Satellite altimetry of the Caspian Sea

S.A. Lebedev [1, 2] , A.G. Kostianoy [3]

[1] Geophysical Center, Russian Academy of Sciences,
3, Molodezhnaya Str., Moscow, 119236 Russia,
E-mail: lebedev@wdcb.ru
[2] State Oceanographic Institute, 6 Kropotkinsky Per., Moscow, 119838, Russia
[3] P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences,
36, Nakhimovsky Pr., Moscow, 117997 Russia,
E-mail: kostianoy@mail.mipt.ru

The oscillations of the Caspian Sea level represent a result of mutually related hydrometeorological processes, which proceed not only in the sea catchment area but also far beyond it (Fig.1). The change in the tendency of the mean sea level variations that occurred in the middle 1970s, when the long-term level fall was replaced by its rapid and significant rise (Fig.2), represents an important indicator of the changes in the natural regime of the Caspian Sea [1]. Therefore, sea level monitoring and long-term forecast of the sea level changes represent an extremely important task. The aim of this presentation is to show the results of application of satellite altimetry methods to the investigation of seasonal and interannual variability of the sea level, wind speed and wave height in different parts of the Caspian Sea and Kara-Bogaz-Gol Bay, and the Volga River level. The work is based on the 1992-2004 TOPEX/Poseidon and Jason-1 data sets.

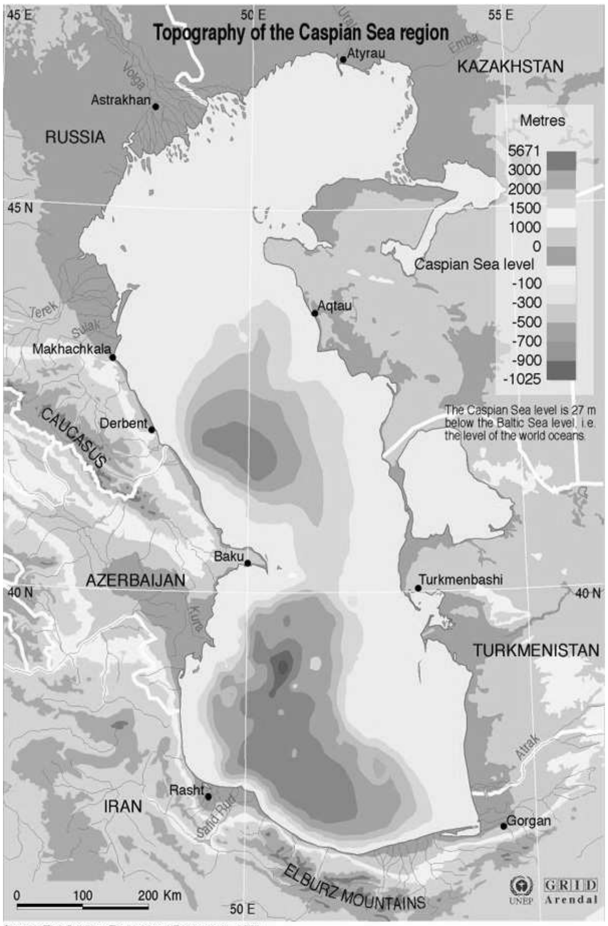
Introduction

The Caspian Sea presents the world's largest isolated water reservoir, 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 (Fig. 1). 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 [1].

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 the Volga River runoff. Since the early 1990s regular measurements of the Caspian sea level and main thermohydrodynamic parameters are practically absent. Today, the monitoring of the Caspian sea surface temperature, sea level, chlorophyll concentration, mesoscale dynamics, wind and waves, and some of the meteo parameters is organized based on the satellite IR and VIS data (AVHRR NOAA, MODIS), altimetry data (TOPEX/Poseidon, Jason-1) and re-analysis data.

