

Analysis of Temporal Sea Level Variation in the Barents and the White Seas from Altimetry, Tide Gauges and Hydrodynamic Simulation

S.A. Lebedev

Department of Geophysical Fields and Geoinformation, Geophysical Center, Russian Academy of Science 3 Molodezhnaya, Moscow, Russia, 117296

lebedev@wdecb.ru

O.I. Zilberstein, S.K. Popov, O.V. Tikhonova

Laboratory of Sea applied Researches, Hydrometeorological Research Center of the Russian Federation 9-13 Bol. Predtechensky per., Moscow, Russia, 123242

Abstract. Seasonal and interannual sea level variability is usually estimated using coastal metocean station data. Presently many Russian stations have been closed, and for the open water areas the continuous series of sea level observations are usually short or missing. At the same time, the importance of this information is obvious because of perspective development continental shelf of resources has begun. To a certain extent modern verified hydrodynamic models taking into account the complex range of driving forces which produce water motions, and also satellite altimetry data help to solve this problem. In this paper temporal sea level variability in the Barents and the White Seas are presented by three independent types of data: tide gauge data, satellite altimetry data, and results of hydrodynamic simulation for coastal zone (in the areas of gauge locations) and for open seas (along satellite tracks and in the areas of gas and oil fields on the sea shelf).

Keywords. Altimetry, sea level anomaly, hydrodynamic model, tide model, Barents Sea, White Sea.

1 Introduction

Historically, sea level variability (tidal, storm surge, seasonal and interannual oscillations) have been investigated based on tide gauge data and hence it was limited within a coastal zone.

Analysis of level variations in open oceans becomes possible with the development of mathematical modelling of different hydrodynamic processes. Coastal tide gauge data and limited number of open-sea tide gauge measurements are

used for model verification and assignment of boundary condition. Until recently, this method was the only one possible for open oceans and for implementation of engineering calculations.

Now the situation has changed. A new source of information about the sea level - satellite altimetry data - has become available. Satellite altimetry gives not only additional input information for analysis of time-space variability of sea level in the open oceans, but can also be combined with other data to verify existing hydrodynamic models. Therefore, processing the physically reasonable models of the short-term and long-term forecasts of sea parameters becomes possible.

2 Features of a Hydrodynamic Regime

The main sea level variations in the Barents and the White Seas are conditioned by tidal and storm surge oscillations (Barents Sea, 1985; Bogdanov et.al., 2000). In the southern part of the Barents Sea the semidiurnal tide has an amplitude of up to 2m, which is large in the Arctic seas. The tidal height decreases in the north and northeast Barents Sea, and it reaches 1-2 m over the Spitsbergen coast. Over the southern coast of the Francis Joseph Earth the tidal height is only 40-50 cm. This is caused by the bottom relief, the coastal line configuration, and the interference of tidal waves, which come from the Atlantic and Arctic oceans and determine spatial variability of tides. The tidal heights in the White Sea vary from 8 m in the Mezensky bay to 1 m in the Dvinsky bay.

Storm surge sea level variations are formed by winds and atmospheric pressure gradients, whose distribution and intensity is determined by cyclone movements. The western and northwestern cyclones

are dominant and amount to 88% of the total cyclones. During the extreme situations the storm surge height is comparable to the tidal height.

