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Volga River • Wave height • Wind speed

## Abbreviations

ALTICORE	ALTImetry for COastal REgions
CERSAT	Center for Satellite Exploitation and Research
COAPS	Center for Ocean Atmospheric Prediction Studies
ECMWF	European Centre for Medium-range Weather Forecasts
FAS	Foreign Agricultural Service
GC RAS	Geophysical Center of Russian Academy of Sciences
GCOS	Global Climate Observing System
GDR	Geophysical Data Record
GFO	Geosat Follow-On
GLOSS	Global Sea Level Observing System
GPS	Global Positioning System
GTOS	Global Terrestrial Observing System
IFREMER	Institut Français de Recherche et d'Exploitation de la MER
INTAS	International Association for the promotion of co-operation with scientists from the New Independent States of the former Soviet Union

IPCC	Intergovernmental Panel on Climate Change
ISADB	Integrated Satellite Altimetry Data Base
LEGOS	Laboratoire d'Études en Géophysique et Océanographie Spatiales
MACE	Multidisciplinary Analysis of the Caspian Sea Ecosystem
MODIS	Moderate Resolution Imaging Spectroradiometer
MSS	Mean Sea Surface
NCEP	National Center for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
RADS	Radar Altimeter Database System
RMS	Root Mean Square
RA	Radar Altimeter
SMMR	Scanning Multichannel Microwave Radiometer
SSH	Sea Surface Height
SSM/I	Special Sensor Microwave/Imager
T/P	TOPEX/Poseidon
T-UGO 2D	Toulouse Unstructured Grid Ocean model 2D
USDA	US Department of Agriculture
WGS 84	World Geodetic System 1984

## 13.1

### Introduction

The Caspian Sea is the largest continental water body on the Earth. Descendant of the ancient Thetys Sea that once comprised the actual Black, Caspian, and Aral seas, nowadays the Caspian Sea has no connection with the World Ocean. However, its size, depth, chemical properties, and peculiarities of thermohaline structure, water circulation, and biodiversity make it possible to classify it as a deep inland sea. The Caspian Sea has an unique and precious ecosystem, including the largest sturgeon population in the world that in the 1990s gave 90% of world supply of caviar. At the same time, the sea has important oil deposits that have been exploited for more than a century near Baku and only recently (since the 1990s) in the shelf regions in the Northern Caspian. The sea is shared by five countries – the Russian Federation, Kazakhstan, Turkmenistan, the Islamic Republic of Iran, and the Azerbaijan Republic.

Owing to its size and geographical location, the Caspian Sea is truly a large-scale climatic and ecological indicator. The main peculiarities of the sea are rapid and considerable changes of hydrophysical, hydrochemical, and hydrobiological states under the influence of external factors (Kostianoy and Kosarev 2005).

All large-scale or global changes, such as temperature variability, rapidly affect natural conditions, sea level, and the ecosystem of the Caspian Sea (Kostianoy et al. 2008). A recent example is the introduction of exotic organisms (such as *Mnemiopsis leidyi Agassiz*) into the Caspian Sea from other regions of the World Ocean.

One of the most important parameters of the Caspian Sea is its level. Explanation of interannual sea level changes puzzles the scientists of many countries and at the same time stimulates studies of water level changes in other seas of the world in the context of

climatic changes. Recent increased importance of the Caspian Sea region and its resources attracts interest of various international organizations for problems of the Caspian Sea. There is a possibility that existing experience for solving various problems (such as potential consequences of global sea level rise and climate change, optimization of wildlife management, etc.) can be applied in the context of large changes in the Caspian Sea.

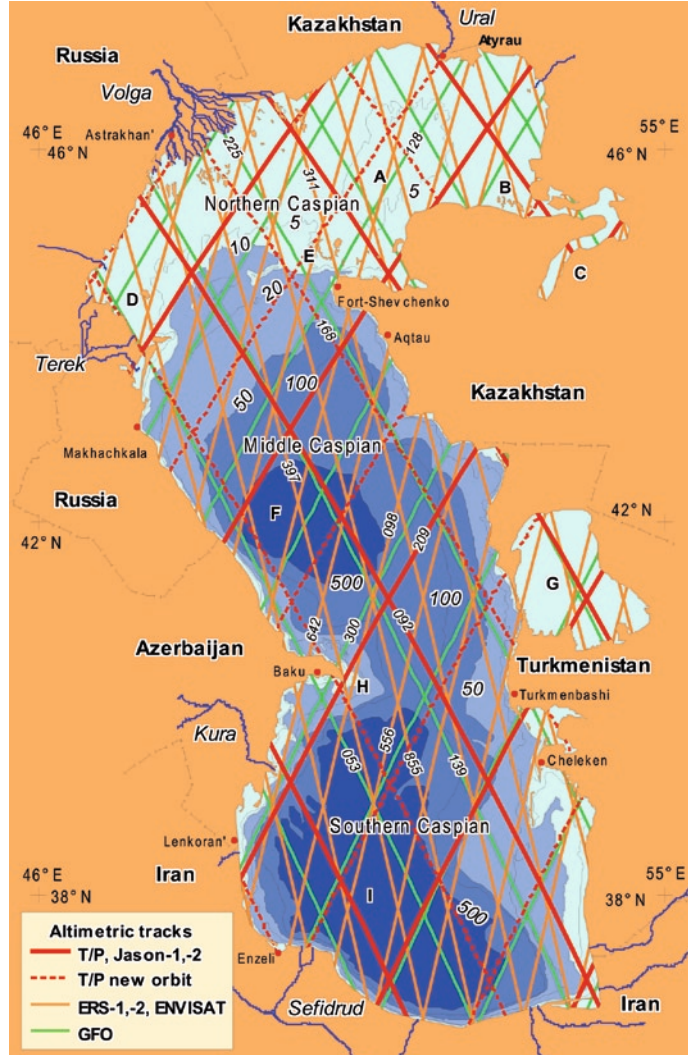
Actually (average data for 2008), the Caspian Sea lies about 27.1 m below the World Ocean (with respect to the Baltic reference altitude system). At this position, the sea surface is more than 410,000 km<sup>2</sup>, and the water volume is about 78,000 km<sup>3</sup>. The sea extends for more than 1,100 km from north to south, and its width is 200–400 km in the central and southern parts, and more than 500 km in the northern part. Such a large extent and great variability of climatic conditions over the sea result in large regional differences in thermal-haline structure and water dynamics.

The Caspian Sea occupies a vast depression in the Earth's crust and comprises three distinct regions with particular bottom topography and natural conditions: Northern, Middle, and Southern Caspian (Fig. 13.1). The shallow Northern Caspian with the mean depth of 5–6 m and maximal depths of 15–20 m completely refers to the shelf zone. The Mangyshlak Ridge separates the Northern Caspian from the Middle Caspian with the Derbent Basin (maximal depth of 788 m). The Middle Caspian is connected through a one-way strait to the large Kara-Bogaz-Gol Bay. Apsheron Ridge (depths of 160–180 m) acts as a boundary between the Middle Caspian and the deepwater Southern Caspian Depression (maximal depth of 1,025 m) (Kosarev 2005).

Being an enclosed water basin, the Caspian Sea is strongly affected by the river input. Among more than 130 rivers entering the Caspian Sea, the most important is Volga. This river has an annual discharge of 236 km<sup>3</sup> and a watershed area of 1,360,000 km<sup>2</sup> (State water cadaster, 1930–1993), and provides more than 78% of the total river input into the Caspian Sea. Other important rivers are Ural, Terek, Sulak, and Kura. River inflow from Volga, Ural, and Terek (84% of the total river input into the Caspian Sea) is especially important for the Northern Caspian. Here, combination of large river runoff, small depths, and significant surface area results in existence of vast zones of fresh water transit and large-scale processes of mixing fresh and saline waters. Main features of this mixing zone explain the high biological productivity in this region of the Caspian Sea.

Winds play an important role in the formation of currents and mixing processes in the upper layer of the sea. In general, two main types of winds dominate over the whole Caspian Sea: the northerly (from northwesterly to northeasterly) and southeasterly. In annual distribution, northerly winds represent 40% of observations (with maximum of up to 50% in summer) and southeasterly winds –36% (with a maximum of about 40% observed in winter and spring) (Kosarev 2005). However, in each specific region of the Caspian Sea, temporal distribution of the wind field has its own particularities. Wind field significantly influences water dynamics and wave field. For the enclosed Caspian Sea, a combination of strong wind and atmospheric pressure can result in significant short-term (from a few hours to 1–2 days) increase or decrease of the sea level (storm surges) compared to its usual values. The highest sea level changes are typical for coastal regions, bays and bights. While in the Middle and Southern Caspian amplitude of storm surges is about 100–150 cm (Kosarev 2005), in the Northern Caspian extreme storm surges have resulted in 3–4 m increase of sea level, flooding large areas and affecting coastal settlements and

**Fig. 13.1** Overview map of the Caspian Sea and coverage of the altimetric ground tracks (selected tracks are numbered). Isobaths are in meters (referring to  $-28$  m). River contours are shown only for the regions near the coast. Coastline position is according to MODIS image of 11 June 2005. A – Ural Furrow, B – Mertviy Kultuk Bay, C – Kaydak Bay, D – Tyuleniy Island, E – Kulaly Island, F – Derbent Depression, G – Kara-Bogaz-Gol Bay, H – Neftyanie Kamni I – Southern Caspian Depression



infrastructure. On a smaller scale, seiche and baric waves also affect short-term Caspian Sea level fluctuations (Kosarev and Yablonskaya 1994; Kostianoy and Kosarev 2005).

Every winter, ice forms in the Northern Caspian and stays there for several months, covering large areas. Ice cover is also observed in the Middle Caspian, but on a much smaller scale. The presence of ice negatively affects navigation, fisheries, and other industrial activities in the coastal areas and on the shelf. Of special concern is the impact of sea ice on industrial structures located in the coastal zone, such as Russian and Kazakh oil prospecting rigs operating on the Northern Caspian shelf. Ice conditions make it necessary to maintain an ice-breaker fleet as well as to use oil drilling rigs of arctic-class in the Northern Caspian. Ice cover also affects the accuracy of altimetric measures over the Caspian Sea (see Sect. 13.4).

In Sect. 13.2, we consider variability of the Caspian Sea level and the in situ level gauge network. In Sect. 13.3, specificity of application of satellite radar altimetry for studies of the Caspian Sea is discussed and in Sect. 13.4, various areas of combination of satellite and in situ data for the studies of natural regime of the sea are presented.

