Investigation Hydrometeorological Regime of the Barents and White Seas Based on Satellite Altimetry Data

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The Barents and White seas

The Barents Sea is one of the shelf Arctic seas. It is located on the continental European shelf between northern coast of Europe and three archipelagoes – Novaya Zemlya, Franz Josef Land and Spitsbergen (Fig. 1a). Its open water area is approximately 1,424,000 km^2 and total volume is 322,000 km^3. The Barents Sea shelf is rather deep. More than 50% of the area has a depth of 200-500 m. The average depth is 222 m, the maximum depth in the Norwegian trench reaches 513 m and in the Franz Josef Land straits it exceeds 600 m. The Barents Sea watershed area is 668,000 km^2 large. The total river runoff is 163 km^3/yr, 80-90% of it falls on southeastern region of the sea. The largest river flow-ing into the Barents Sea is the Pechora River which has about a half of watershed area 322,000 km^2 ; its runoff is 130 km^3/yr. The river runoff is essentially re-flected in hydrological conditions only in a southeastern part of the sea. Therefore this area is sometimes referred to as the Pechora Sea.

The White Sea is a semi-enclosed mediterranean sea (Fig. 1b). The sea border with the Barents Sea is a line joining Cape Svyatoy Nos (northeastern coast of Kola Peninsula) with Cape Kanin Nos (northwestern extremity of Kanin Peninsula). The northern part of the sea is called the Voronka (funnel). The southern and central parts of the White Sea called the Basin are the largest and deepest parts of the sea. There are also several large and shallow bays in the area, namely the Dvinsky, Onega, Mezen and Kandalaksha bays. The Gorlo (neck) is a narrow strait connecting the Basin and Voronka. The total water surface area is 90,873 km^2 including islands, and the total volume is 6,000 km^3 including also the Voronka area opening to the Barents Sea. Thus the White Sea covers approximately 6% of the total open water area of both seas and comprises only 2% of the total volume of marine water, but it assumes more than half of the river runoff in the region. The White Sea watershed area is 729,000 km^2 (Atlas of Arctic 1985). The total river runoff is 259 km^3/yr that is about 4% of the total amount of the White Sea water volume. The main rivers are the Severnaya Dvina, Onega and Mezen having runoff of 111, 18 and 26 km^3/yr correspondingly.

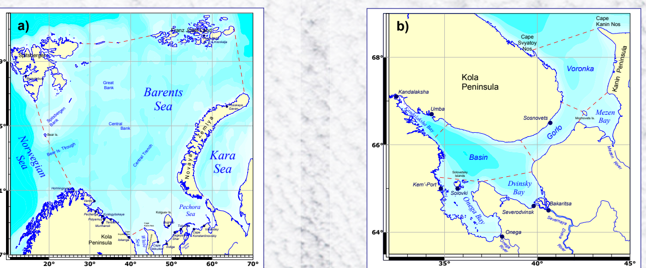

Fig. 1. Maps of the Barents (a) and the White (b) seas. Dashed lines show boundaries of the seas and their internal parts. Circles mark tide gauges location..

Meteorological conditions in the Barents Sea are determined by atmospheric cyclones that are formed in the North Atlantic and move to the Barents Sea. In winter, southwesterly and southerly winds prevail in the southern part of the sea, whereas southeasterly and easterly winds are most frequent in the northern regions. Monthly mean wind speed in the southern regions (in particular, nearby Kanin Nos) reaches about 10 m/s, to the north it decreases to 6 m/s. In summer the pressure gradients are weakened. Homogeneous wind conditions, with predominance of winds of northern directions, dominate over almost the whole sea. Monthly mean wind speed in this season is about 6 m/s, on the north – 5 m/s.

In the White Sea, winds from the south, southwest and west prevail from October to March, whereas in May - August winds from north, northeast and east are most frequent. Southeasterly winds are frequently observed at the top of the bays (in ports Mezen', Kandalaksha, Onega). Monthly mean wind speed in the open sea and on islands is 7-10 m/s from September to April and 5-7 m/s from May to August. In the bays running deep in land, mean wind speed does not exceed 3-5 m/s during whole year.

The general circulation and sea level variations in the Barents and White seas are formed under cumulative effect of wind forcing, water interaction and ex-change between surrounding seas, strong tides, peculiarities of bottom topography, seasonal variability of river runoff, precipitation and ice cover, and other factors. Thus, sea level variations in the Barents and White seas have a complex nature and are characterized by a significant spatial and temporal variability.