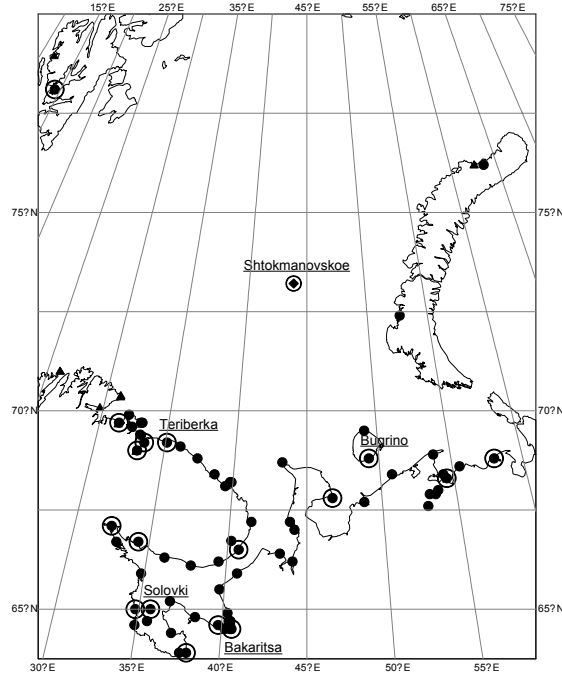


Fig. 1 Position of tide gauge: ● - Russian national network; ▲ - GLOSS and PSMSL network; ◆ - perspective Shtokmanovskoe shelf deposit of gas. The circles show tide gauges, where the data were used in this paper.

The storm surge values are greatest in the southeastern part of the Barents Sea (up to 2 m and even more). Over the Kola Coast and the Spitsbergen they are about 1 m; the smaller values (about 0.5 m) are observed near the New Land coast.

Except for tidal and storm surge oscillations, seasonal variations of sea level in the Barents Sea are caused by a cumulative effect of the atmospheric pressure and wind, as well as by the interannual temperature and salinity variations. The maximum of the seasonal sea level variation is observed in November to December and its minimum is observed in May to June, which is in accordance with the conception of static atmospheric pressure effect upon the sea surface. This can be explained by the sea level rise under decreasing pressure and vice versa. Such a barometric situation and the sea level response are observed in the Barents Sea in winters and springs. The difference between the maximum and minimum mean sea levels in Murmansk can reach 40-50 cm.

3 Data

Three types of the independent sea level measurements, namely, tide gauge data, results of hydrodynamic simulation and satellite altimetry data. We interpreted the sea surface height as the deviation of the physical sea surface with respect to any reference system. For tide gauges it is the Baltic reference system, for results of hydrodynamic simulation it is the non-perturbed surface $z=0$, for the satellite altimetry it is a reference ellipsoid. Anomalies of sea surface height and tidal height are calculated as the deviation from the average value for both data types (mean sea surface model CSRMSS95IB for altimetry and average value from the period 1948-2000 for tide gauge and simulation data)

3.1 Coastal Tide Gauge Data

We have tide gauge measurements on 17 stations, 9 in the Barents Sea and 8 in the White Sea for the period 1986-2000 (see Fig. 1). Eight stations contain hourly values and the others contain monthly values. Despite of the obsolete equipment, level rod and floating tide gauges, the accuracy of hourly measurements is better than 1-2 cm.

3.2 Results of Hydrodynamic Simulation

Three dimensional baroclinic model with free surface was developed in Laboratory of Sea Applied Researches of Hydrometeorological Research Center of Russian Federation (HMRCRF). This model reproduced storm surges and tidal in Barents and White Seas with a sufficient accuracy. We use a time step of 240 s for the coarse grid while the mesh size is 15 nautical miles. For the fine grid the time and spatial steps are 120 s and 6 nautical miles, respectively.

While simulating tides in the Barents Sea, as the liquid boundary condition we use the temporal variation of tidal level resulting from the harmonic constants presented as a sum of the fixed number of tidal components

$$\zeta(x,y,t)|_{\Gamma_2} = \sum_{i=1}^n R_i A_i(x,y) \cos[\sigma_i t + \psi_{oi} - g_i(x,y)] \quad (1)$$

where $A_i(x,y)$ and $g_i(x,y)$ are harmonic constants representing the amplitude and the phase of the i -th tidal component, σ_i is the angular velocity; ψ_{oi} and R_i are initial phase and nodal factor determined from the astronomic data at the moment of the

beginning and the middle of the calculations, respectively (Duvanin, 1960).

Harmonic constants are determined from the sea level observations made in a fixed number of stations on the liquid boundary and then interpolated to its nodes. Equations, boundary conditions and finite difference scheme are described in Popov et al. (2000) and Zilberstein et al. (2001).

Using the mean temperature and salinity data and on basis of atmospheric fields of the "reanalysis" project hydrodynamic of level and currents calculations for the Barents Sea were carried out over the period from 1948 to 2000. Now it is used as a calculation procedure in the operational storm surge model for the Caspian Sea (Verbitskaya et al., 2001).