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## 13.2

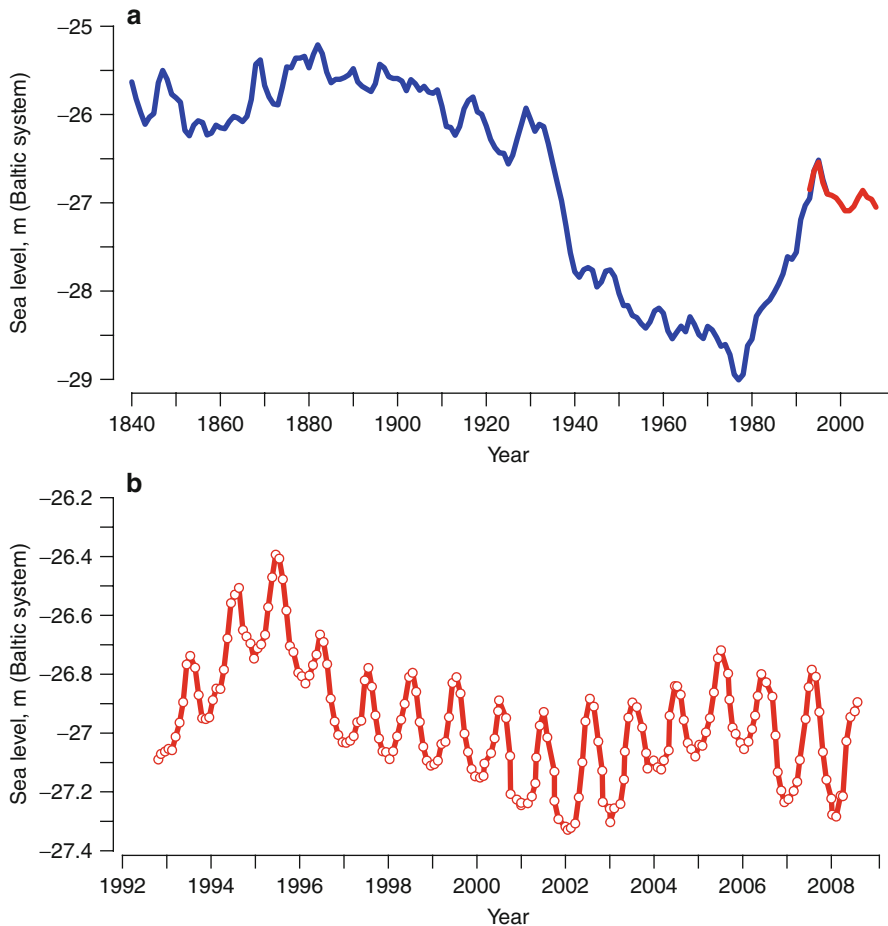
### Caspian Sea Level Variability and Its Observations by Level Gauges

The Caspian Sea is characterized by cyclic and high-amplitude water level variations over historical timescales. For the last 2,000 years, fluctuations were around 11 m (Lebedev and Kostianoy 2005) and for the last five centuries around 7 m, with an extreme level of  $-23$  m at the end of first century, mid-seventeenth century, and end of seventeenth century, and  $-29$  m in 1977. Since the start of observations and until the beginning of the twentieth century, sea level was about  $-25.8$  m (Fig. 13.2). Between 1900 and 1929, sea level remained around  $-26.2$  m and its variability was low. In the 1930s, creation and filling of large reservoirs on the Volga River, as well as regional climate change over the watershed, led to level decrease by 1.8 m between 1930 and 1941. Since that time, the study of sea level variability became important not only from the scientific, but also from the applied point of view. After 1941 and until the 1950s, the sea level decrease slowed and in the 1960s level was stable around  $-28.4$  m. Since the 1970s, a rapid sea level decrease started and in 1977 the level reached  $-29$  m: the lowest mark for the last 400 years. Since then, and quite unexpectedly, the Caspian Sea level rapidly began to rise by about 2.5 m ( $-26.5$  m in 1995). After 1995, the level started to decrease again and in winter 2001–2002 reached  $-27.3$  m (Lebedev and Kostianoy 2005). Short-term increase by about 20 cm until 2005 was followed by a decrease of the Caspian Sea level at about the same rate.

Variations of the Caspian Sea level are closely related with components of the sea water balance. However, despite years of study and investigation, the physical mechanism generating long-term sea level changes is not well understood yet, neither are we able to predict the rise or fall of the level in the future. Significant water level fluctuations displace thousands of shoreline inhabitants, bring damage to industrial constructions and infrastructure, and are clearly a topic of public concern for riparian countries.

Sea level measurements of the Caspian Sea started in 1830, when the first level gauge was installed in Baku. The measurements have then been gradually extended to Astrabad Bay (1853), Makhachkala and Kuuly lighthouse (1900), Krasnovodsk (actual Turkmenbashi), Fort-Shevchenko, and Kara-Bogaz-Gol Bay (1921) (Pobedonostsev et al. 2005). After the creation of the Hydrometeorological service in 1929, many more observation points have been opened along the Caspian Sea coast until 1937. The changes of the coastline position led to closing of many stations. Four stations: Baku, Makhachkala, Fort-Shevchenko, and Krasnovodsk (Turkmenbashi) have been considered “century” stations (Terziev et al. 1992).

Sea level measurements were initially made in different height systems (Black Sea, Baltic Sea, local relative systems). In 1961, data for 31 level gauges were catalogued and a new “zero” mark was defined at  $-28$  m (Baltic system). In the 1970s, a new leveling survey was done on the western coast of the sea. As a result, levels of level gauges have been



**Fig. 13.2** (a) Annual Caspian Sea level (m, Baltic system), from in situ (*blue line*) and altimetric (*red line*) observations (Hydroweb data, initial values referred to GGM02C geoid are adjusted to in situ observations by subtracting 46 cm). (b) Seasonal variability of the Caspian Sea level (m, Baltic system) from altimetric data (Hydroweb)

recalculated. Because of increased accuracy of leveling and vertical movements of zero marks between the 1950s and 1977 (that are in the order of 2–5 mm/year), new zero marks have shifted (+7 to +11 cm) referring to the 1950s (Pobedonostsev et al. 2005). At the same time, the leveling survey has not been done on the eastern coast of the sea and actually there are two different height systems – 1950 system for the eastern and 1977 system (adopted since 1979) for the western coast. Pobedonostsev et al. (2005) state that as a result, differences between mean annual sea level measurements at the west and east coasts can reach up to 30 cm. To compensate for this, observations at the western coasts often are corrected back to the 1950s system, which creates ambiguities. There is a need for homogenization of sea level measurements at various level gauges and currently a new catalogue of the Caspian

Sea level is being prepared at the State Oceanographic Institute (A.N. Kosarev, personal communication 2010).

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### 13.3

#### **Application of Satellite Radar Altimetry for the Caspian Sea**

Continuous weather-independent observations from radar altimetry are a natural choice to complement the existing in situ sea level observations and to provide new information for open sea regions that have been never covered by direct sea level observations. The large Caspian Sea is extremely well sampled by the different radar altimeters' ground tracks (see Fig. 13.1). The existence of the altimetric datasets of decommissioned (TOPEX/Poseidon, or T/P, GFO and potentially ERS-1,-2) or currently in orbit satellites (Envisat, Jason-1 and -2) offers the possibility of continuous high-precision monitoring of the Caspian Sea level since the early 1990s. Future missions (AltiKa Sentinel-3, HY-2) will assure continuity of the altimetric datasets. The Caspian Sea can be considered an intermediate target between the open ocean and closed lakes, and it is an interesting object for evaluating the potential of satellite altimetry for enclosed water bodies. The sea has significant temporal and spatial variability in its sea level; it has been monitored for more than 150 years by in situ level gauges, yet the reasons of the sea level changes are still not fully known and its impact in the coastal zone is considerable.

Numerous studies based on coupled satellite altimetry and in situ gauges measurements have been published in different domains of continental hydrology. Some of them covered broad issues (Morris and Gill 1994a, b; Birkett 1995) while others focused on more specific lake or river basin case studies (Cazenave et al. 1997; Birkett 2000; Mercier et al. 2002; Maheu et al., 2003; Kouraev et al. 2004; Aladin et al. 2005; Coe and Birkett 2005; Crétaux et al. 2005; Frappart et al. 2005; Kouraev et al. 2008, 2009; Crétaux et al. 2009a, b). These studies show that radar altimetry is currently an essential technique for different applications: assessment of hydrological water balance (Cazenave et al. 1997; Crétaux et al. 2005), prediction of lake level variation (Coe and Birkett 2005), studies of anthropogenic impact on water storage in enclosed seas and reservoirs (Aladin et al. 2005; Zakhrova et al. 2007), correlation of interannual fluctuations of lake level on a regional scale with ocean-atmosphere interaction (Mercier et al. 2002), study of the impact of climate variability on river basins (Maheu et al. 2003), variability of river level and discharge (Kouraev et al. 2004a; Lebedev and Kostianoy 2005; Zakhrova et al. 2006), and analysis of floodplain water storage in the river basin (Frappart et al. 2005), as well as ice cover in enclosed seas and lakes (Kouraev et al. 2008).

Various studies have shown that altimetry data can be successfully used for the studies of sea level variability of the Caspian Sea (Cazenave et al. 1997; Vasiliev et al. 2002; Kostianoy et al. 2004; Lebedev and Kostianoy 2005, 2008b; Crétaux and Birkett 2006).

Prior to proper use of altimetric data, several issues should be addressed. Influence of tides, atmospheric forcing, and dry and wet tropospheric corrections have particularities for the Caspian Sea. Assessment of accuracy of existing geoid fields and definition of an alternative, e.g., a mean sea surface (MSS), need to be done. Potential influence of ice on altimetric measurements and bias between various satellite missions should be estimated, and validation of altimetric results by in situ measurements should be done.



### 13.3.1

#### Tides and Atmospheric Forcing

For the correction of both tides and atmospheric forcing, a regional model for high frequency motions for the Caspian Sea based on the T-UGO 2D hydrodynamic code (Mog2D follow-up) has been made. Model horizontal resolution is 7 km offshore, increasing to 1.5 km at the coast. Outputs from the model simulations permit us then to compute tides and short-term atmospheric loading response to be used for dealiasing correction in the X-TRACK processor of altimetric data (see the chapter by Roblou et al., this volume). From the model outputs, it seems that only M2 and S2 tidal constituents (Fig. 13.3) are relevant (with mean amplitudes of 2 and 1 cm and maximal amplitudes of 4 and 1.5 cm, respectively) and other constituents are very small (virtually negligible) in the model. However, there was no hourly level gauge data to validate the model in response to both astronomic and atmospheric loading. There is a strong need for permanent, GLOSS-compliant in situ data for validation and to confirm the regional tides and atmospheric forcing response in the model.

### 13.3.2

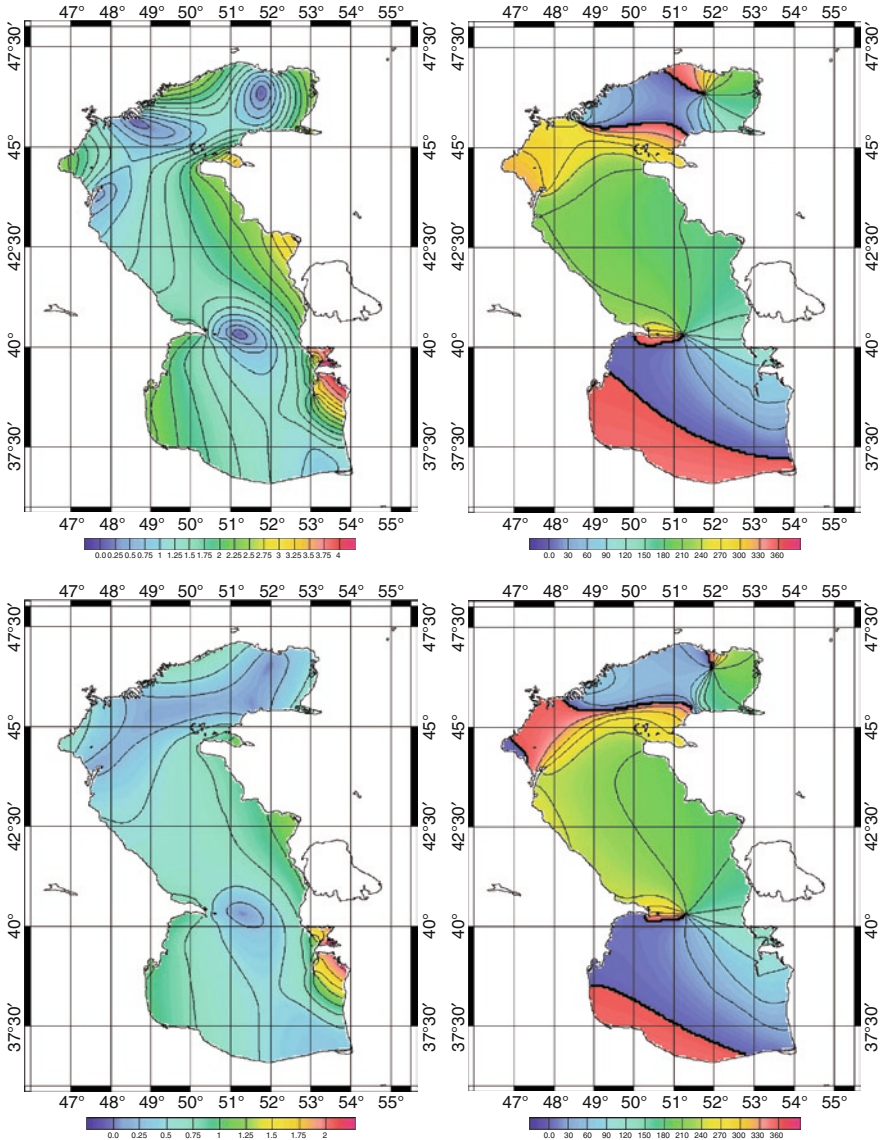
#### Atmospheric Corrections

Dry tropospheric correction is also one of the problems for using altimetry on enclosed water bodies. The value of this correction is altitude dependant, but T/P and GFO Geophysical Data Records (GDRs) incorrectly compute the correction at sea level, while for other satellites the correction is calculated strictly following the topography – i.e., to the lake bed. There might be large differences between data processing for various satellites, as some of them use the “wrong” pressure for the computation (i.e., they do not account for height of the water body). As for the wet tropospheric correction, it is possible over some enclosed water bodies to recover a radiometer correction, away from land, but sidelobe contamination issues remain (especially for Jason) and there is the need for the best possible models. In that case, one could use a wet tropospheric model based on gridded meteorological data sets at the altitude of the lake such as the European Centre for Medium-Range Weather Forecasts (ECMWF) (Mercier and Zanife 2006).

