Interannual Variability of Water Exchange Anomalies Between the Northern, Middle and Southern Caspian Based on Satellite Altimetry Data

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Abstract
The paper presents the results of estimation of interannual and seasonal variability of water exchange between the Northern, Middle and Southern Caspian Sea based on the TOPEX/Poseidon and Jason–1/2/3 satellite altimetry data. The boundaries between the Caspian Sea sub-basins were taken along the 133 and 209 tracks of the satellites. Temporal variability of surface geostrophic velocities directed perpendicular to the tracks showed that positive values correspond to the southeast direction of the currents, negative values correspond to the northwest direction. It is clearly seen that the main water exchange associated with the Volga River runoff is concentrated along the western coast of the Caspian Sea. In this area, anomalies of geostrophic velocities exceed 20 cm/s. Total water exchange anomalies through the 133 and 209 tracks show seasonal variability with an amplitude up to ±18x10⁵ m³/s for track 133 (a line between the Northern and Middle Caspian) and ±11x10⁵ m³/s for track 209 (a line between the Middle and Southern Caspian). The maximum values of water exchange anomalies were observed in 1993, 1994 and 2012 through 133 track (±16-18x10⁵ m³/s) and in 1993, 1996 and 1997 (±11x10⁵ m³/s) through 209 track.

Key words: climate variability, water exchange, the Caspian Sea, Volga River, remote sensing, satellite altimetry.

Introduction
The Caspian Sea is the world’s largest isolated water body, with only isolation being its significant dissimilarity from the open seas. The other features of the Caspian Sea including its size, depth, salinity, chemical properties, peculiarities of the thermohaline structure and water circulation enable to classify it as a deep inland sea. The sea is divided in three sub-basins: the Northern, Middle and Southern Caspian Sea. The sea occupies an area of 392,600 km², with mean and maximum depths being 208 m and 1,025 m, respectively (Fig. 1). In 2019, the Caspian Sea level was about -28 m relative to the World Ocean level. The
longitudinal extent of the Caspian Sea 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, rivers runoff, and atmospheric forcing for the sea level variability, formation of its 3D thermohaline structure and water circulation (Kosarev, Yablonskaya, 1994; Kostianoy, Kosarev, 2005; Zonn et al., 2010; Chen et al., 2017).

Figure 1. The Caspian Sea. Main parts of the Caspian Sea: (1) – the Northern Caspian; (2) – the Middle Caspian; (3) – the Southern Caspian; (4) – the Kara-Bogaz-Gol Bay. Isobaths are shown in meters. The coastline corresponds to year 1934, when the sea level was -26.46 m relative to the World Ocean level (Lebedev, 2018).

About 130 rivers enter the Caspian Sea; a few of them are large and numerous rivers are small. The catchment basin of the sea covers an area of 3.5 mln km². The ratio between the areas of the sea and the catchment basin of 1:10 explains a significant impact of the atmospheric and hydrological processes in the entire basin on the Caspian Sea natural conditions. The most important is the Volga River basin, whose area equals to about 1.4 mln km², i.e., about 40% of the total catchment area (Kostianoy, Kosarev, 2005; Zonn et al., 2010).
The riverine network around the Caspian Sea is extremely irregular. All the major rivers either enter the Northern Caspian or are confined to the western coast of the sea. The mean annual river runoff of these rivers (the Volga, Ural, Terek, Sulak, and Kura) covers more than 90% of the total runoff of all rivers into the sea. The rest of the river runoff is related to the Iranian rivers and minor streams of the western coast of the Caspian Sea. The eastern desert coast of the sea is almost free from permanent river runoff into the sea.

Over the past decades, the intensive use of the water resources of the rivers of the Caspian Sea and the regulation of the discharge of all the principal rivers (except for the Ural River) resulted in a decrease of the surface runoff into the sea and its significant redistribution throughout the year (Kostianoy, Kosarev, 2005; Zonn et al., 2010).

The river runoff represents the principal income in the water balance providing up to 80% of the total water delivery to the Caspian Sea. In 1881-2013, the Volga River runoff varied from 149 to 368 km³/year or in average from 4,700 to 11,000 m³/s (Kostianoy et al., 2014; Chen et al., 2017). About 25% of the Volga River runoff is supplied to the sea in May–June during the flood periods. About 15% of the total runoff to the Caspian Sea is provided by the Ural River and the rivers of the western coast – Terek, Sulak, Samur, and Kura. The runoff of minor rivers including those of the Iranian coast makes about 5%. The river runoff greatly affects in the changes in the vertical thermohaline structure of the entire water column of the Caspian Sea, which affects the ecological state and development of biological communities in the sea (Kostianoy, Kosarev, 2005; Zonn, Kostianoy, 2016; Lavrova et al., 2016). One of the mechanisms of the spread of pollutants is general water circulation in the sea, therefore it is very important to know the water exchange between parts of the Caspian Sea.