The results obtained show that significant interannual changes in the Caspian thermohaline structure are inevitably reflected in the functioning of the sea ecosystem. So far as the Caspian ecosystem undergoes growing human-induced impacts, especially associated with an oil production, further research of the links between physical, chemical and biological parameters of the ecosystem, complex monitoring of the Caspian Sea state, and assessment of the future scenarios are of great importance.

Traditionally, the sea level variations, which are conditioned by different factors, were investigated basing on the sea level gauge data. But these data usually give information on sea level change only nearby the coastline



Source: The Caspian Environment Programme, 2002.

Fig. 1. The Caspian Sea

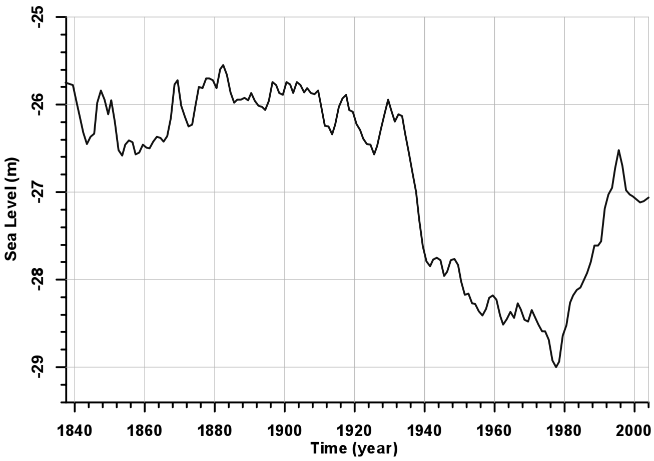


Fig. 2. Interannual variations of the Caspian Sea level measured by sea level gauges (1837–2004)

which has a significant impact on the measured data. Also, according to the last GPS measurements, some of the sea level gauges, for example, in the Barents, Baltic and Caspian seas [2], have a positive vertical lift, which is conditioned by the motion of earth crust. It also introduces considerable error in the interannual variability of sea level. Moreover, regular sea (lake) level measurements are practically absent for some regions in Africa and Central Asia [3]. For instance, in Former Soviet Union it was 79 gauge stations in the Caspian Sea in 1960, then – 51 in 1972, 36 in 1992, 3 in 2004 in Russia plus 4–5 stations in other Caspian countries (Fig.3).

These problems can be solved by use of satellite altimetry. It measures the sea surface height (SSH) relative to a reference ellipsoid (or the gravity center) that allows to eliminate a vertical lift of the earth crust from the interannual level variation. Spatial and temporal resolution of the satellite altimetry data allows to investigate seasonal and interannual variability of ocean, sea, lake and river levels [3–12].

Cazenave et al. [8] and Vasiliev et al. [13] have shown that satellite altimetry data can be successfully used for the investigation of the Caspian Sea level variability in a deficiency of the traditional sea level gauge measurements. The spatial location of the TOPEX/Poseidon (T/P) and Jason-1 (J1) ground tracks at the sea surface makes it possible to investigate different features of hydrological and hydrodynamic regimes of the Northern, Middle and Southern Caspian Sea, as well as of the Kara-Bogaz-Gol Bay (Fig.3).

In this paper we show the results of application of satellite altimetry to monitoring of sea level, wind speed and wave height variations in the Caspian Sea, as well as the Volga River water level.