### 13.3.3

#### Mean Sea Surface

For large water bodies, the satellite altimetry data should be averaged over long distances and in order to transform altimetric measures to relative sea level anomalies, a subtraction of geoid is necessary. While the existing geoid models are sufficient for large-scale ocean studies, for inland waters a calculation of a regional mean sea surface represents a better solution. Usually MSS is 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. First of all, interannual changes of sea level here are sometimes much higher than seasonal ones (that are about 30 cm). Formation of ice cover should be



**Fig. 13.3** Amplitude (cm) and phase (degrees) of the M2 (*upper panel*) and S2 (*lower panel*) constituents from T-UGO 2D tidal solutions

accounted for in altimetric measures (through exclusion or correction of the data), as well as influence of river input, seiches, and baric waves.

Existing MSS models essentially differ according to the used information or temporal averaging interval. One of the possible solutions implemented in the Integrated Satellite Altimetry Data Base (ISADB) developed in the Geophysical Center of the Russian Academy of Sciences (GC RAS) is to analyze sea level variability at crossover points of ascending and descending

passes of T/P and Jason-1 (Lebedev and Kostianoy 2005). In this database, the GCRAS08 MSS model of the Caspian Sea was calculated according to the following scheme. At first from the T/P and Jason-1 Satellite altimetry data, the sea surface height (SSH) synoptic and seasonal variations for all passes of each repeat cycle were eliminated. In the last phase, the GCRAS08 MSS Model was constructed as a function of latitude, longitude, and time with consideration for climatic dynamic topography. This MSS is maximally close to the geoid height, calculated on model EGM96 with decomposition to 360°. In this case, the root-mean-square (RMS) deviation of a difference between SSH and geoid height is minimal at 17 cm, and the correlation coefficient between these two values is maximal at 0.999 (Lebedev and Kostianoy 2005). A possible explanation for this is that this model uses the longest time series available (September 1996–December 2008) of T/P and Jason-1 data. Every year GCRAS08 MSS is recalculated.

### 13.3.4

#### **Influence of Ice Cover on Altimetric Measurements**

Estimates of range between satellite and the echoing surface are obtained using procedures known as altimeter waveform retracking. Retracking retrieves the point of the radar echo that corresponds to the effective satellite-to-ground range. As the primary goal of most altimeters is the study of ocean topography, most of the retracking algorithms used are suited to the open ocean conditions. For example, T/P, Jason-1, and GFO all have only one onboard retracker that is adapted to the ocean surface. For the Caspian Sea, where stable ice cover is present every year for several months in the Northern Caspian, this poses a problem. Presence of ice significantly affects the shape of the returning radar waveform and could result in erroneous range estimates in winter.

In order to assess the degree in which ice presence affects altimeter range measures of the enclosed seas and estimate associated uncertainties, a study for the neighboring Aral Sea has been done using data from Envisat RA-2 altimeter (Kouraev et al. 2009). For this satellite, four different retracking algorithms (one – Ocean – for ocean conditions and three – Ice1, Ice2, and Sea Ice – for ice) are used to process raw RA-2 radar altimeter data. Presence of the four simultaneous range values from these retrackers for each 18 Hz RA-2 measure gives a possibility to precisely quantify the difference between various retrackers. Using the ice discrimination methodology (see Sect. 13.4.6 and Kouraev et al. 2008 for more details), each 18 Hz data has been classed as either open water or ice. Using this dataset, we have calculated the range differences between various retrackers and calculated separate statistics for the open water and ice cases.

It has been found (Kouraev et al. 2009) that because of its algorithm Ice1 retracker provides constantly higher sea level measures (about 25 cm for ice cover and 15–20 cm for open water) than the two other ice retrackers and this should be taken into account. For ice-covered sea, Ocean retracker constantly shows much higher level values than any of ice-adapted retrackers, with differences coming up to 40–45 cm. Thus, for Envisat, it is obviously better to use other retrackers than Ocean when ice cover is present. In the absence of in situ time series of the sea level for the Aral Sea, it was not possible to estimate the absolute difference for each altimetric satellite mission. However, in order to homogenize sea level time series for open water and ice-covered sea, it is suggested to subtract 40–45 cm from sea level measures from T/P, Jason-1,

and GFO (all of them use Ocean retracker) when the sea is ice-covered. These findings should also be relevant for the Aral Sea's neighbor and close relative – the Caspian Sea.

### 13.3.5

#### **Multi-satellite Bias**

Same as for ocean studies, merging of time series from different satellite missions requires an accurate assessment of biases and drifts for each parameter contributing to the final estimate of the sea level. To compute the Caspian Sea and Kara-Bogaz-Gol Bay water level in a multi-satellite mode, it is first necessary to estimate biases between satellites. In general, these values are in the range of 10–20 cm. After the MSS is computed (using data from all satellite missions) and subtracted, each satellite data are processed independently and potential radar instrument biases between different satellites are removed using T/P data as reference. Then water levels from the different satellites are merged to provide uniform time series.

### 13.3.6

#### **Calibration/Validation (Cal/Val) Activities**

The calibration technique over enclosed water bodies is however still immature even though important progress has already been achieved. A Cal/Val experiment in the Lake Erie (North American Great Lakes, Shum et al. 2003) has shown interesting limitation on the Sea State bias correction's calculation when algorithms developed over the ocean are used for other types of water surface. They also calculated altimeter biases for Jason-1 quite different from what was observed with ocean calibration sites. This is achievable when measurements of specific and numerous field campaigns and a permanent ground network of level gauges and meteo stations are processed to detect biases, errors in the geophysical corrections, etc.

There is a clearly expressed requirement (cf. Proceedings of the 2nd Space for Hydrology Workshop, WPP-280) calling for a number of regional validation efforts on the basis of in situ data – which most of the time are lacking and may require dedicated validation campaigns.

Shum et al. (2003) pointed out that the variety of calibration sites for altimetry had to be enlarged in order to have more global distribution and more robust assessment of the altimetry system, and to check if specific conditions lead to different estimation of absolute bias of the instruments. Calibration over lakes and enclosed seas surfaces has specific characteristics with respect to the ocean surface: wave and ocean tides are generally low, and dynamic variability is much weaker than in the oceans. On the other hand, while satellite altimeters are capable of providing a detailed picture and regular monitoring of ocean level, they are not optimized for coastal/inland retrievals. This is related to some processing and quality control issues, for example, the fidelity of corrective terms in coastal areas and possible contamination due to the presence of land in the radar footprint. These issues are currently impeding the effective use of altimeter-derived products in coastal areas and continental water bodies.

While the comparison of altimeter-derived Caspian annual mean sea level with level gauge data from different stations generally shows good agreement (maximal discrepancies

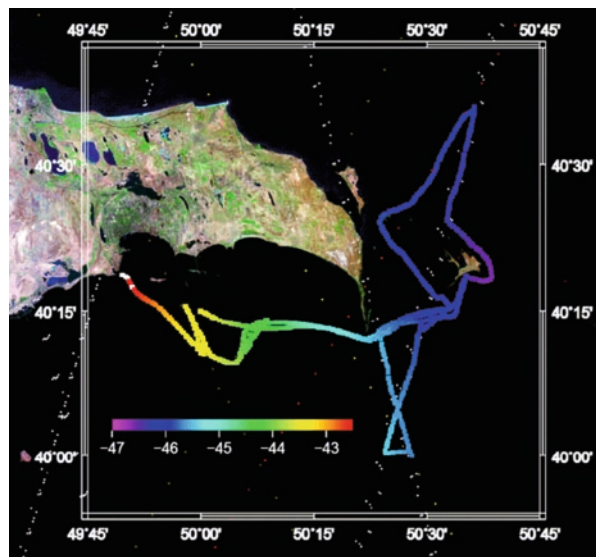
of 7 cm in 1995), careful and independent validation against in situ data is necessary. This validation should help to assess the uncertainties in the data products and separate instrumental changes from environmental ones. A regional Cal/Val site and experiments in the Caspian Sea would supply invaluable data to formally establish the error budget of altimetry over continental water bodies, in addition to the global mission biases and drift monitoring.

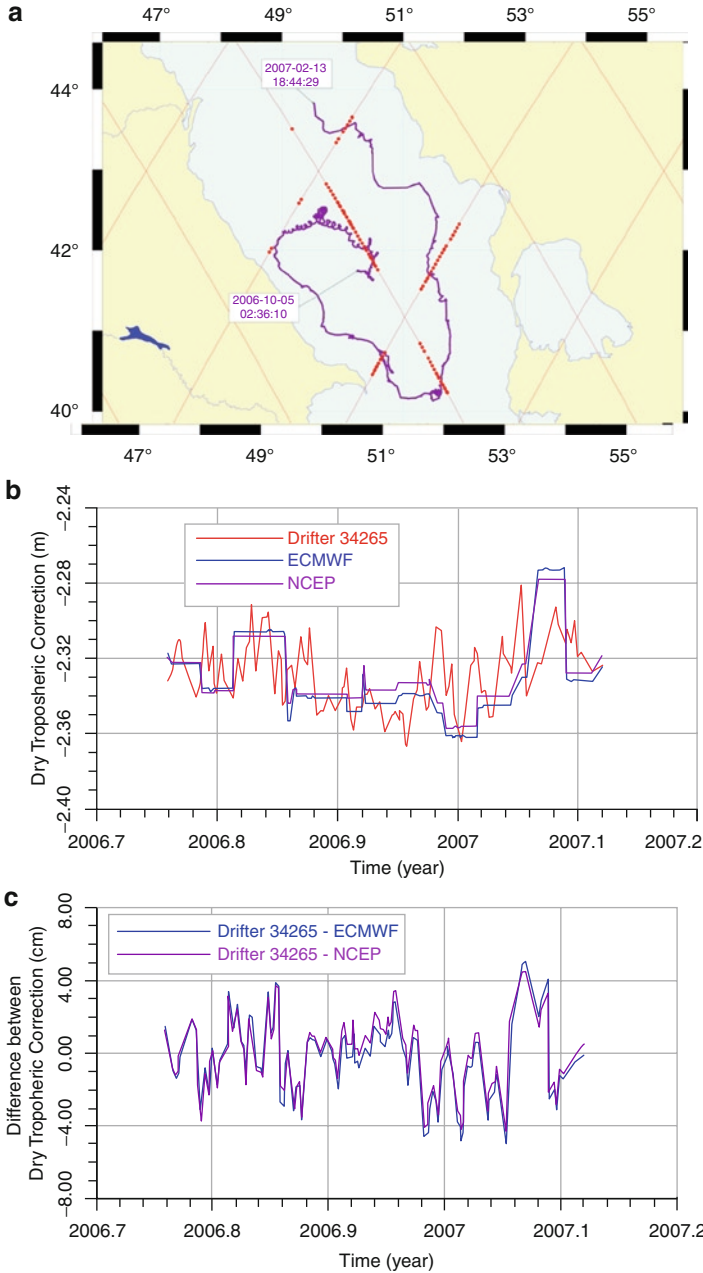
LEGOS (Laboratory of Space Geophysics and Oceanography, Toulouse, France) has taken part in a number of campaigns for absolute calibration of altimetry over lakes and enclosed seas, including one campaign in the Caspian Sea in 2005. In those campaigns, a GPS receiver along the track of the satellite at the time of an overpass has been used (Fig. 13.4). Such an approach helps to reveal specific features of altimetry over continental water bodies, such as the one found at Cal/Val site in Lake Issyk-Kul, in Central Asia, where a big slope of the mean lake surface – up to 5 m from one side to the opposite of the lake – was revealed (Crétaux et al. 2009a, b). Other issues specific to continental water bodies have also been studied during those campaigns to better understand the error budget of the geophysical corrections, and the precision of the different algorithm of retracking (Crétaux et al. 2009a, b).