The Caspian Environment Program notes that the Caspian Sea is subjected to increasing anthropogenic impact. As a result, there is an increase in water eutrophication, water pollution with oil products, heavy metals, chemical products, as well as a catastrophic decrease in the biological resources of the Caspian Sea. The main sources of oil pollution of the sea are river runoff; industrial and municipal wastewater; oil production at sea areas and onshore; petroleum products transportation; flooding of the coastal zone as a result of a rise in the level of the Caspian Sea (Kostianoy, Kosarev, 2005; Zonn, Kostianoy, 2016; Lavrova et al., 2016). One of the mechanisms of the spread of pollutants is general water circulation in the sea, therefore it is very important to know the water exchange between parts of the Caspian Sea.

Currently the only source of knowledge on the Caspian Sea water circulation and exchange between its parts is numerical modelling on the basis of thermohydrodynamic models using three-dimensional temperature and salinity fields and atmospheric forcing (Trukhchev et al., 1995; Tuzhilkin et al., 1997; Ibrayev, 2001; Zil’bershtein et al., 2001; Ibrayev, Kurdyumov, 2003; Kurdyumov, Oszoy, 2004; Popov, 2004; Ibraev, 2008; Knysh et al., 2008; Popov et al., 2009; Sarkisyans, Südermann, 2009; Ibrayev et al., 2010; Kara et al., 2010; Farley Nicholls et al., 2012; Kitazawa, Yang, 2012; Arkhipkin et al., 2013; Popov et al., 2013; Gunduz, Oszoy, 2014; Zyrjanov, 2015; Diamsky et al., 2016; Shiea et al., 2016; Zyrjanov, 2016; Popov, Lobov, 2017; Diansky et al., 2018; Dyakonov, Ibrayev, 2019).

The papers by Popov et al. (2015) and Monakhova et al. (2016) demonstrate the fundamental possibility of using the operational hydrodynamic model of the Caspian Sea in its improved form to estimate the transboundary transport of pollutants at the border of the Russian sector of the Caspian Sea.

However, calculations using numerical models contain uncertainties in the boundary and initial conditions, atmospheric forcing, and a set of assumptions, which may lead to the results different from the observations. Regular in-situ measurements of current velocities are very expensive and difficult to do because of the Caspian Sea division between five countries. The experience of using remote sensing data, in particular, satellite altimetry to analyze the circulation of the Caspian Sea is well established (Lebedev, Kostianoy 2005; Lebedev, Kostianoy, 2008; Kouraev et al., 2011; Lebedev, 2015; Lebedev, Kostianoy, 2016; Lebedev, 2018).

Data and Methods

For the analysis of variations of water exchange between parts of the Caspian Sea altimetry measurements from TOPEX/Poseidon (T/P), Jason–1 (J1), Jason–2 (J2) and Jason–3 (J3) satellites were used for the following reasons. Accuracy of sea surface height (SSH) measurements by T/P, J1/2/3 is 1.7 cm, which is better than the accuracy of other altimetry missions. Accuracy of sea level measurements is about 4 cm, which is an adequate value for studies of water circulation. The orbital repeat period of about 10 days along the tracks and 5 days in crossover points enables analysis of interannual and seasonal variability of the sea level and currents (Lebedev, Kostianoy 2005; Lebedev, Kostianoy 2008; Kouraev et al., 2011; Lebedev, 2015; Lebedev, Kostianoy, 2016; Lebedev, 2018).
Spatial resolution of T/P, J1/2/3 sea level measurements is better than the typical Rossby radius of deformation for the Caspian Sea (7.5–10 km) (Baidin, Kosarev, 1986). T/P data represent the longest time-series of satellite measurements of sea level anomalies (SLA) from September 1992 to August 2002 (or 1–364 cycles) with the option to extend the data series with J1 data from August 2002 to January 2009 (1–259 cycles), J2 data from August 2008 to October 2016 (1–303 cycles), and J3 data from February 2008 to present time along the same ground tracks.

The position of the 133 and 209 ground tracks of T/P, J1/2/3 is optimal for an analysis of water exchange between parts of the Caspian Sea, but they do not coincide with the geographical boundaries of the Northern, Middle and Southern Caspian (Fig. 2). The length of both tracks is of about 330 km, taking in mind that track 209 crosses the sea from the Absheron Peninsula in Azerbaijan to the coast of Kazakhstan.

According to the geostrophic approximation, the zonal component $u_y$ (along the Y axis) of the surface current velocity is determined as
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\[ u_y = \frac{g}{f} \frac{\partial h_{\text{dyn}}}{\partial x}, \]  

(1)

where \( g \) is the acceleration of gravity, \( f \) is the Coriolis parameter, \( h_{\text{dyn}} \) is dynamic topography. If we rotate the coordinate axes so that the ordinate axis coincides with the positions of 133 and 209 tracks, then the gradient of the dynamic topography along the track will correspond to the component of the surface currents velocity directed perpendicularly to the tracks (Fig. 2). The water exchange component through the track was calculated as follows:

\[ U_y = \int_0^H u_y \, dz. \]  

(2)

On the sea surface \((z = 0)\) the velocity was determined from the geostrophic relation (1), at the bottom \((z = H)\) – from the non-leakage conditions \( u_y = 0 \).

