«Living Planet Symposium 2016»
Prague, Czech Republic, 9-13 May 2016

Investigation Seasonal and Interannual Variability of the Caspian Sea Dynamics based on Satellite Altimetry Data

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The Caspian Sea

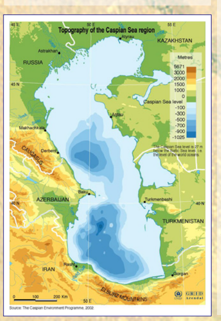


Fig. 1. Map of the Caspian.

The Caspian Sea presents the world's largest isolated water reservoir (Fig. 1), with only an 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. Currently its level is at − 27 m 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 1025 m, respectively. The Caspian's longitudinal extent is three times larger than its latitudinal one (1000 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 runoff for the sea level variability, formation of its 3D thermohaline structure and water circulation.

Over the past half-century, there was a regression of the Caspian Sea until 1977 when the sea level lowered to −29 m (Fig. 2). This drop is considered to be the deepest for the last 400 years. In 1978 the water level started to rise rapidly, and now it has stabilized near the −27 m level. There has been increasing concern over the Caspian Sea level fluctuations. Estimates provide support for the view of these fluctuations as climatically conditioned and show their intimate connection with components of the Caspian water budget, especially Volga River run-off.

Between October 1992 and May 1995 the Caspian Sea level was still rising at a rate of +20.27 cm/yr. In June 1995, the sea level started to drop abruptly and a negative trend was observed until winter 2001/2002, when a local minimum (−27.3 m) was reached (Fig. 3). From June 1995 to November 2001 the rate of sea level drop was −7.22 cm/yr. From December 2001 until July 2005 the Caspian Sea level rose at a mean rate of +10.49 cm/yr.

Fig. 2. Interannual variations of the Caspian Sea level measured by sea level gauges (blue line) and satellite altimetry (red line) since 1837 till 2015

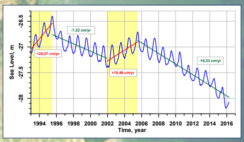


Fig. 3. Temporal variability of the Caspian Seas level from January 1993 to March 2016 based on to satellite altimetry of TOPEX/Poseidon and Jason−1&J2 data (blue line) and interannual linear trends are shown by read (rise) and green (drop) lines. Rise periods are showed on yellow color area

At the present time he sea level rate is decreasing at −10.33 cm/yr. on March 31, 2016 the sea level was −28.01 m.

Synoptic Dynamic Topography

Dynamic topography fields were used to analyze the spatial and temporal variability of the general dynamics in the Caspian Sea. They were constructed on the basis of the superposition of the sea level anomalies distribution over the climatic dynamic topography (Fig. 8).

The sea level anomalies were calculated on the base of GCRAS12 Mean Sea Surface of the Caspian Sea The climatic dynamic topography (or hydrodynamic level) was calculated from three dimensional baroclinic model with free surface. Average monthly fields of temperature and salinity, climatic Volga River run-off and irregular evaporation from sea surface were taken in consideration. Also atmospheric pressure and wind fields from the regional model over the period from 1948 to 2012 were used. This model was developed in. Laboratory of Sea Applied Research of Hydrometeorological Research Center of Russian Federation (Fig. 8a).

Verification synoptic dynamic topography 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.

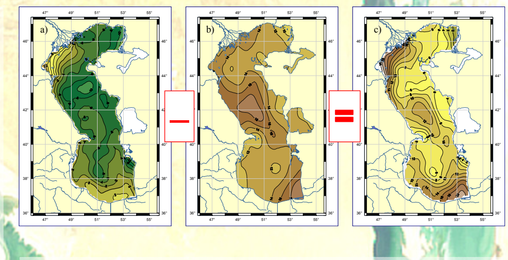
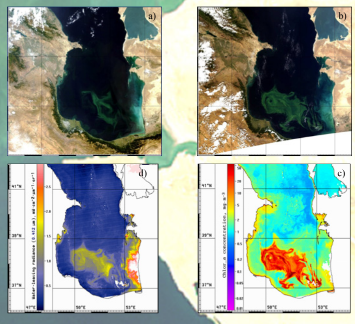


Fig. 8. (a) − Average or climatic dynamic topography (cm), calculated by the model of Laboratory of Sea Applied Research of Hydrometeorological Research Center of Russian Federation. (b) − Monly anomalies of the Caspian Sea level (cm) for July 2005. (c) − Synoptic dynamic topography (cm) for July 2005.