The first drifter experiment in the Caspian Sea was carried out in October 2006–February 2007 in the framework of the MACE project (Lebedev and Kostianoy 2008a) (Fig. 13.5). Data on atmospheric pressure were used for computing a dry tropospheric correction, and RMS differences in the derived dry tropospheric correction between drifter and closest (in time and space) altimeter overpasses were between 2.25 and 3.86 cm.

Within the framework of the INTAS project ALTICORE (ALTimetry for COastal REgions) (Vignudelli et al. 2007), a pilot sea level station consisting of a bottom pressure recorder has been recently installed and put into operation in June 2008 at Apsheron Port, Azerbaijan (Vignudelli et al. 2008) to produce a high-quality data set of in situ sea level measurements. It is hoped that in 2–3 years this station will be part of the Global Sea Level

**Fig. 13.4** GPS measurements of sea level (m) with respect to the ellipsoid of reference (WGS84) along the altimeter tracks (T/P, GFO and Envisat) during the ship cruise in July 2005 near Apsheron Peninsula. It is supposed to match the geoid surface with respect to the ellipsoid. The colour scale is expressed in meters: observe the 4 m slope of the geoid between Baku and Jiloy Island





**Fig. 13.5** Data from the MACE drifter experiment. (a) Red marker shows on pass 092, 133, and 209 altimetry data which are used for comparison with result dry tropospheric corrections calculation on atmospheric sea level pressure 34265 drifter data. Dry tropospheric corrections (in m) on ECMWF and NCEP model and drifter data (b) and its difference (drifter minus ECMWF and NCEP, cm) for drifter 34265 from 5 November 2006 to 13 February 2007 (c) (Lebedev and Kostianoy 2008a)

Observing System GLOSS. This can be a good Cal/Val site for other missions as it is close to several altimeter ground tracks (including planned AltiKa satellite). The intention is to perform further geodetic leveling campaigns, including GPS measurements at land and sea, and to collect a preliminary accurate record of in situ sea level measurements at high temporal resolution.

It is important to mention that at present there are globally no stations maintained to GLOSS standards and therefore none of the numerous past or current level gauges is really usable for satellite altimetry validation. In addition, the absence of a transnational uniform geodetic leveling network along the coasts does not permit the comparability of in situ measurements of sea level at different sites. As no Caspian Sea country is currently participating in GLOSS programs, a regional example would better convince Caspian Sea countries of the value of sea level measurements and enhance co-operation with international institutions to build up competence in new technologies for sea level observation.

As stated previously, a study and demo project of Cal/Val site in inland waters to be tested using Envisat/Jason is necessary. The Caspian Sea would be the optimal target, being a big water object with perfect location of Envisat and Jason tracks and a station already in operation since June 2008 but with the need to be upgraded to achieve GLOSS-ALT quality requirements. It is important to highlight that no similar existing Cal/Val site in Europe would satisfy these requirements.

Further developing and validating a calibration and drift monitoring system over lake are necessary to reach requirements for planned satellite mission Sentinel-3 and for lake level monitoring with the accuracy required for an Essential Climate Variable (GCOS 2006).

The infrastructure on Apsheron site will include level gauge, permanent GPS satellite receivers, meteorological station, communication systems for data transmission, etc. The place is located close by a crossover point between Envisat and Jason tracks and is well suitable for altimeters calibration tasks.

### 13.3.7

#### Existing Datasets

There are several databases of long time series of altimetric sea level observations for the Caspian Sea and its parts. Some are publicly available online (Hydroweb, USDA Reservoirs database), while others not (cf. ISADB). On the basis of the same initial altimetric GDR data, each group of researchers uses different methods to estimate the resulting sea level for the given period.

*Hydroweb* ([Hydroweb web site 2009](#)). This altimetric water level data base at LEGOS, Toulouse, France, contains time series of water levels of over 150 lakes and enclosed seas, and 250 sites over large rivers and wetlands around the world. These time series are mainly on the basis of altimetry data from T/P for rivers, but ERS-1 & -2, Envisat, Jason-1, and GFO data are also used for lakes. For the Caspian Sea, observations since 1992 are used. The altimeter range measurements used for lakes consist of 1 Hz data.

*USDA Reservoir Database* ([USDA Reservoir Database web site 2009](#)). The US Department of Agriculture's Foreign Agricultural Service (USDA-FAS), in co-operation with the National Aeronautics and Space Administration, and the University of Maryland, is monitoring lake and reservoir height variations for about 100 lakes worldwide using T/P

and near-real time Jason-1 data. For the Caspian Sea water level, variations are computed with respect to a 10-year mean level derived from T/P altimeter observations and are provided with 10 days resolution without median filtering.

*Integrated Satellite Altimetry Data Base (ISADB).* This database has been developed at the Geophysical Center of the Russian Academy of Sciences (Medvedev et al. 1997; Lebedev and Kostianoy 2005). For the Caspian Sea, the satellite altimetry data of T/P and Jason-1 are used.

*Caspian Sea dataset from the X-TRACK processor.* In the framework of the ALTICORE project, a dedicated dataset for the Caspian Sea was developed using the X-TRACK processor (Roblou et al. 2007; Roblou et al., this volume). The objective of this processor is to improve both the quantity and quality of altimeter sea surface height measurements in coastal regions, by improving the correction phase (postprocessing). This X-TRACK-derived dataset for the Caspian Sea is on the basis of the use of 15 years of 1 Hz T/P plus Jason-1 data with a coastal-dedicated data edition strategy, an improved retrieval of environmental and sea state, tidal and atmospheric forcing corrections (provided by T-UGOm 2D simulations outputs), and a high resolution MSS. Currently, the dataset consists of (a) improved sea surface height estimates along each ground track, (b) a high resolution mean sea surface along each ground track, and (c) time series of sea level anomalies along the track or projected onto mean track.

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## 13.4 Results

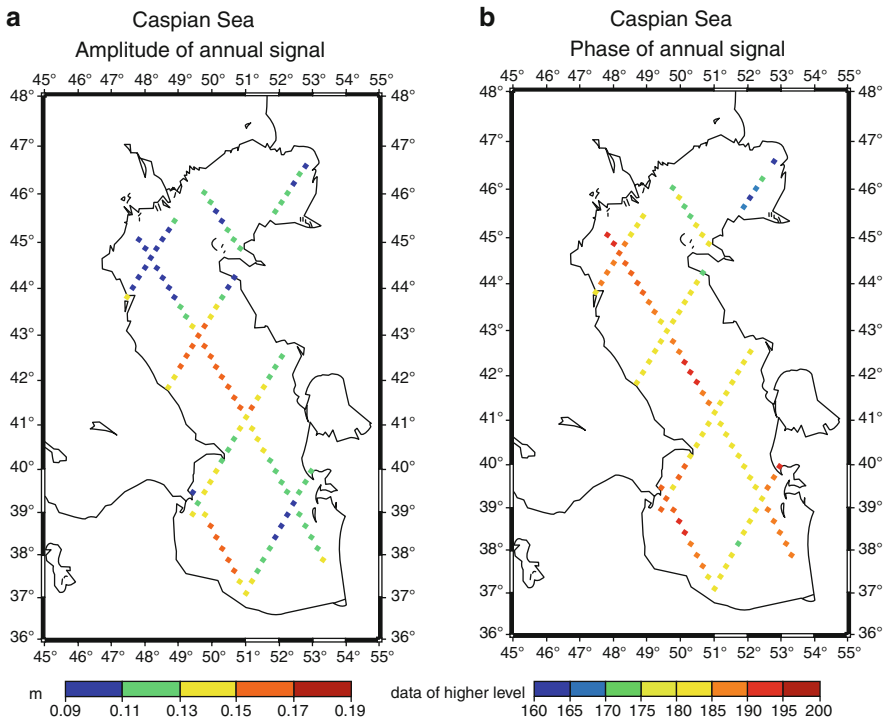
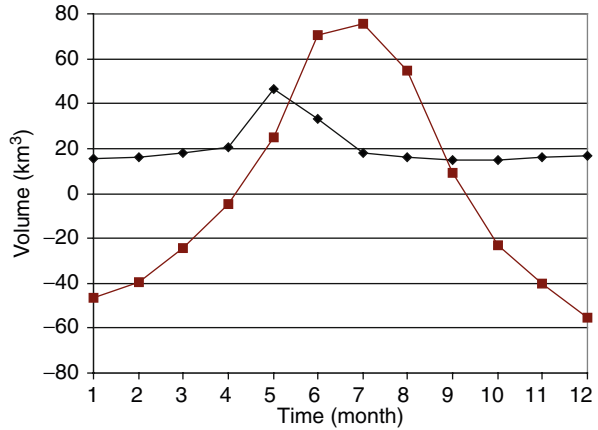
Besides monitoring interannual changes of the sea level, altimetry provides a valuable tool to monitor level changes at different temporal (from seasonal to short-term) and spatial scales. It can also provide useful information on sea level for storm surge events, as well as on water level of large rivers flowing to the sea, such as Volga. Sea level variability coupled with observations of other constituents of water budget can provide estimations of evaporation over the Caspian Sea or Kara-Bogaz-Gol Bay. Among other less direct applications of altimetry are observation of wind and wave regime over the sea, and study of its ice cover regime using synergy of active (radar altimeter) and passive (radiometer) microwave observations from altimetric satellites.

### 13.4.1 Seasonal Variability of the Caspian Sea Level/Volume

One of the main drivers of seasonal changes in the Caspian Sea is the river input, especially from the Volga which provides more than 78% of total inflow. Using mean monthly data of river runoff, we can compare (Fig. 13.6) the variability of river discharge and variations of the Caspian Sea volume (recalculated from sea level using a hypsometric curve). There is a marked temporal shift in the maxima – while Volga spring flood is observed in May–June, maximal peak of volume is observed 1–2 months later (June–July). Obviously not all the Caspian Sea volume variation can be explained by the Volga and other rivers discharge: one should also take into account seasonal changes in precipitation and evaporation.



