and vorticity shows that the average velocity is inversely proportional to the vorticity (Fig. 8). Since 1993 to 2007. vorticity rose at a rate of -0,17±0,02·10^{-7} per year, and average velocity has increased at rate of +0,11±0,06 cm/year. After 2008 the situation has changed to the opposite. The vorticity has increased at a rate +0,75±0,12·10^{-7} per year, average velocity rose at rate of -0,47±0,19 cm/year.

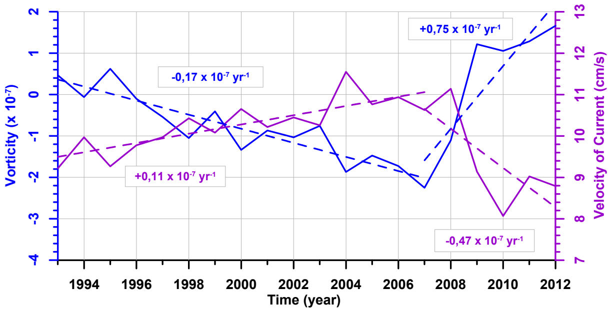


Figure 8. The interannual variability of the average annual values of vorticity (blue line) and geostrophic current velocities (purple line) according to altimetric measurements of satellite T/P and J1/2 scince 1993 to 2012

5. ACKNOWLEDGEMENTS

This study was supported by grants of the Russian Science Foundation (No 14-17-00555)

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