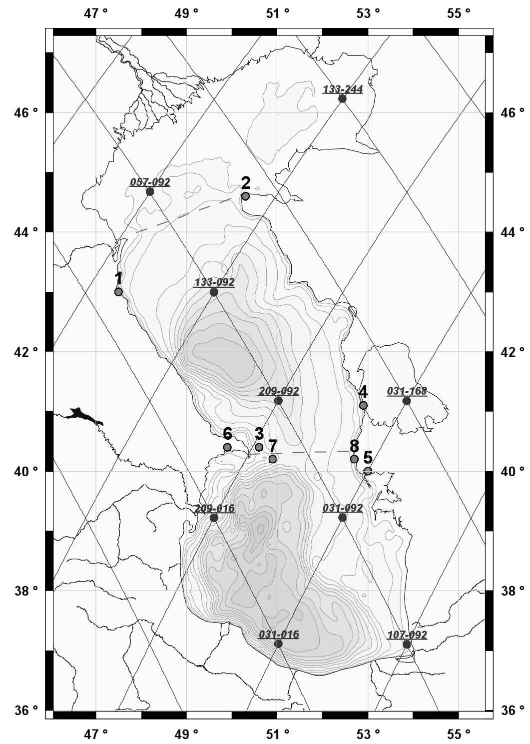


Fig. 3. Map of the Caspian Sea and ground tracks of the T/P and J1. Sea level gauges are shown as follows: 1 – Makhachkala, 2 – Fort Shevchenko, 3 – Zhiloy Island, 4 – Kara-Bogaz-Gol, 5 – Turkmenbashi, 6 – Baku, 7 – Neftyanye Kamni, 8 – Kuuli Mayak

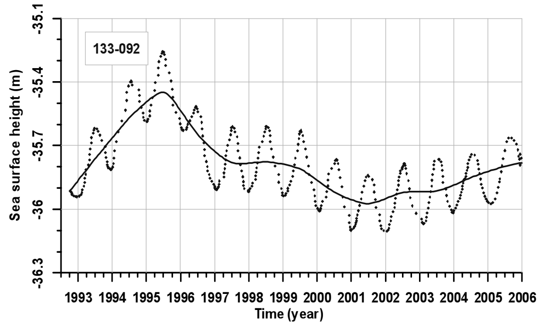


Fig. 4. The Caspian Sea level variability (SSH, m) at crossover point 133-092 since September 1992 till January 2006 on the base of satellite altimetry data of TOPEX/Poseidon and Jason-1

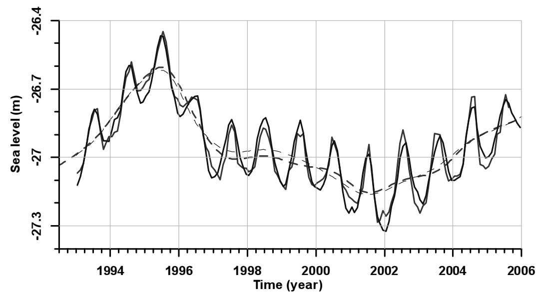


Fig. 5. The Caspian Sea level variability (m) since January 1993 till January 2006 on the base of satellite altimetry data of TOPEX/Poseidon and Jason-1 (black) and sea level gauges (grey). Dashed lines – interannua variability, solid lines – seasonal variability

DATA AND METHODOLOGY

For the analysis of the Caspian Sea level variations the measurements of T/P and J1 satellites were used for the following reasons. The precision of the measurements of SSH by T/P and J1 to the relative reference ellipsoid is 1.7 cm [14] that is higher than in other altimetry missions [15]. At the same time, accuracy of sea level measurements is of ~4 cm [6, 10] that allows to conduct the studies with an adequate accuracy. The position of the T/P and J1 ground tracks (Fig. 3) is optimal for the analysis of sea level variations in the Caspian Sea. The orbital repeat period (~10 days) enables the analysis of interannual and seasonal variability of the sea level. The T/P data represent the longest time-series of satellite altimetric measurements (since September 1992 to August 2002 or from 1 to 365 cycle) with a possibility of its extension by the J1 data along the same tracks (since August 2002 to present time).

We have analyzed 13 years of T/P and 3.5 years of J1 data since September 1992 till December 2005. Satellite altimetry data from T/P and J1 were obtained from the NASA Goddard Space Flight Center (GSFC) Ocean Altimeter Pathfinder Project [16]. Besides, the T/P merged geophysical data records (MGDR) were obtained from the NASA Physical Oceanography Distributed Active Archive Center (PODAAC) at the Jet Propulsion Laboratory (JPL) of California Institute of Technology [17]. The J1 Interim Geophysical Data Record (IGDR) and Geophysical Data Record (GDR) were obtained from AVISO (Archivage, Validation et Interprétation des données des Satellites Océanographiques) and PODAAC [18]. Information and software of Integrated Satellite Altimetry Data Base (ISADB) developed in the Geophysical Center of Russian Academy of Sciences [19] have been used for data processing and analysis. Methodology of data processing and analysis as well as the obtained results on the Caspian Sea level, wind speed and wave height variations were described in detail in [20].