**Fig. 13.6** Mean monthly values of Volga inflow (km<sup>3</sup>, black) and the Caspian Sea volume anomalies with respect to mean volume of each year (km<sup>3</sup>, dark red)



**Fig. 13.7** Amplitude (cm) and phase (day of the year when maximum amplitude was observed) for the Caspian Sea level calculated along the T/P tracks

Another interesting aspect is the spatial variability of the sea level that could provide more insight into the influence of Volga discharge on the Caspian Sea level. Spatial variability of amplitude and phase of T/P sea level observations (Fig. 13.7) shows the complexity of sea level changes. There is a marked spatial pattern with more than 15 cm of

annual amplitude in the Middle Caspian, while in the Northern or Southern Caspian this value does not exceed 10 cm. The timing of maximal seasonal level has an early (160–175 days, i.e., 9–25 June) peak in the eastern part of the Northern Caspian; 30–35 days later (185–195 days, i.e., 4–14 July) the maximum is observed in the western Northern Caspian, as well as in the Middle and Southern Caspian. It is interesting to note that the latest dates (200 days, i.e., 19 July) are typical for the region near the Volga delta in the Northern Caspian. Apparently, this spatial and temporal variability of sea level can not be attributed to Volga inflow alone – evaporation and precipitation play an important role, as well as influence of wind field on short-term sea level changes.

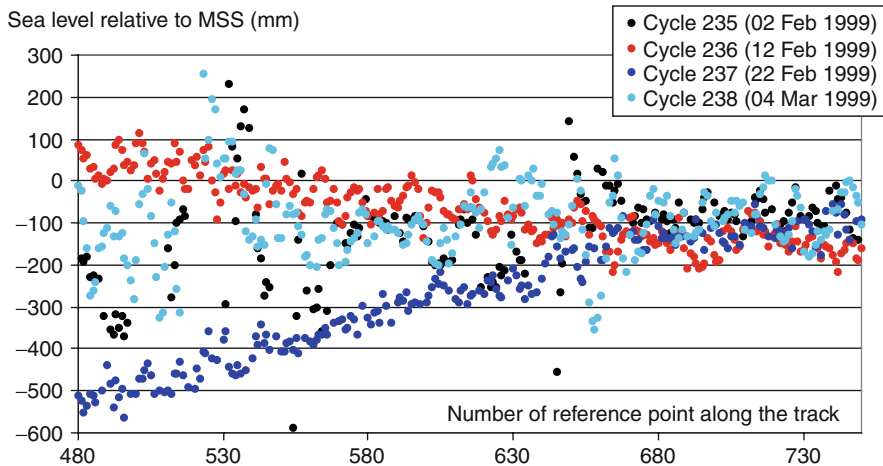
### 13.4.2

#### Storm Surges in Altimetry

The wind-induced storm surges occur along all the shores of the Caspian Sea. The most important and dangerous ones are observed in the large and shallow Northern Caspian. Usually they take place in spring and autumn, when winds from the north–northwest or southeast dominate. The storm surges last from several hours to several days, while the maximal registered duration was 8 days (Terziev et al. 1992).

Storm surge occurrence varies from 2–3 to 15–20 times per year and 60-cm high water level rises, due to the storm, are observed every year in the near-shore zones. Such rises are typically caused by winds with a speed of 10–12 m/s. Winds with a speed of 16–25 m/s can cause the water level rise of 1.5–2 m and for the Northern Caspian with average depth of just 5–7 m this is a dangerous event. The 3–4 m high sea level rise is catastrophic and can lead to an inundation of 30–40 km wide coastal band and to serious damages. Such extreme surges are formed under special wind situations when the strong effective wind is preceded by winds of opposite directions and the sea level decreases. This surge is a combination from wind-induced wave propagation and water level restoration. The catastrophic storm surges took place in 1877, 1910, 1952, and 1995 (Terziev et al. 1992; Kabatchenko 2006). As all the coastal zone of the Northern Caspian represents the low flat plain, the impact and scope of floods from storm surges will increase with the sea level rise.

In spite of some limitations, satellite altimetry is capable of observing the storm surges, as was the case at the beginning of 1999 (in this season sea level is not significantly affected by Volga River discharge). The T/P 10 Hz altimetric data have been processed to derive sea level anomaly above the mean sea surface for cycles 1–360. These values were plotted (Fig. 13.8) and the mean (median) sea level anomalies for the northern part of the ground track 092 (part between the coastline and isobath 20 m) have been calculated. For cycle 235 (02 February 1999) this value was –25.7 cm. The spatial distribution along the track is noisy near the coast and more stable (around –50 mm) seaward. Ten days later, we observe a significant increase of sea level anomaly – mean value rises up to 3.7 cm but extreme values near the Volga delta go up to 100 mm. At cycle 237 (22 February 1999) we observe a rapid decrease – mean values go down –54.7 cm and extreme values near the Volga delta are –500 mm. By the beginning of March (cycle 238), sea level has been restored (mean value is –11.1 cm) and closely resembles the initial sea level observations on 2 February.

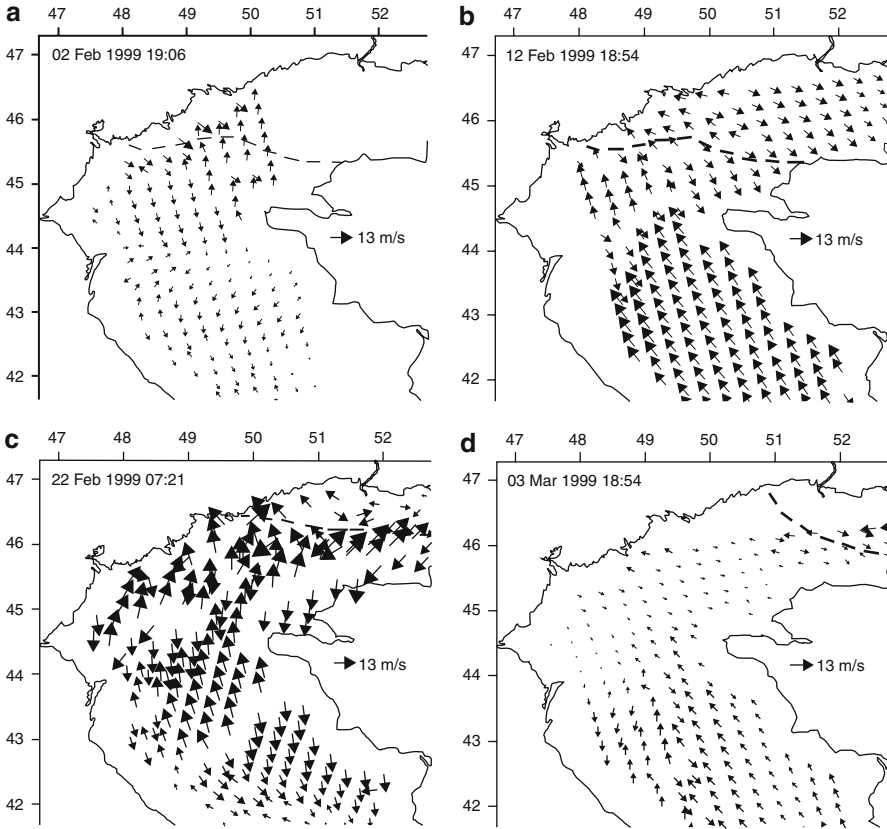


**Fig. 13.8** Variability of sea level in the Northern Caspian (mm, relative to the MSS). T/P data for ground track 092, X-axis – number of reference point (each point is separated by about 600 m) along the track (480 – intersection with 5 m isobath, 620 – with 20 m isobath, 745 – 50 m isobath, see also Fig. 13.1)

In order to complement these altimetric values and enhance the analysis, wind fields from AMI-Wind scatterometer have been used (IFREMER CERSAT web page 2009). These are the data from the C-Band active microwave instrument that provides radar backscatter measurements, from which wind speed and direction can be retrieved. Depending on satellite coverage, data for the Caspian Sea are available from two to three times per day to once every several days. We also have used the data on the ice extent and ice edge position using a methodology described in Sect. 13.4.6 (see Kouraev et al. 2008 for more details).

Four wind situations corresponding to the time of the T/P overflight (by ground track 092) have been selected (Fig. 13.9). On 2nd February, the wind was weak, with speed up to 5 m/s in the Middle Caspian and up to 12 m/s for north-westerly winds in the coastal region in the Northern Caspian. In the western Northern Caspian north-westerly winds did not exceed 3–4 m/s. In the next few days, the wind field was unstable but southeasterly winds started to dominate over the large areas, such as for 5 February (not shown). On 12 February we observed steady and uniform southeasterly winds over the whole Middle Caspian with speeds of 10–12 m/s. By entering the Northern Caspian, winds became less strong and their direction became more chaotic. Though in the eastern part of the Northern Caspian north-westerly winds were observed with speeds of 7–10 m/s, this area was ice-covered (see ice edge position on the corresponding image on Fig. 13.9) and the correctness of wind speed retrieval over ice was not known. Ice cover in the eastern part acted as a solid “lid” hindering sea surface increase and apparently the southeasterly winds created a pile-up of water (+30 cm on average for southern part of ground track 092) in the western part of the Northern Caspian.

For 22 February, we observe strong (up to 17 m/s) winds coming from southeast in the Middle Caspian and gradually turning to south and southwesterly winds in the Northern Caspian. In the western part of the Northern Caspian, some wind vectors have direction opposite to the main flow. This could be related to the so-called aliasing of wind solutions



**Fig. 13.9** Wind fields (m/s) from AMI-Wind scatterometer onboard ERS-2 for selected dates in February–March 1999. Dashed line – approximate ice edge position (westward from ice edge – open water, eastward – ice cover) obtained using an ice discrimination methodology (Kouraev et al. 2008)

from the scatterometer. The principle of deriving wind direction from scatterometer lies in determining the angle that is most likely to be consistent with the backscatter observed from multiple angles. Then a mathematical function fitting the observed backscatter as a function of the wind direction is applied. This function usually has multiple minima (ambiguities), with the best fit corresponding to the real wind direction and the next best fit being the opposite direction. Noise in the observations can lead to the choice of wrong direction. This problem is typical for weak winds (less than 8 m/s), where signal can be confounded with noise (COAPS web site 2009), and various “dealiasing” algorithms are usually applied by distributing agencies to remove this ambiguity. Apparently in this case for 22 February, dealiasing provided some wrong vectors that should be corrected to the opposite direction (this also applies for some vectors on the boundary between the Middle and Northern Caspian for 12 February). As a result, we would observe a homogeneous wind flow entering the Northern Caspian from the south and then gradually turning northeast. This situation has been confirmed by another satellite overpass later this day (not shown).

Retreat of ice cover to the far end of the eastern Northern Caspian has opened a large area in the central part of the Northern Caspian, and this is where the water has been moving, leading to decrease of water level in the northwestern part (level decrease of 58 cm).

By 3 March 1999, the wind field was weak: less than 6 m/s for mainly southeasterly winds in the Middle Caspian, and no wind in the western part of the Northern Caspian (except several wind vectors up to 6 m/s near the Volga delta). The water level in the northern part of ground track 092 rose by 43 cm, back to similar level anomaly as for 2 February.

The satellite altimetry does not permit to reliably and continuously monitor the storm surges because of inadequate temporal resolution. There is also an issue of the deterioration of the altimetric data quality in the near-shore zone. Often the number of valid observations dramatically decreases during and soon after the storms. As a result, the catastrophic surge of 12–16 March 1995 was not observed by T/P, which flew over on 8 and 18 March. The altimetric measurements of 18 March are scattered near the coastal zone, but show the decrease of sea level that normally takes place soon after the storm surge.

Nevertheless, when altimetric data are available for a specific storm surge situation, they provide information on the surge wave characteristics along the ground track. Such data can successfully complement in situ observations of storm surges and can be used for validation/parameterization of numerical models.

Use of scatterometer-derived data on wind vectors in combination with satellite altimetry can improve our understanding of the water dynamics in the Caspian Sea and can provide detailed information on storm surges, with better spatial coverage as compared to solely in situ observations. However, there are some inherent limitations for this approach. One is that spatial sampling for altimeters is possible only for region covered by the ground tracks. Another problem is limited temporal resolution of both scatterometer and radar altimeter, which does not allow continuous monitoring of storm surges at their typical temporal scale (several hours to 1–2 days). The most appropriate solution will be to combine (a) in situ observations with high temporal sampling from the coastal and island stations, (b) satellite observations from radar altimeters and scatterometers, and (c) numerical modelling of water dynamics response to the wind field.