3.3 Satellite Altimetry Data

For sea surface height and the level variation of the Russia Arctic seas, satellite altimetry from the Geosat Exact Repeat Mission (ERM) can be used for satellites with a high orbit inclination angle only (see Table 1). The exception is the White Sea, where TOPEX/POSEIDON and JASON-1 are available. Ground tracks of ERS, GEOSAT and TOPEX/POSEIDON in the Barents and the White Seas are shown in Figure 2., and availability of satellite altimetry data is shown in Table 2. In this work TOPEX/POSEIDON data for the White Sea and ERS-1 and ERS-2 for the Barents Sea were used.

To calculate sea level from satellite altimetry data it is necessary to apply tidal correction, instrumental and environmental corrections (Nerem and Mitchum, 2001). Usually tide heights calculated from a global tidal model are used for tidal correction. Unfortunately, the spatial resolution of global models cannot account for the morphological peculiarities of the Barents and the White Seas, especially in the coastal zone (Shum et al., 1997).

The comparison between the tidal heights obtained from the global model of the Texas University CSR3.0 (Le Provost, 2001), and those from the regional tidal model of the Barents and the White Seas (Popov et al., 2000), which is developed by the Laboratory of Marine Applied Researches of HMRCRF, show good agreement in phase (see Fig. 3). During the period 1996-2000, the differences in tidal height from the two models range from 0.01 to 2.93 m in the southeast part of the Barents Sea, and from 0.01 to 4.52 m in the bottleneck of the White Sea (see Fig. 4) (Lebedev and Tikhonova, 2000).

Table 1. Main exact repeat mission (ERM) of satellite altimetry measurements

Mission	Time of active work (month/year)	Parameter of orbit		
		Height (km)	Inclination angle (deg)	Repeat period (day)
GEOSAT ERM	11/86–12/89	780	108	17
ERS-1	Phase A	785	98.5	3
	Phase B			3
	Phase C			35
	Phase D			3
	Phase G			35
TOPEX	08/92–present time	1300	66	10
ERS-2	04/95–present time	785	98.5	35
GFO-1	05/98–present time	800	108	17
JASON-1	12/01–present time	1300	66	10
ENVISAT-1	03/02–present time	800	98.5	35

Table 2. Availability of satellite altimetry data for Barents and White seas

Mission		Barents Sea		White Sea	
		Quantity of track	Quantity of measurements	Quantity of track	Quantity of measurements
GEOSAT ERM		64	218 564	23	6 261
ERS-1	Phase C	131	144 652	13	1 275
	Phase G	148	125 967	33	5 406
TOPEX/POSEIDON		-	-	18	78 106
ERS-2		148	452 371	33	18 660

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It is important to note that the regional model was thoroughly verified by a Fourier analysis of tide gauge measurements at coast stations. It shows clearly the most significant features of the

space-time variability in tide (for example, bright tidal resonance in some bays of the Barents and the White Seas). Therefore the regional tidal model was used for tidal correction to the satellite altimetry observations.

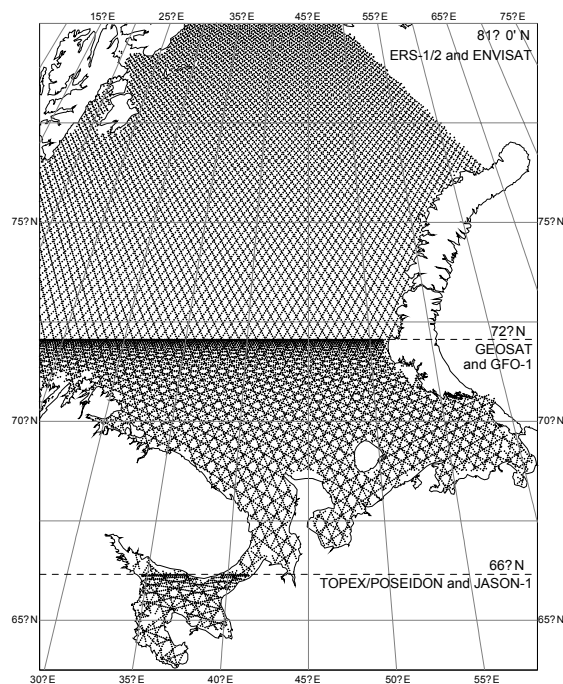


Fig. 2 Satellite ground tracks of altimetry missions in the Barents and White Seas. Dashed lines show the maximum latitudes of ground tracks.