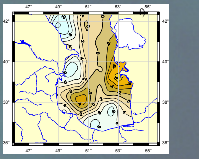


Fig. 9. The anomalous algal bloom Cyanobacteria Nodularia according spectroradiometer MODIS of satellite Aqua (a) on 17 August 2005, (b) September 1, 2005 ; (c) map of chlorophyll concentration (mg/m^3); (d) the upwelling radiation of sea water on wavelength of 412 nm (mW / cm^2) as of September 1, 2005; and (d) of the synoptic dynamic topography (cm) for August 2005 calculated according to the altimetric measurements of satellite Jason−1.

Consider the case anomalous algal bloom *Cyanobacteria Nodularia* in the Iranian coast in the Southern Caspian in 2005. 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. The anomalous algal blooms have been reported according to the spectroradiometer MODIS of satellite Aqua on August 12 and peaked September 1, 2005 (Fig. 9a-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.

Dynamic Topography Seasonal Variability

Analysis of monthly dynamic topography fields shows that in February (Fig. 10) cyclonic eddy, located in the northern part of the Middle Caspian, is more powerful declined to the climatic position (Fig. 8a), 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. 10) 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. 10) 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. 10) general circulation of the Caspian Sea is close to the climatological (Fig. 8a).

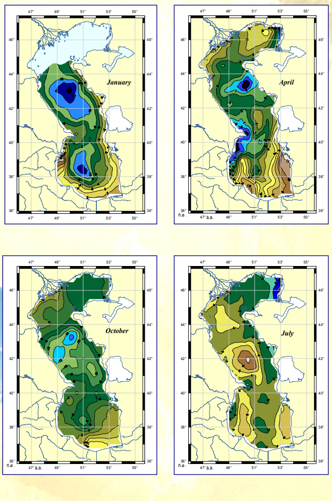


Fig. 10. The seasonal dynamic topography of the Caspian Sea (cm) in February, April, August and November based on altimetric measurements of TOPEX/Poseidon and Jason−1&J2 satellite scince January 1993 to December 2012. The shading shows the area of ice in mild winters.

GCRAS12 Mean Sea Surface Height Model for the Caspian Sea

Usually mean sea surface height (MSS) models are calculated by averaging altimetric measures over a given region and over a given time period. However, in the case of the Caspian Sea this represents a certain challenge.

Firstly, it is storm surges, which depend on wind field and local physicogeographical conditions. The highest onsets are characteristic of the shallow-water North Caspian, where, in extreme cases, surges can reach heights of 3–4 m.

Secondly, there is the issue of sea ice. On the North Caspian ice formation begins in the middle of November and starts to decay in March in moderate winters. On average, the duration of the ice period is 120–140 days in the eastern part of the Northern Caspian and 80–90 days or less in the western part. On the eastern coast of the Middle Caspian, ice formation is possible in severe winters.

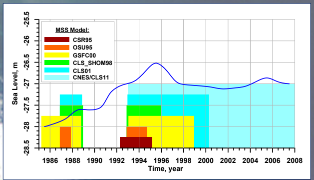


Fig. 4. Comparison of temporal intervals of average satellite altimetry data for principal MSS model and the Caspian Sea level variability from January 1985 to December 2008

Thirdly, there is the issue of Caspian Sea water balance peculiarities. The most important of these are the Volga River discharge (more 80%), evaporation from the sea surface and the dynamics between the Caspian Sea and the Kara-Bogaz-Gol Bay. Thus for the period of time when satellite altimetry measurements were conducted from 1985 until 2012 water discharge in the Volgograd power station oscillated from 5609.25 m^3/c (2006) to 1,136,983 m^3/c (1994).

Fourthly, interannual changes of sea level (that are about 3 m for 1929–1977 and about 2.5 m for 1977–1995) here are sometimes much higher than seasonal ones (that are about 30 cm).

Existing MSS models essentially differ according to the used information or temporal averaging interval (Fig. 4).

Variation along 092 tracks for the time interval 1993–2008 after filtration of the sea level synoptic and seasonal variability showed on Fig 6. It is apparent, that a sea surface heigth (SSH) maximum for the period from September 1992 to June 2004 at latitude 43.5°N corresponds to the Caspian Sea level maximum observable in the summer of 1995.