THE CASPIAN SEA

Temporal variation of the Caspian Sea level was calculated on the base of the sea surface height (SSH) variation in different crossover points of ascending and descending passes (Fig.3). We took two points in the Northern Caspian (057–092 and 133–244), two points in the Middle Caspian (133-092 and 209-092) and three points in the Southern Caspian (209–016, 031–092, 031–016). An example for the point 133–092 is shown in Fig.4 and an integrated sea level variability for the whole Caspian Sea – in Fig.5.

Between October 1992 and March 1995 the Caspian Sea level was still rising at the rate of +20.4 cm/yr. In August 1995 the sea level started to drop abruptly and a negative trend was being observed until winter 2001/2002, when a local minimum (–27.3 m) was achieved (Fig.5). Since November 1995 to September 1996 the rate of the Caspian Sea level drop was 23.1 cm/yr, later it decreased to –5.3 cm/yr in October 1996 – June 1998 and to –9.1 cm/yr in December 1998 – April 2001.

Since January 2002 till December 2005 the Caspian Sea level was rising with a mean rate of +7.5 cm/yr. We have to note that the Northern, Middle and Southern Caspian have a little bit different temporal behavior of their sea levels as well as their rate of change [20]. On the average the seasonal amplitude of sea level variability was about 25–30 cm (Fig.9a).

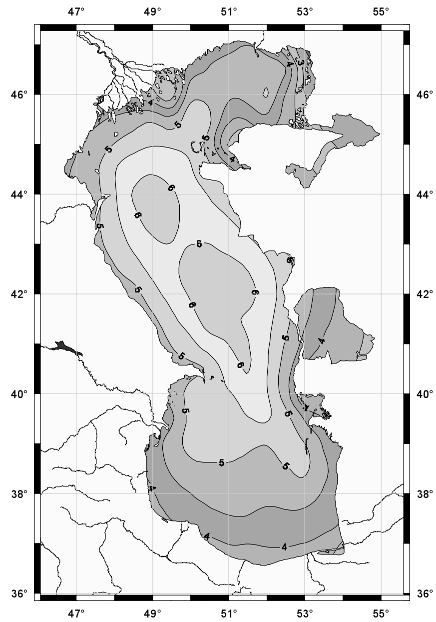


Fig. 6. Mean wind speed (m/s) at the sea surface basing on T/P and J1 data for September 1992 – June 2004

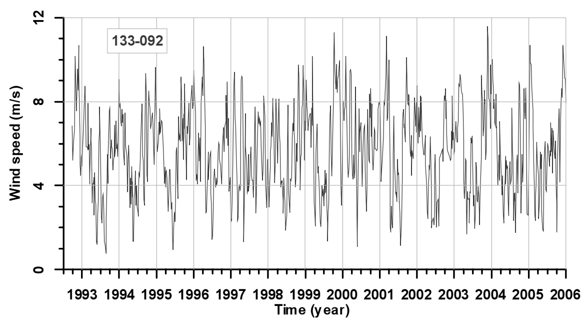


Fig. 7. Wind speed (m/s) at crossover point 133-092 in the Middle Caspian in Sept. 1992 – Dec. 2005