4 Results

The analysis of the temporal level dependence of the Barents and the White Seas was conducted in two steps. At the first phase, the tide gauge data, results of model calculations and satellite altimetry data were compared in 1996 (this year was chosen because of the available observations in the White Sea). At the second phase, sea level variations from these three types of data were analysed. Sea level in the open parts of the Barents Sea, where the Shtokmanoskoe gas and Prirazlomnoe oil fields are located, was calculated separately.

4.1 Comparison of Tide Gauge Data with Hydrodynamic Model Calculations

Sea levels from tide gauges and a model in 1996 were compared. For the comparison The knot of the computational grid nearby a tide gauge was selected.

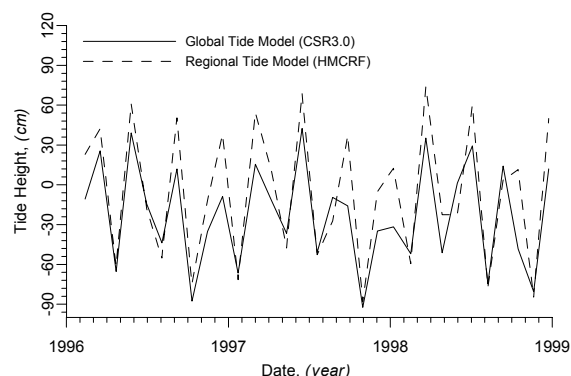


Fig. 3 Temporal tidal variation in point (47,491°E, 67,383°N around the Kolguev Island and Bugrino tide gauge) corresponding to track 208 of ERS-ERM calculated with a time step of 35 days.

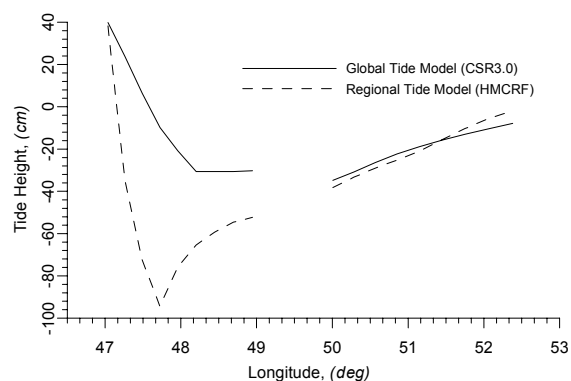


Fig. 4 Change of tide height along part of ERS track360, around the Kolguev Island and the estuary Pechora River at 27, February

The comparison was conducted using both hourly measurements and the data averaged over 12h and 24h interval.

Results of the comparisons at Solovki in the White Sea and at Teriberka b at the Kola Coast of the Barents Sea are shown in a Figures 5 and 6. The estimated correlation coefficient and standard deviation are 0.871 and 0.29 at Solovki, respectively, and are 0.867 and 0.50 at Teriberka, respectively. These comparisons show satisfactory results.

Time variations at the Bakaritsa station near the estuary of the Northern Dvina River in May 1996 show that our hydrodynamic model cannot model the variability at the spring flood with a sufficient accuracy (see Fig. 7).

4.2 Comparison of Tide Gauge Data with Satellite Altimetry Data

To conduct this investigation the hourly tide gauge data measured at the White Sea were compared with the TOPEX/POSEIDON altimeter data (Benada, 1997) over 1996.

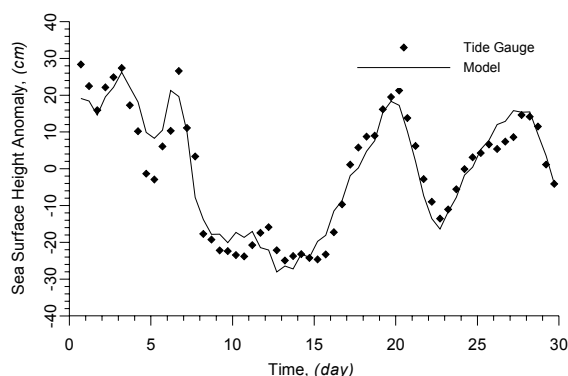


Fig. 5 Sea surface height anomaly variation of Teriberka tide gauge data (Kola shore in the Barents Sea) and results of model calculation for March 1996 with 12 hours average.