### 13.4.3

#### **Volga Water Level from Altimetry**

River water level variability has been studied using 1 Hz T/P data for September 1993–August 2000 observations at the cross section of ground track 235 with the river (Lebedev and Kostianoy 2005, 2008b). The obtained time series were compared to water discharge rates at the Volgograd hydroelectric power station. The correlation coefficient was about 0.83 for annual values and 0.71 for monthly mean values. The low spring flood in spring 1996 was well observed in altimetric data. The negative water level trend of 46.7 cm/year in 1993–1996 corresponds to the decrease in average annual water discharge in the Volgograd power station from 10,654 to 5,609 m<sup>3</sup>/s. Comparison of satellite water height with daily observations of water level at the three hydrological stations close to the ground track 235 (Enotaevka, Seroglazovka and Verkhnee Lebyazhye) shows a much better correlation of 0.8–0.9 (Lebedev and Kostianoy 2005, 2008b).

#### 13.4.4

#### Water Budget of the Caspian Sea and the Kara-Bogaz-Gol Bay

Another application of sea level deduced from satellite altimetry is the study of water budget constituents of the Caspian Sea and Kara-Bogaz-Gol Bay. Sea level/volume changes are a dynamical response to the variations in incoming (precipitation, river, and underground inflow) and outgoing (evaporation and, in the case of the Caspian Sea, outflow to the Kara-Bogaz-Gol Bay) components. For the Caspian Sea, the water balance has been computed for the last century thanks to in situ data based on the network of hydrometeorological stations along the coast and on the islands of the Caspian Sea. Traditionally some of these parameters are easily measured (river runoff, precipitation), while for the others their estimation imposes the use of hydrological or climatic modelling (evaporation, underground seepage). For calculating evaporation, information on many parameters pertaining to atmospheric and sea surface conditions (air and sea temperature, air humidity, wind speed, wave heights) is necessary.

Mean values for 1900–1993 (Kouraev 1998) show that river discharge (768 mm/year of water equivalent) is the most dynamically changing constituent of the water budget. Precipitation (191 mm/year) is much lower and while underground discharge is not measured directly, it is estimated around 12 mm/year. Evaporation (969 mm/year) is the highest outgoing constituent but its seasonal changes are low. Mean outflow to the Kara-Bogaz-Gol Bay varied during the twentieth century, but on average it was about 20 mm/year.

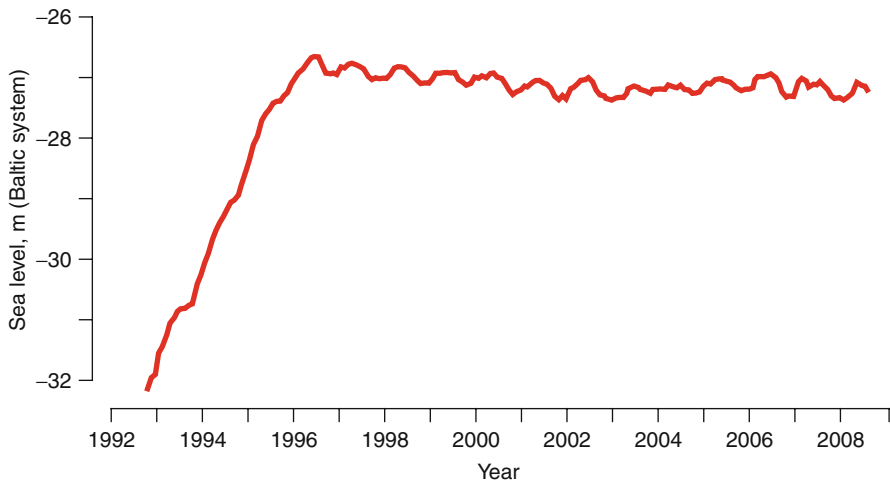
Evaporation, which is difficult to measure directly, is usually computed as the residual term of the water balance. Using altimetric time series of sea level and estimating volumetric changes, and by an inversion of the water budget equation, one can estimate the difference between evaporation and precipitation ( $E-P$ ). Evaporation deduced using this approach for the period 1993–2001 shows an increase of effective ( $E-P$ ) evaporation of around 22 mm of water/year. At the same time, models of evaporation that use in situ observations of sea level indicate only an increase of evaporation of 17 mm/year during the same period. One of possible reasons for this is the difference between in situ and altimetric observations (see Sect. 13.3.6) and this stresses the need to have very precise measurements of the Caspian Sea level.

Natural conditions of the Kara-Bogaz-Gol Bay are unique and its water budget has been heavily perturbed in the twentieth century by natural and anthropogenic influence (Kosarev and Kostianoy 2005; Kosarev et al. 2009). The bay's depression is a shallow bowl with a flat bottom and bare shorelines. The climate of the region is arid with hot summers and strong winds in the autumn and winter. This is the largest lagoon in the world, separated from the sea by sandbars. A strait 7–9 km long and 400–800 m wide is located between bars. Its depth is about 3–4 m. Seawater races along the strait at speeds of 50–100 cm/s into the bay, where it completely evaporates.

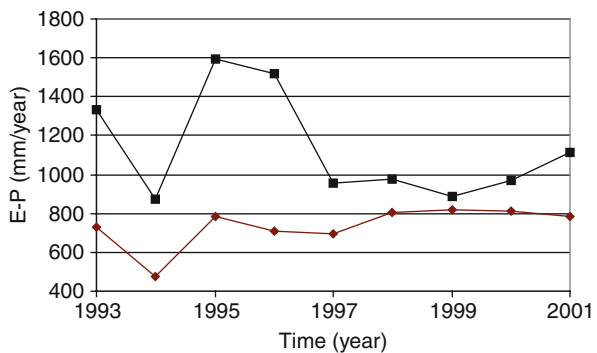
In the first few decades of the 20th century, when sea level was at the high marks, differences between Caspian Sea and bay levels were relatively small. This stipulated hydraulic connection between them and moderated bay level variations. The long-term fall in the Caspian Sea level that began in the 1930s resulted in a decrease in the volume of sea water inflow into the bay. The bay area shrank and the bay became shallower. In order to cut Caspian water losses and stabilize the sea level, in March 1980, the strait was blocked by a solid sandy dam and the Caspian inflow was stopped completely. After its separation the bay began to dry out rapidly and was all but completely dried out by the middle of 1984.

As the sea level had started to rise even before the separation of the Kara-Bogaz-Gol, the opening of the strait was eventually decided upon. In September 1984, tubing was put through the dam and Caspian water once again flowed into the bay. The Kara-Bogaz-Gol began to come back to its usual shape. In the summer of 1992, the dam was destroyed and natural inflow of the Caspian water into the bay took place. Since that time, its level can be followed with the satellite altimetry data (Fig. 13.10). Until the middle of 1996, the Bay has been rapidly filling, and then the level rise stopped and its variations started to reflect seasonal changes well correlated with the seasonal level changes of the Caspian Sea. At present, the level of the bay oscillates near an absolute mark of  $-27.5...-27.7$  m.

Altimetric data can be used to estimate evaporation over the Kara-Bogaz-Gol Bay (Fig. 13.11).  $E-P$  over the bay is much higher than that on the Caspian Sea. There is also no increasing trend of  $E-P$ , as observed for the Caspian Sea and this is a surprising result. If  $E-P$  on the Kara-Bogaz-Gol is mainly driven by variation of temperature, then both curves should follow more or less the same trend. But  $E-P$  is also controlled by temporal



**Fig. 13.10** The Kara-Bogaz-Gol water level (m, Hydroweb data, values referred to GGM02C geoid)



**Fig. 13.11** Visible evaporation ( $E-P$ ) over the Caspian Sea (Dark red line) and Kara-Bogaz-Gol Bay (black line)

variability of precipitation that is influenced by the presence of the Caspian Sea in the west, in particular under a general eastward wind regime. It is generally known (Krapivin and Phillips 2001) that precipitations over the central Asian region, and in areas close to the Caspian Sea, like the Aral Sea or Kara-Bogaz-Gol, are partially generated by water evaporated from the Caspian Sea. This indicates that an increase of evaporation over the Caspian Sea can be followed by an increase of precipitation over the bay. This may have occurred in 1993 and from 1996 to 2001: when evaporation rose in the Caspian Sea, it was attenuated or even decreasing over the Kara-Bogaz-Gol, which indicates more precipitation. In the years when E–P decreased in the Caspian Sea, it was either amplified on the Kara-Bogaz-Gol (decrease of temperature observed for both lakes, but Kara-Bogaz-Gol still receives some additional precipitation) or reversed (which probably indicates that impact of lesser precipitation than in the previous year prevails on the decreasing evaporation rates because of decreasing of temperature). A better assessment of water balance of the Kara-Bogaz-Gol could be done with precise measurements of lake and air temperature as well as wind on the Kara-Bogaz-Gol and high spatiotemporal resolution precipitation gridded data set. Altimetry data that give monthly-based level of the Caspian Sea and Kara-Bogaz-Gol can then be assimilated within a climatic model of the region, as control or forcing data of the model.

### 13.4.5

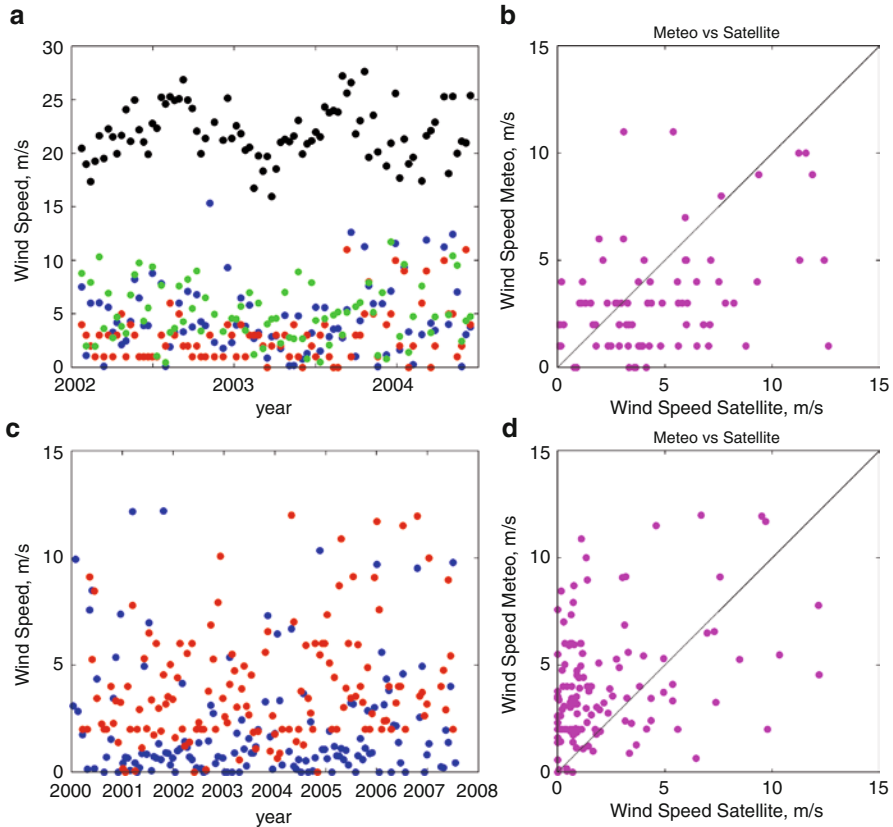
#### Wind and Wave Regime

Analysis of the relation between wind speed and wave height estimates from altimetric data RADS (Schrama et al. 2000) and in situ measurements was made for a number of places on the Caspian Sea coast in the framework of the ALTICORE Project (Vignudelli et al. 2007). For the methodology of in situ wind speed data selection, processing, analysis, and decomposition of wind vectors in relation to the coastline orientation with the aim to improve the correlation with satellite altimetry data, see the chapter by Ginzburg et al., this volume.