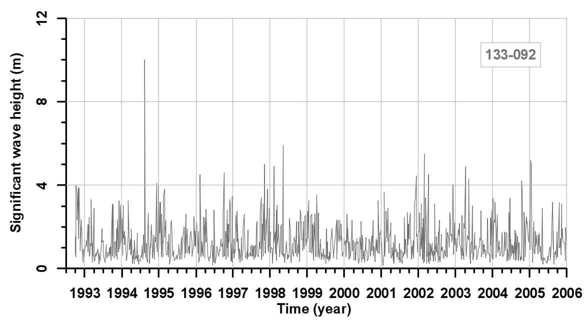
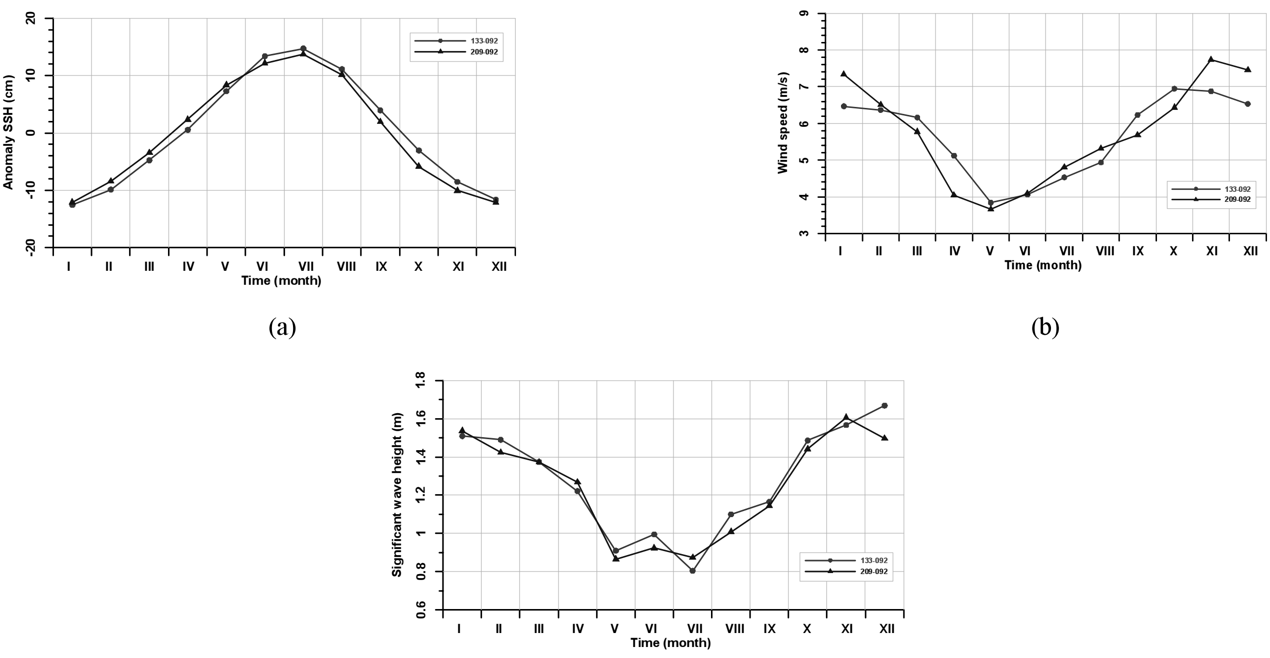


Fig. 8. Wave height (m) at crossover point 133-092 in the Middle Caspian in Sept. 1992 – Dec. 2005



(a) (b) (c)

Fig. 9. Seasonal variability of (a) SSH (m), (b) wind speed (m/s) and (c) wave height (m) at crossover points 133-092 and 209-092 in the Middle Caspian for September 1992 – August 2002