Between 43°N and the boundary of the Northern and Middle Caspian Sea strong modification of SHH gradient along a 092 track is observed in spatial position isoline at −35.5 m (Fig. 6b). This SSH response is explicable due to this area depth changing from 10 to 50 m. Gravity anomaly increases from 11.4 to 22.6 mGal and also the gravity anomaly gradient along the track has maximum 0.27 mGal /km (Fig. 6c). At latitude 39.8°N SSH minimum vanish from 1994 to 1997, and then reappears. It is readily visible in the spatial position isoline at −46 m (Fig. 6b). The position of this minimum correlates well to about a GA minimum of −98.8 mGal (Fig. 6c).

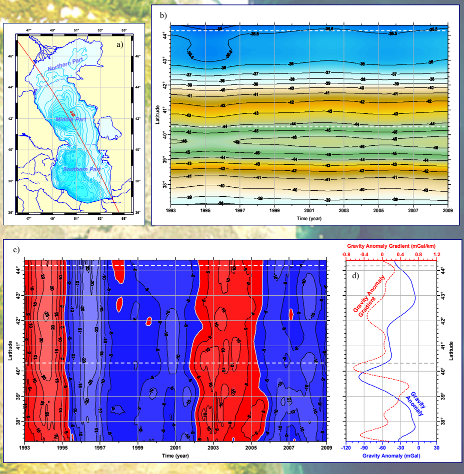


Fig. 6. Ground track 092 pass satellite TOPEX/Poseidon and Jason−1&J2 (b); time variability: (a) of SSH without seasonal and synoptic variability or part of the GCRAS12 MSS Model (m), (c) annual GCRAS12 MSS gradient (cm/year) along the descending 092 track from September 1992 to December 2012 on the basis of satellite altimetry data of the ; (d) Variability of gravity anomaly (firm line) and gravity anomaly gradient (dashed line) calculated by EGM2008 model, decomposing to 360 degrees.Dashed lines show borders of the Northern-Middle and the Middle-Southern parts of the sea

The SSH gradient over time behaves differently. We would like to illustrate this with calculations of the annual SSH gradient over time along 092 tracks (Fig. 6d). These results confirm our assumption for the necessity to create a new MSS model for the Caspian Sea.

The GCRAS12 MSS model of the Caspian Sea was calculated according to the following scheme. At first from the TOPEX/Poseidon and Jason−1&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 Model was constructed as a function of latitude, longitude, and time with consideration for climatic dynamic topography. This MSS model considers the spatial inhomogeneity of the interannual variability in the Caspian Sea level (Fig. 7).

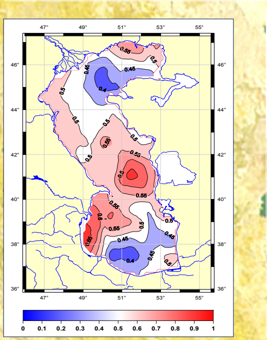
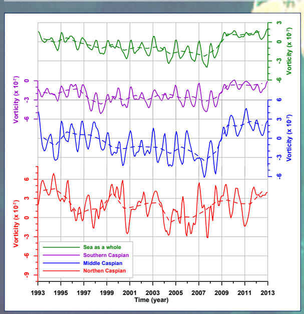
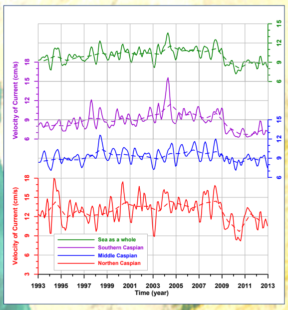
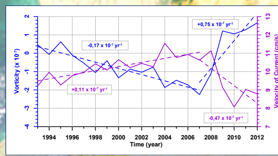


Fig. 7. Normalized rates of the Caspian Sea level change based on the TOPEX/Poseidon and Jason-1/-2 satellite altimetry data from January 1993 till December 2012.

The Interannual Variability of Geostrophic Current Velocities and Vorticity







After 2008, the swirl in almost all parts of the sea rose, indicating a change in the regime of atmospheric circulation over the water area of the Caspian Sea. 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. 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.

Acknowledgements

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