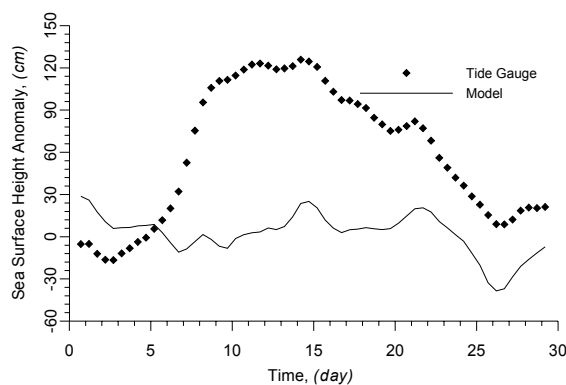


Fig. 7 Sea surface height anomaly variation Bakaritsa tide gauge (estuary Northern Dvina – White Sea) and results of model calculation for May 1996 with 12 hours time average.

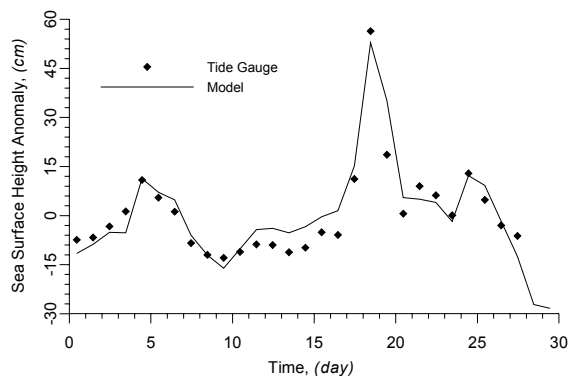


Fig. 6 Sea surface height anomaly variation of Solovki tide gauge (Solovetskie Islands of in the White Sea) and results of model calculation for September 1996 with 24 hours time average.

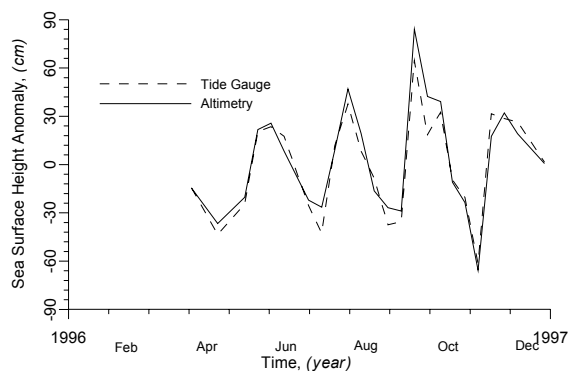


Fig. 8 Sea surface height anomaly variation of Solovki tide gauge data (Solovetskie Islands of the White Sea) and satellite altimetry data TOPEX/POSEIDON for year 1996.

The TOPEX/POSEIDON altimeter data at a point nearest to the tide gauge are selected, and the hourly tidal measurements close to the period of the satellite passing above the area of the tide gauge are selected. This is explained by the fact that for a period of one year entry on-off time ratio of the satellite data TOPEX/POSEIDON (~ 10 days) allows us to conduct the full analysis.

The result of comparison at Solovki is shown in Fig. 8. The comparison demonstrates that the temporal variations derived from TOPEX/POSEIDON and from the tide gauge measurements agree very well. It is planned to increase the number of tide gauges and the time frame over 1992-2003 later.

4.3 Comparison of Satellite Altimetry and Hydrodynamic Model Calculation

Sea surface height anomalies along a satellite track were analysed. For this purpose two tracks of ERS-2 exact repeat mission (Koblinsky, 1999) were selected. There are 17 descending tracks and 437

ascending tracks. The crossover points of ground tracks are near to the Stokmanovskoe gas field offshore in the Barents Sea.

The calculated sea surface heights were interpolated over space in points along the tracks, and the value nearest in time to the moment of satellite measurements was selected. As a control interval 1996 was chosen. Sea surface height anomalies were calculated relative to the mean sea level for the model and relative to the mean sea surface for the satellite altimetry.