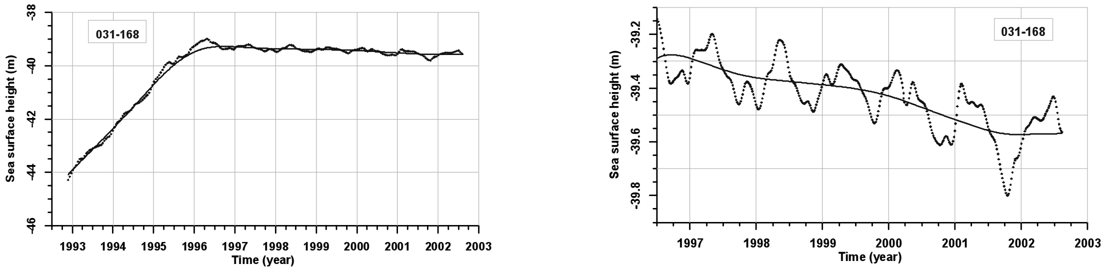
Comparison of SSH variations in 7 crossover points with data of 8 sea level gauges has shown that the maximal value of correlation coefficient 0.96 was observed between a station in Baku and 209–092 crossover point (Fig.3). For the sea level time variability of the whole sea, which is traditionally calculated basing on four gauges (Makhachkala, Baku, Fort Shevchenko and Krasnovodsk (nowadays Turkmenbashi)), the correlation coefficient for all crossover points is higher than 0.9.

Interannual and seasonal variability of wind speed and wave height have been investigated on the base of the same data sets [20]. Some of the results are shown in Figs.6-9.

THE KARA-BOGAZ-GOL BAY

In March 1980, in order to restrict the losses of the Caspian waters and to decelerate the fall of the level of the Caspian Sea, which, in 1977, had been the lowest over the past 400 years (–29 m), the Kara-Bogaz-Gol strait was closed by a nonoverflow sand dam; this way, the delivery of the seawater to the bay was stopped. After the separation of the bay, it was rapidly dried off. By the middle of 1984, the bay had been almost completely dried off and transformed into a "dry" salt lake. In order to protect and develop the unique salt field on the Caspian Sea under the conditions of the rapid sea level rise (Fig.2), it was decided to rehabilitate the water supply to the Kara-Bogaz-Gol. In September 1984, the feed of the Caspian water to the bay at a rate of 1.5-1.6 km3/yr was resumed. This restricted seawater supply did not result in an active restoration of the hydrological and hydrochemical conditions of the bay. In April 1992, the area of the bay reached 4,600 km2, the absolute level mark was –33.71 m, and the depths varied from 0.2 to 1.4 m. In June 1992, the dam was destroyed and the natural seawater runoff to the bay resumed.

The process of the filling of the bay and its acquisition of the climatic regime is well traced in the satellite altimetry data of T/P and J1. Fortunately, a start of the T/P mission successfully coincided with the beginning of filling the bay (Fig.10) and the area of the bay is



(a) (b)

Fig. 10. Interannual and seasonal variability of SSH (m) in the Kara-Bogaz-Gol Bay at crossover point 031-168 in (a) September 1992 – August 2002 and (b) July 1996 – August 2002

crossed by two tracks of the above-mentioned satellites. Up to the middle of 1996, the bay was rapidly filled with the Caspian water (Fig.10a) causing a rate of the level rise of about 168 cm/yr [20]. Then, the level rise stopped and its variations started to reflect seasonal changes (Fig.10b) well correlated with the seasonal level changes in the Caspian Sea. Thus, the rate of the level fall (until winter 2001/2002) in both of the basins comprised approximately 6 cm/yr. At present, the level of the bay oscillates near an absolute mark of –27.5 m.

THE VOLGA RIVER

About 80% of the total riverine runoff to the Caspian Sea is provided by the Volga River, whose mean annual runoff makes about 240 km^3/yr. The greatest runoff equal to 368 km^3/yr was recorded in 1926, while the minimum and extremely small values equal to 150 and 163 km3/yr were noted in 1921 and 1973, respectively. Thus, during the past century, the differences in the runoff of the Volga River exceeded 200 km^3/yr. Up to 25% of the Volga River runoff is supplied to the sea in May–June during the flood periods.