In this paper, we analyze the variability of water exchange through the tracks based on the variability of surface velocities calculated from the dynamic topography or sea level anomaly (SLA) derived from the satellite altimetry data. It is necessary to calculate SLA relative to the mean sea surface (MSS) height model. The Caspian Sea is not included in most of the global MSS models of the World Ocean. When calculating global MSS models, tidal corrections and inverse barometer corrections are always taken into account. For the Caspian Sea, this method is not suitable, therefore, it is necessary to create a regional MSS model, which will take into account the characteristics of its gravitational field, hydrological (strong interannual variability of the sea level), and thermohydrodynamic regimes.

Based on the definition of the MSS as a surface closest to the equipotential sea surface, the regional MSS model of the Caspian Sea (GCRAS19 MSS), developed in the Geophysical Center of the Russian Academy of Sciences (GCRAS), was calculated according to the following scheme. The satellite altimetry data were processed with all necessary corrections, including a systematic error. From the T/P and J1/2/3 satellite altimetry data the synoptic (for example, surges caused by atmospheric forcing) and seasonal variations of SLA were eliminated for all passes of each repeat cycle of the satellite. Finally, the GCRAS19 MSS was constructed as a SSH function of latitude, longitude, and time with correction on climatic dynamic topography (Fig. 3). Integrating anomalies of current velocities vertically to a depth of active layer (about 30 m) and along the track, we can get the total water exchange anomalies through 133 and 209 tracks, i.e. between the Northern and Middle Caspian and between the Middle and Southern Caspian.

Results

Temporal variability of the anomalies of surface geostrophic velocities directed normal to 133 and 209 tracks is presented in Fig. 4. Positive values of the anomalies correspond to the southeast direction of currents, negative values correspond to the northwest direction of currents. The largest velocity anomalies are observed in the western part of the satellite tracks which are associated with the Volga River runoff concentrated along the western coast of the Caspian Sea and propagating in the southern direction. In this area, anomalies of geostrophic velocities exceed 20 cm/s and have a notable seasonal character (Fig.4). The other part of the 133 and 209 tracks displays anomalies of geostrophic velocities in the range from -5 cm/s to +5 cm/s which are caused by variability in the water dynamics related to general currents, eddies, filaments, upwellings, etc.

Temporal variability of total water exchange anomalies through 133 and 209 tracks (Fig. 5a) shows seasonal and inerannual variability of its values. Maximum amplitudes of this variability reach \( \pm 18 \times 10^5 \text{ m}^3/\text{s} \) for 133 track and about \( \pm 11 \times 10^5 \text{ m}^3/\text{s} \) for 209 track. The maximum values of water exchange anomalies were observed in 1993, 1994 and 2012 through 133 track \((\pm 16-18 \times 10^5 \text{ m}^3/\text{s})\) and in 1993, 1996 and 1997 \((\pm 11 \times 10^5 \text{ m}^3/\text{s})\) through 209 track. A comparison of these values with an average Volga River runoff \((4,700 - 11,000 \text{ m}^3/\text{s})\) shows that the last one is responsible for about only 1% in the anomaly of water exchange between the Caspian Sea sub-basins. Thus, the main reason for anomalies in water exchange between the Northern, Middle and Southern Caspian is a variability in the general circulation in the sea.
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Figure 3. Temporal variability of (a) GCRAS19 MSS (m) along 133 track of the T/P and J1/2/3 and (b) SLA (m) calculated relative to this MSS.

Figure 4. Temporal variability of anomalies of surface geostrophic velocities (m/s) directed normal to 133 (a) and 209 (b) tracks. Positive values correspond to the southeast direction of currents, negative values correspond to the northwest direction.
It was interesting to estimate anomalies in water transport through the Middle Caspian. To obtain these values we extracted anomalies in water transport through 209 track from the anomalies of water transport through 133 track. As a result, in Fig.5b we have temporal variability of anomalies in water transport, which was accumulated in the Middle Caspian. These values ranged from $+15 \times 10^5$ m$^3$/s to $-20 \times 10^5$ m$^3$/s with maximum positive values in the summer time and minimum values in the winter time. This seasonal variability corresponds to seasonal variability of the Caspian Sea level which has a maximum in summer and minimum in winter. Interannual variability of this signal was irregular with periods of large and small seasonal amplitudes, which can differ three times (Fig.5). The reasons of this variability are not yet defined and requires special comparative analysis with data on water circulation derived from numerical models and with data on atmospheric forcing derived from re-analysis models.
Conclusions

In the present study we demonstrated the capabilities of the satellite altimetry data to be used in the analysis of temporal variability of anomalies in water exchange between the Northern, Middle and Southern Caspian. The proposed method showed to be very effective because it allows to calculate these values every 10 days which is impossible to do with in-situ measurements and is not so accurate if derived from numerical circulation models. This method seems to be very useful for other inland seas, for example, the Mediterranean, Adriatic, Black, Baltic, White and other seas where satellite tracks cross different parts of the seas at different angles which allows to estimate anomalies in water exchange between their sub-basins. Water exchange is an important basic parameter both for hydrodynamics of the seas and for estimates of pollutants transfer between sub-basins of the seas.

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