Fig. 9 shows the good qualitative conformity of the data. Difference in amplitude can be explained by the fact that in model calculations the synoptic variability was caused largely by the wind field.

The calculation of the sea level around tide gauges and in the open oceans was implemented as follows. Sea surface anomalies were averaged along segments of ascending and descending tracks near to the corresponding crossover point, with a temporal interval of 3 to 5 s, and a spatial interval of around 10 miles.

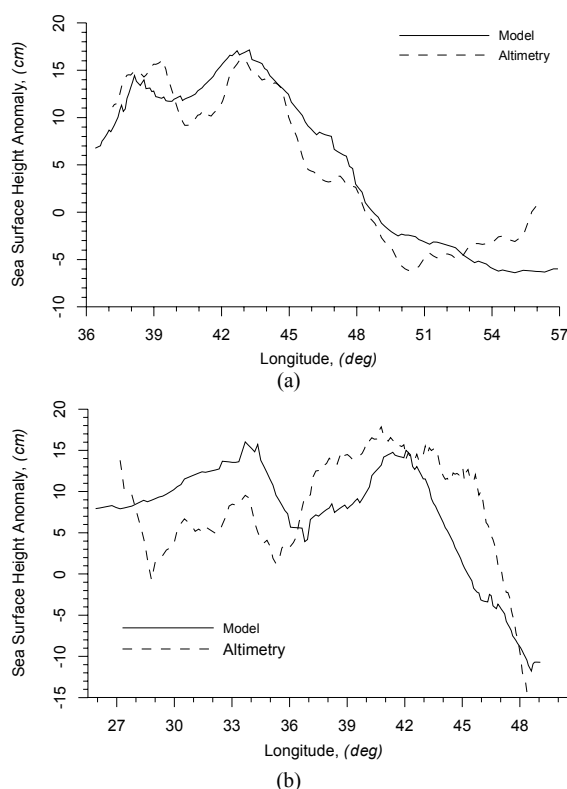


Fig. 9: Variation of sea level along ERS-2 satellite track from model data calculation and from satellite altimetry for cycle 16; (a) track 017 (5 October 1996); (b) track 437 (3 November 1996).

Hereinafter data from both tracks were integrated. Comparison of the satellite data and model result in the Stokmanovskoe gas field region (see Fig. 10) shows good agreement between independent data types despite the above mentioned remarks.

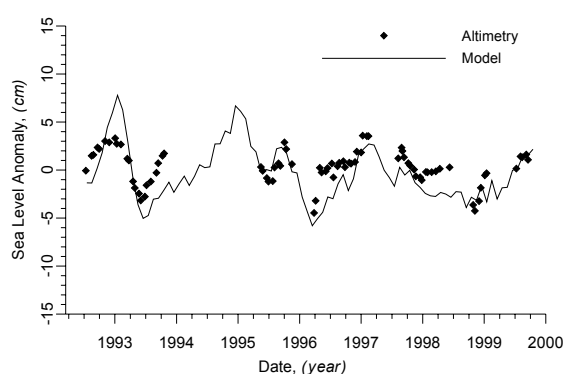


Fig. 10 Interannual variation of sea level anomaly by results of model calculation and by satellite altimetry data ERS-1 and ERS-2 for the Shtokmanovskoe gas field region from the Barents Sea.

5 Conclusion

This analysis of sea level variations in the Barents and White Seas using tide gauge data, satellite altimetry data and results of model calculations showed a satisfactory reproduction of both synoptic and seasonal (and partly interannual) variability of the sea level. As a rule, the greatest errors occur in the winter months, which may be caused by an ice cover.

Acknowledgements. Satellite altimetry data for ERS-1/2 and TOPEX/POSEIDON of the NASA Goddard Space Flight Center (GSFC) Ocean Altimeter Pathfinder Project, were used (<http://iliad.gsfc.nasa.gov/opf/main.html>). Information and software Integrated satellite Altimetry Data Base (ISADB) designing in Geophysical Center (Medvedev et al., 1997) were used.

The research was undertaken with partial support from the Russian Basic Research Foundation (Project 01-07-90106).

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