River water level variability was analyzed also basing on SSH in crossover points of 235 passes with river-bed (Fig.11). The obtained results were verified with water discharge rate at the Volgograd hydro-electric power station located far upstream (Fig.12). The correlation coefficient was about 0.83 for annual values and 0.71 for monthly mean values. The flood low volume in spring 1996 was well tracked in both data types. Negative SSH trend 46.7 cm/yr in 1993–1996 corresponds to the decrease of average annual water discharge in the Volgograd power station from 10,654 to 5,609 m^3/s. Close to the track pass there are three hydrological stations at the river – Enotaevka, Seroglazovka and Verkhnee Lebyajye. Satellite SSH correlates with daily measurements at these stations much better – 0.8–0.9 [20].

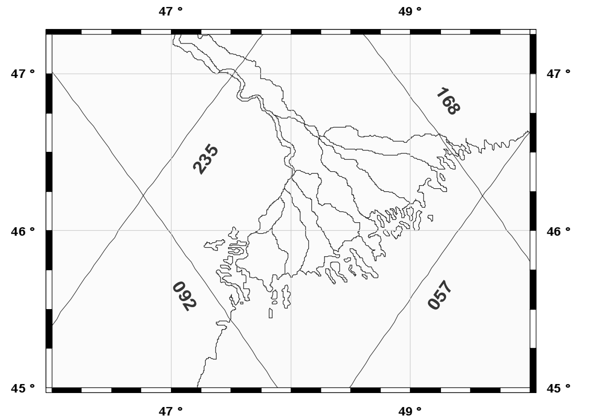


Fig. 11. The Volga River delta and T/P and J1 tracks

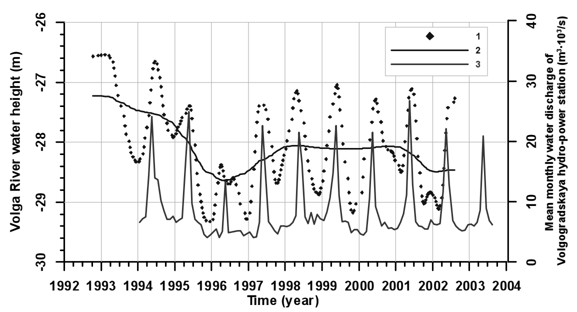


Fig. 12. Variations of (1) the Volga River SSH (m) and (2) SSH interannual variability derived from T/P altimetry (January 1992 – December 2003), and (3) mean monthly water discharge at the Volgograd power station

ACKNOWLEDGEMENTS

This study was supported by the Project "Elaboration of technologies for multi-level regionally adapted ecological and geodynamical monitoring of the Russian seas" of the Federal Program of the Ministry of Education and Science of the Russian Federation "Investigations and elaborations in the priority fields of science and technology", a series of grants of the Russian Foundation for Basic Research (04-05-64239, 06-05-64871), and by the NATO SfP PROJECT №981063 "Multidisciplinary Analysis of the Caspian Sea Ecosystem" (MACE).