For the comparison of wind speed retrieved from altimeter and in situ data, two places at the Caspian Sea coast were chosen: Baku Airport and Fort-Shevchenko. For Baku Airport, selected ground tracks (see Fig. 13.1 for tracks position) were from ERS/Envisat (642), T/P and Jason-1 (092, 209), and GFO (053, 300). For Fort-Shevchenko, they were from ERS/Envisat (311), GFO (128, 225), and T/P new orbit (168).

For the Jason-1, three estimates of wind speed are provided: one based on the backscatter in Ku band, another based on brightness temperature from JMR radiometer, and a third one from interpolation of ECMWF meteorological fields (called here as “altimeter,” “radiometer,” and “model” estimates, respectively). For Baku Airport, wind speed values from radiometer are considerably higher (15–25 m/s and higher) than those from model and observations (mostly below 10 m/s). Altimeter and model values are in good agreement, while correlations between altimeter and in situ data (Fig. 13.12a and b) are less. Low values of wind speed (less than 5 m/s in most cases) from in situ database for Baku Airport, which are not typical for this region, raise doubts in the reliability of this database for 2002–2004 taken from Russian Hydrometeorological Center web site (<http://meteo.infospace.ru>). In Terziev et al. (1992), typical values of wind speed for the Baku region are higher than those on this web site.



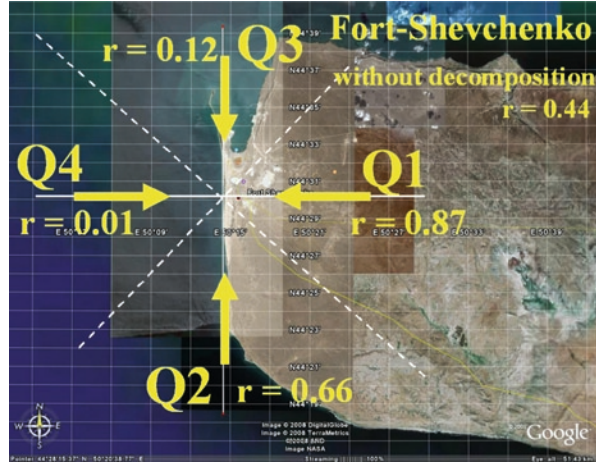


**Fig. 13.12** Results of data processing for Baku Airport during 2002–2004: (a) wind speed from Jason-1 (track 209) altimeter (*blue circles*), observations (*red*), model (*green*), and radiometer (*black*); (b) scatter plot of observed versus altimeter data. The same for Fort-Shevchenko during 2000–2007; (c) wind speed from GFO (track 128) altimeter (*blue*) and observations (*red*); (d) scatter plot of observed versus altimeter data

For Fort-Shevchenko, GFO altimeter-based estimates of wind speed were compared to in situ observations (Fig. 13.12c and d) presented in meteo databases 2 (2000–2004) and 3 (2004–2007). Wind speed values from in situ measurements are in most cases higher than those from altimeter; correlation coefficient between altimeter and observed data (database 2) is equal to 0.44. The decomposition of wind directions in four quadrants as a function of coastline orientation similar to that described for the Gelendzhik case in the Black Sea (see the chapter by Ginzburg et al., this volume) can increase this correlation. Maximum correlation ( $r = 0.87$ ) is observed for easterly winds, and minimum one for westerly winds (Fig. 13.13).

Satellite-derived estimates of wind speed in general show poor correlation with in situ data. Apparently radiometer-based estimates are significantly affected by land contamination in the radiometer field of view and in the coastal regions they should not be considered as reliable. Possible reasons of such discrepancy, provided altimeter measurements are trustworthy, may be local differences between wind observed at the meteorological station

**Fig. 13.13** Decomposition of wind direction in four quadrants (Q1–Q4) in relation to the orientation of the coast line for the Fort-Shevchenko case, and the appropriate correlation coefficients between wind speed from altimetry and in situ meteo record. Without decomposition  $r = 0.44$ . Arrows show prevailing wind direction for each quadrant

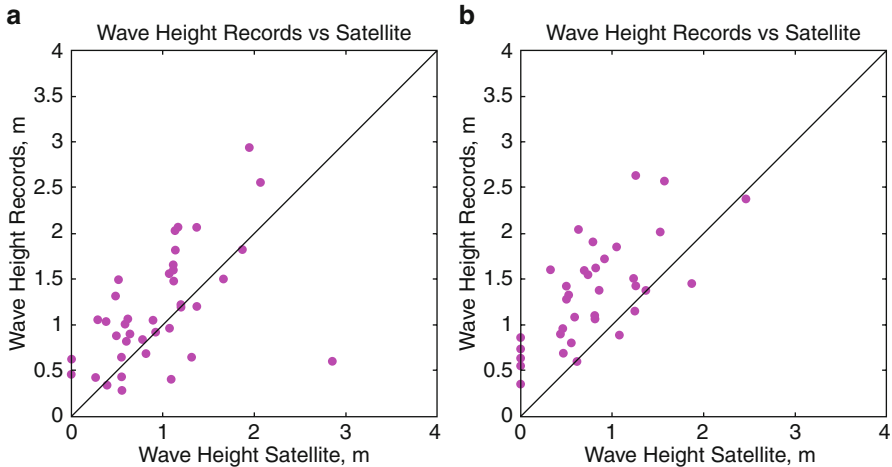


and along the satellite ground track, influence of land on the backscatter coefficient, as well as temporal difference between in situ and satellite measurements.

To improve the correlation, some additional techniques must be used (e.g., a correct choice of the distance between coordinates of a satellite track point of the measurement and meteo station position in order to exclude a possible influence of land; the decomposition of the winds in the four quadrants in relation to the orientation of the coastal line). It is also possible that some increase of the correlation can be obtained by taking into account the angle at which the satellite track approaches the coast, as well as the direction of the flight – from land to the sea and vice versa.

Comparison of in situ measurements of wave height and corresponding altimeter data was carried out for the Neftyanje Kamni region (outside of Baku), Caspian Sea. Data from satellite tracks of Envisat (098, 397, 556, 855), GFO (053, 139, 300), and Jason-1 (209) were used (see Fig. 13.1). For Envisat (Fig. 13.14a), the total number of observations was low compared to that for Jason-1 (Fig. 13.14b) because of difference in the repeat cycle (35 versus 10 days, respectively). Both datasets show that altimeter underestimates the observed waves. The reason of this discrepancy might be the fact that the current wave algorithms are on the basis of calibration done over the open ocean.

Two other factors – eddies and coastal upwelling – can also contribute to poor correlation between satellite-derived sea level and corresponding data of level gauge stations. The enclosed Caspian Sea, especially its southern part, is rich in mesoscale eddies. In particular, intense cyclonic eddies 10–20 km in diameter are frequently observed during upwelling in the Fort-Shevchenko region (Ginzburg et al. 2006). It is not known whether they are formed during the upwelling events (Fig. 13.15) or cold upwelling water only serves as an indicator for their surface manifestation. It is also still a question under which wind direction they are formed. Physical nature of upwelling along the Caspian eastern coast is also ambiguous – some authors suppose that upwelling in this region may not be wind-driven, but conditioned by along-shore current (see Ginzburg et al. 2006). Therefore, detailed information on local wind speed and direction is needed. Such information is also required for revealing the physical nature of upwelling filaments directed from the coast to the deep sea and propagated over distances up to 150 km in the open sea (see Fig. 13.15).



**Fig. 13.14** Comparison of altimeter-derived and in situ data of wave height. (a) Envisat data from ground track 556 and in situ data for 2003–2006. (b) Jason-1 data from ground track 209 and in situ data for 2006

### 13.4.6

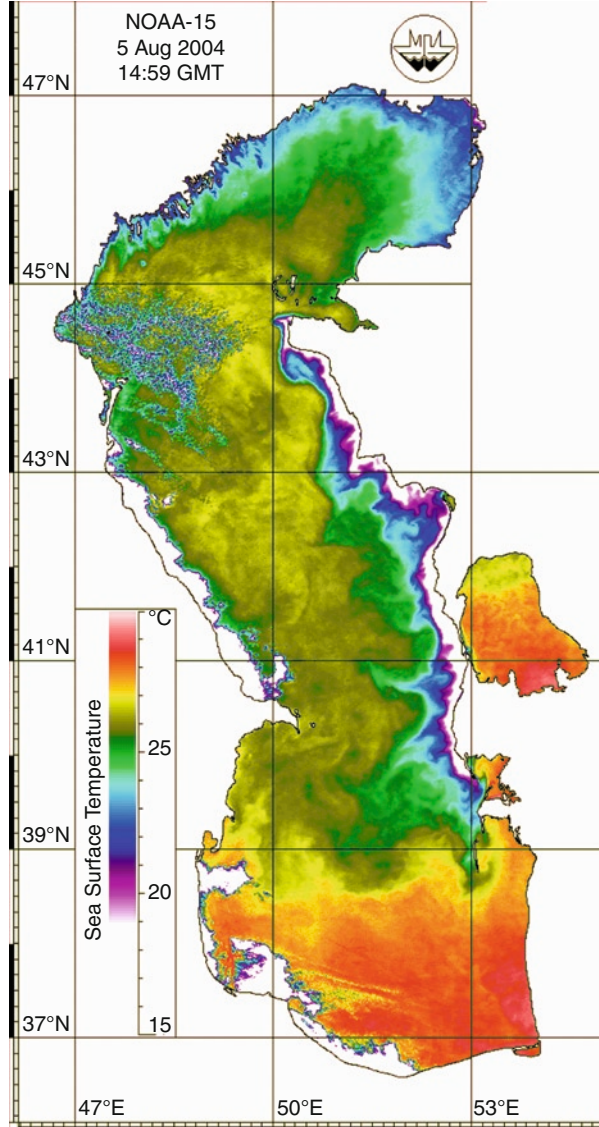
#### Ice Cover Regime

Studies of the ice cover of the Caspian Sea from the coastal stations began in the second part of the nineteenth century. In the second part of the twentieth century, ice studies became part of the Soviet Union's national hydrometeorological monitoring system and were performed on a regular basis using aerial surveys. However, starting from the late 1970s, the high cost led to a dramatic decrease of aerial ice cover observations. The lack of information was partially compensated for by the use of satellite imagery, mainly in the visible and infrared range (Krasnozhan and Lyubomirova 1987; Buharizin et al. 1992). However, because of frequent cloud cover in the winter, satellite observations have been used only occasionally. Actually all historical published time series of various ice cover parameters for the Caspian Sea stopped in 1984–1985.

To fill in the information gap on ice regime since the mid-1980s, an evident solution is the use of microwave satellite observations that provide reliable, regular, and weather-independent data on ice cover. A promising source of information is presented by radar altimeter satellites that provide continuous and long time series of both active (radar altimeter) and passive (radiometer used to correct altimetric observations) simultaneous observations, from the same platform and with the same incidence angle (nadir-looking).