REFERENCES

1. The Caspian Sea Environment. /Eds. Kostianoy A.G. and Kosarev A.N. Springer-Verlag, Berlin, Heidelberg, New York, 2005. 271 pp.
2. *Scherneck H.-G. et al.* BIFROST project: 3-D crustal deformation rates derived from GPS confirm postglacial rebound in Fennoscandia // Earth Planets Space, 2001, 53, P. 703–708.
3. *Kostianoy A.G., Zavialov P.O. and Lebedev S.A.* What do we know about dead, dying and endangered lakes and seas? In: Dying and Dead Seas. /Eds. J.C.J. Nihoul, P.O. Zavialov, Ph.P. Micklin. NATO ARW/ASI Series, Kluwer Acad. Publ., Dordrecht, 2004, P. 1–48.
4. *Morris G.S. and Gill S.K.* Variation of Great Lakes water levels derived from GEOSAT altimetry // Water Resour. Res., 1994, 30(4), P. 1009–1017.
5. *Morris G.S. and Gill S.K.* Evaluation of the TOPEX/POSEIDON altimeter system over the Great Lakes // J. Geophys. Res., 1994b, 99(C12), P. 24527–24540.
6. *Birkett C.M.* The contribution of TOPEX/ POSEIDON to the global monitoring of climatically sensitive lakes // J. Geophys. Res., 1995, 100(C12), P. 25179–25204.
7. *Larnicol G., Le Traon P.-Y., Ayoub N. and De Mey P.* Mean sea level and surface circulation variability of the Mediterranean Sea from 2 years of TOPEX/POSEIDON altimetry. // J. Geophys. Res., 1995, 100(C12), P. 25163–25177.
8. *Cazenave A., Bonnefond P., Dominh K. and Schaeffer P.* Caspian sea level from TOPEX/ POSEIDON altimetry: Level now falling // Geophys. Res. Lett., 1997, 24(8), P. 881–884.
9. *Fenoglio-Marc L.* Analysis and representation of regional sea-level variability from altimetry and atmospheric–oceanic data // Geophys. J. Int., 2001, 145, P. 1–18.
10. *Nerem R.S. and Mitchum G.T.* Sea Level Change // Satellite altimetry and earth sciences. A handbook of techniques and applications /Eds. L.-L. Fu and A. Cazenave. Academic Press, San Diego, 2001, P. 329–350.
11. *Mercier F., Cazenave A. and Maheu C.* Interannual lake level fluctuations in Africa (1993-1999) from Topex-Poseidon: connections with ocean-atmosphere interactions over the Indian Ocean // Global and Planetary Change, 2002, 32, P. 141–163.
12. *Lebedev S.A., Zilberstein O.I., Popov S.K. and Tikhonova O.V.* Analysis of temporal sea level variation in the Barents and the White Seas from altimetry, tide gauges and hydrodynamic simulation. In: International Workshop on Satellite Altimetry. /Eds. C. Hwang, C.K. Shum, J.C. Li, International Association of Geodesy Symposia, Vol. 126, Springer-Verlag, Berlin, Heidelberg, 2003, P. 243–250.
13. *Vasiliev A.S. et al.* Research of the Caspian Sea level by satellite altimetric measurements. In: Investigations of the oceans and seas. Proceedings of State Oceanographic Institute, Hydrometeoizdat, St. Petersburg, 2002, Vol. 208, P. 277–292 (in Russian).
14. *Fu L.-L. and Pihos G.* Determining the response of sea level to atmospheric pressure forcing using TOPEX/POSEIDON data // J. Geophys. Res., 1994, 99(C12), P. 24633–24642.
15. *Chelton D.B. et al.* Satellite Altimetry. In: Satellite altimetry and earth sciences. A handbook of techniques and applications. /Eds. L.-L. Fu and A. Cazanave. Academic Press, San Diego, 2001, P. 1–131.
16. *Koblinsky C.J. et al.* NASA Ocean Altimeter Pathfinder Project. NASA Goddard Space Flight Center. Report 1: Data Processing Handbook, NASA/TM–1998–208605, 1999. – 55 pp. Report 2: Data Set Validation, NASA/TM–1999–209230, 1999. 56 pp.

17. *Benada R.J.* Merged GDR (TOPEX/POSEIDON) – Generation B Users Handbook. Version 2.0. Physical Oceanography Distributed Active Archive Center (PODAAC), Jet Propulsion Laboratory, Pasadena, JPL D–11007, 1997. 131 p.
18. AVISO and PODAAC. User Handbook IGDR and GDR Jason Products. SMM–MU–M5–OP–13184–CN (AVISO), JPL D–21352 (PODAAC), Edition 2.0, 2003. 107 pp.
19. *Medvedev P.P., Lebedev S.A. and Tyupkin Y.S.* An Integrated Data Base of Altimetric Satellite for Fundamental Geosciences Research. In Proc. First East-European Symp. Adv. in Data Bases and Information Systems (ADBIS'97) St.-Petersburg, Russia, September 2-5, 1997. St.-Petersburg, St.-Petersburg Univ., 1998, Vol. 2, P. 95–96.
20. *Lebedev S.A. and Kostianoy A.G.* Satellite Altimetry of the Caspian Sea // Moscow: Sea, 2005. 366 pp. (in Russian).