An ice discrimination methodology that uses more than 15 years long simultaneous active and passive data from several radar altimeters (TOPEX/Poseidon, Jason-1, Envisat and Geosat Follow-On) and complemented by passive microwave observations (SMMR and SSM/I) has been developed. This methodology has been initially tested and applied for the Caspian and Aral seas (Kouraev et al. 2003, 2004a, b). Later on, this approach has been extended to (a) complement the T/P observations by Jason-1, GFO and Envisat data, and

**Fig. 13.15** Upwelling along the eastern coast of the Caspian Sea. (NOAA IR image for 5 August 2004) (Courtesy of Dmitry Soloviev, Marine Hydrophysical Institute, Sevastopol, Ukraine)

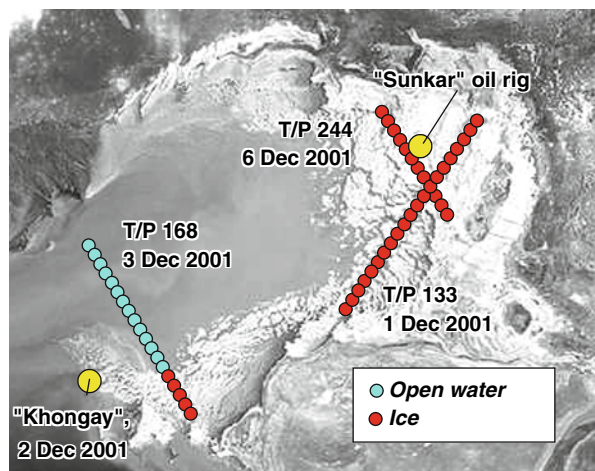


(b) provide better spatial and temporal resolution using an improved ice discrimination approach that combines all altimetric and SSM/I data. This approach has been implemented for the Lake Baikal (Kouraev et al. 2007a, b) and Large and Small Aral seas (Kouraev et al. 2009). A comprehensive description of the existing state of the art of this methodology, with discussion of drawbacks and benefits of each type of sensor, influence of sensor footprint size, ice roughness and snow cover on satellite measurements, and validation is given in (Kouraev et al. 2008). There, the particularities of the application of the methodology have been demonstrated for the two salt water (Caspian and Aral seas) and three freshwater (lakes Baikal, Onega and Ladoga) water bodies.

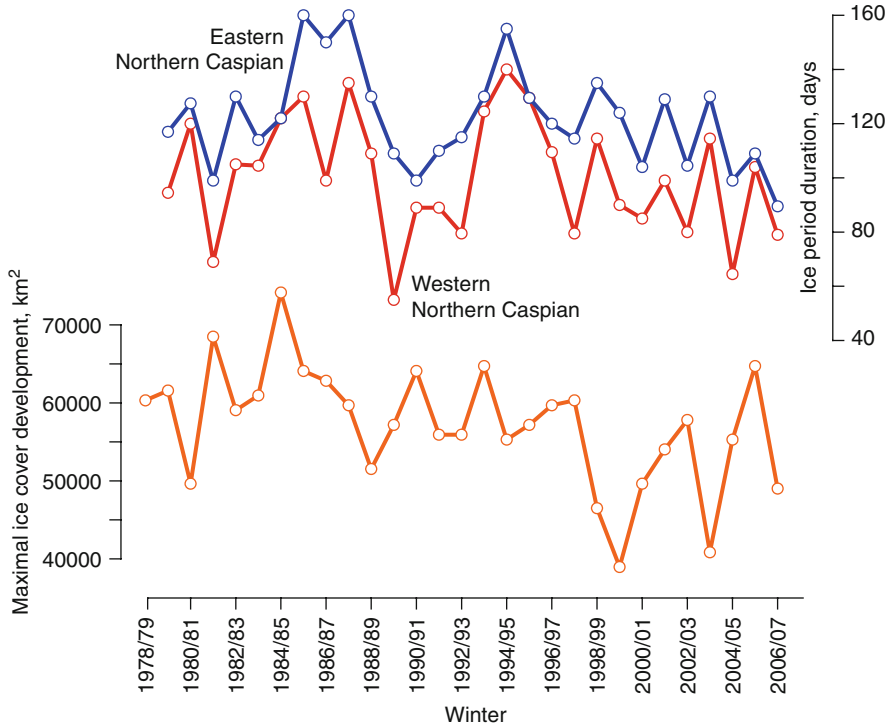
This methodology has been successfully validated for the Caspian Sea using independent in situ and visible satellite data in November–December 2001 (Kouraev et al. 2003). In situ observations of sea ice cover (Buharizin 2003) were made on the ships “*Khongay*” and “*Nord*,” operating in the Northern Caspian. “*Nord*” was in the vicinity of the Kazakh oil rig “*Sunkar*.” Analysis of the spatial distribution of ice cover is further extended using satellite image of 3 December 2001 from MODIS sensor aboard the Terra (EOS AM-1) satellite.

The first appearance of close ice in the Northern Caspian in winter 2001 was observed on 30 November from the “*Khongay*” in the region of the “*Sunkar*” oil rig (Fig. 13.16). Decrease of near-surface air temperature (down to  $-9^{\circ}\text{C}$ ) during the next few days stipulated ice formation, its spreading over the sea, and increase of ice thickness. Under the influence of strong easterly winds, ice drifted rapidly westward, reaching as far west as the region of the Kulaly Island (see Fig. 13.1), where it was observed on 2 December from the “*Khongay*.” The winds also caused a decrease in sea level in the eastern part of the Northern Caspian. Comparison of these in situ observations with T/P data for pass 244 shows that the onset of ice formation is well determined: the surface type in the region of the oil rig was characterized as open water on 26 November 2001 and as ice on 6 December 2001. Ice edge position derived from data for T/P track 168 agrees well with its position on the same day on the MODIS image. In the eastern coastal region, surface type for ground tracks 133 (1 December) and 244 (6 December) was classified as “ice”, which corresponded to the ice distribution seen on the MODIS image. The validation described above shows that the proposed method provides robust results for discriminating between open water and ice.

Using this approach, new improved time series of ice events (ice formation, break-up, and duration of ice period) for the eastern and western parts of the Northern Caspian and estimates of mean and maximum ice extent for the whole Northern Caspian have been obtained (Fig. 13.17). Overall variability shows the complicated structure and existence of various cycles in ice conditions. A warming trend seen in the second part of the 1980s (seen both in ice duration and maximal ice development) has been followed by a cooling trend until 1993/94. Since 1995, a steady decrease of ice duration is observed both for



**Fig. 13.16** Sea ice distribution from MODIS image for 3 December 2001, surface types derived from T/P data and locations of in situ ship observations (After Kouraev et al. 2003)



**Fig. 13.17** Ice duration (days) for the eastern and western part of the Northern Caspian, and maximal area of ice cover development ( $\text{km}^2$ , within the EASE-Grid coverage of the Northern Caspian)

western and eastern parts, while for maximal ice cover development we observe general decrease but increase of amplitude associated likely with alternation of warm and cold winters. The same character was observed in the Caspian Sea sea surface temperature interannual variability (Ginzburg et al. 2005). There is a need to continue monitoring of ice conditions, for practical applications for ship routing and protection of industrial objects, for scientific studies of environmental conditions and climate variability, as well as for forcing and verification of general circulation models.

## 13.5

### Discussion and Conclusions

We have seen that the spatial and temporal coverage of the Caspian Sea by different radar altimetry missions offers the possibility of continuous high-precision monitoring of the Caspian Sea level since the early 1990s. Being an intermediate target between open ocean and closed lakes, this sea is an interesting natural object to evaluate the potential of satellite altimetry for enclosed water bodies.

A specificity of application of satellite radar altimetry for the studies of the Caspian Sea suggests several issues to be addressed in order to obtain high-quality and reliable datasets. Influence of tides and atmospheric forcing could be successfully estimated using numerical modelling, such as has been done using the regional model for high frequency motions for the Caspian Sea based on the T-UGO 2D. However, as there are no hourly level gauge data to validate the model, there is a strong need for permanent, GLOSS-compliant in situ data to confirm the regional tides and atmospheric forcing response in the model.

Dry atmospheric correction is altitude dependant, but T/P and GFO GDRs incorrectly compute the correction at sea level, and this needs to be accounted for. Though it is possible over some enclosed water bodies to retrieve a wet tropospheric correction from radiometer, issue of land contamination in the radiometer field of view remain and there is the need for the best possible models. In that case, one could use wet tropospheric model based on gridded meteorological data sets at the altitude of the lake such as ECMWF.

While the existing geoid models are sufficient for large-scale ocean studies, for the Caspian Sea, a calculation of a regional mean sea surface represents a much better solution and this is implemented by various research groups.

Ice cover that is present every year in the Northern Caspian significantly affects altimetric measures. Using Envisat data for the Aral Sea, it has been found that ocean retracker (T/P, Jason-1, and GFO use only this kind of retracker) shows much higher values than any of ice-adapted retrackers. It is suggested to subtract 40–45 cm from sea level measures from T/P, Jason-1, and GFO when the sea is ice-covered.

Cross-calibration of various satellite missions and calibration/validation of altimetric measurements demand dedicated calibration/validation campaigns. GPS measurements from the ship, drifter experiments, as well as installation of a permanent GLOSS-compliant tide-gauge in Baku are all extremely important to ensure high-quality estimates of the Caspian Sea level from radar altimetry.

Currently several altimetric databases for the Caspian Sea exist online or offline and these are sources that need to be promoted for and exploited by a large research community.

Application of radar altimetry and other satellite techniques in combination with in situ observations show various promising results for the Caspian Sea. Temporal and spatial variability of the sea level and its relation with the Volga discharge can be investigated. When altimetric data are available for a specific storm surge situation, they, in combination with wind fields from scatterometers, provide unique information on the surge wave characteristics along the ground track. Such data can successfully complement in situ observations of storm surges and can be used for validation/parameterization of numerical models.

Altimeters also give us a tool to study the water level variability of Volga River levels. Altimeter-derived sea level measures coupled with observations of other constituents of water budget can provide estimations of evaporation over the Caspian Sea or Kara-Bogaz-Gol Bay. There is an increasing trend of visible (E–P) evaporation over the Caspian Sea. For the Kara-Bogaz-Gol Bay, this trend has not been observed, which could be linked to a dynamical relation between both water bodies: increased evaporation over the Caspian Sea can be followed by an increase of precipitation over the bay. A better assessment of water balance of the Kara-Bogaz-Gol could be done with precise measurements of water and air temperature and wind on the Kara-Bogaz-Gol Bay and high spatio-temporal resolution precipitation gridded data set. Altimetry data that give monthly based level of the Caspian

Sea and Kara-Bogaz-Gol can then be assimilated within a climatic model of the region, as control or forcing data.

Less direct applications of altimetry are observations of wind, wave, and ice regime of the Caspian Sea. For the wind field, radiometer-based estimates are significantly affected by land contamination and in the coastal regions should not be considered as reliable. Radar altimeter-derived estimates of wind speed show in general poor correlation with in situ data. Possible reasons of such discrepancy could be local differences between wind observed at the Meteorological Station and along the satellite ground track, influence of land on the backscatter coefficient, as well as temporal difference between in situ and satellite measurements. This could be improved by better geoselection of the altimetric data, and the decomposition of the winds in four quadrants in relation to the orientation of the coast line. For the wave height, comparison of in situ measurements shows that altimeters generally underestimate the observed waves. The reason of this discrepancy might be the fact that the current wave algorithms are on the basis of calibration done over the open ocean. Two other factors – eddies and upwelling – can also contribute to poor correlation between satellite-derived data and corresponding in situ observations.

Study of the Caspian Sea ice cover regime using synergy of active (radar altimeter) and passive (radiometer) microwave observations onboard altimetric satellites in combination with radiometric data from SMMR and SSM/I is a promising tool to provide reliable, regular, and weather-independent data on ice cover. This well developed and validated approach provides new improved time series of ice events (ice formation, break-up, and duration of ice period) for the eastern and western parts of the Northern Caspian and estimates of mean and maximum ice extent for the whole Northern Caspian. Since 1993/94, a steady decrease of ice duration is observed both for western and eastern parts, while for maximal ice cover development we observe general decrease but increase of amplitude.

On the basis of these interesting results, there is a clear need to continue monitoring of various environmental parameters of the Caspian Sea, for practical applications as well as for scientific studies of environmental conditions and climate variability. The most appropriate solution would be the combination of dedicated high-quality in situ observations, satellite observations from radar altimeters and other Earth Observation data, and numerical modelling of the Caspian Sea water dynamics.

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