The seasonal variations of the sea level in the Barents and White seas are caused by an impact of atmospheric pressure and wind, temperature and salinity, river runoff, precipitation, and ice cover. For the Barents Sea the maximum of seasonal sea level variation is observed in November-December and its minimum is registered in May-June, that is in accordance with the atmospheric pressure effect upon the sea surface. For example, the difference between maximum and minimum mean sea level in Murmansk can amount to 40-50 cm. A range of seasonal variations in the White Sea level is observed in the estuary zones of the Onega and Severnaya Dvina rivers and may reach 30-60 cm.

Sea level variations related to storm surge are formed by strong winds associated with passage of intense atmospheric cyclones. The western and northwestern cyclones dominate and amount to 88% from their total number. During the extreme situations the storm surge height can be comparable with the tidal height. The storm surge values are greatest in the southeastern part of the Barents Sea (up to 2 m). For the Kola coast and Spitsbergen area storm surge heights are about 1 m; the smaller values of 0.5 m are observed near the Novaya Zemlya coast. As concerns the White Sea, on the average the storm surge is of 30-70 cm, but in the Onega Bay it can reach about 80 cm.

Tides play the key role in the coastal water dynamics in the Barents and White seas, and dominate in total sea level variations. In the southern part of the Barents Sea the semidiurnal tide reaches amplitudes up to 2 m which is the largest in the Arctic seas. In the northern and north-eastern Barents Sea the tidal height decreases and for the Spitsbergen coast equals to 1-2 m. For the southern coast of the Franz Joseph Land it is of 40-50 cm only. It is explained by the peculiarities of the bottom relief, the coastline configuration, and the interference of tidal waves, which come from the North Atlantic and Arc-tic oceans. The tidal heights in the White Sea vary from 8 m in the Mezen Bay to 1 m in the Dvinsky Bay . As a result of nonlinear tidal phenomena and nonlinear interaction of the main tidal components (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1) there is a set of additional tidal harmonics. According to the results of numerical simulation an amplitude of nonlinear harmonics in the average is about 5% of the total tide height for the Barents Sea and about 50% for the White Sea with the exception of the Voronka (10-25%). The maximum value (more than 25%) is observed between the Spitsbergen Bank and Central Bank in the Barents Sea, and in the Pechora Sea. In the White Sea the maximum value is about 100% for the Severnaya Dvina and Kandalaksha bays (Fig. 2).

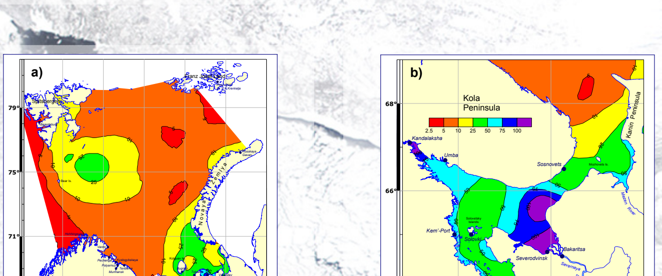

Fig. 2. The ratio (%) of the total nonlinear harmonics amplitudes to the total main tidal components amplitudes for the Barents (a) and White (b) seas.

Calibration/Validation Wind Speed

In the framework of the ALTICORE project, the consistency between altimeter-derived wind speed and measurements on coastal meteorological stations was checked. Satellite-derived wind data used were obtained from the RADS data base. For the comparison, 30 MS on the Barents Sea coast and 21 MS on the White Sea coast were selected. As an example, we show results of the comparison for two MS – Kem' Port (White Sea) and Kanin Nos (Barents Sea).

The ERS & ENVISAT, GFO and T/P & J1 satellite tracks, which were used when obtaining satellite-derived wind speed data for Kem' Port and Kanin Nos are shown in Fig. 3. Examples of altimeter and observed (*in-situ*) data on wind speed and corresponding scatter plots for these MSs are given in Figs. 4, respectively.

In the cases of both Kem' Port and Kanin Nos (Fig. 3) MS databases for 2000-2007 were used. Altimeter wind speed values for Kem' Port were in most cases noticeably less than meteo ones and correlation between them was practically absent ($r = 0.16$). Influence of land may be supposed as a possible reason of such poor correlation. Better correlation ($r = 0.45$) was observed in the Kanin Nos case. Improvement in correlation between meteo and altimeter data on wind speed can be obtained when using decomposition of the winds in four quadrants according to wind direction relative to coastline direction. An example of its application for the Kanin Nos case is shown in Fig. 5. The reference line was chosen to be parallel to the axis of this Peninsula.

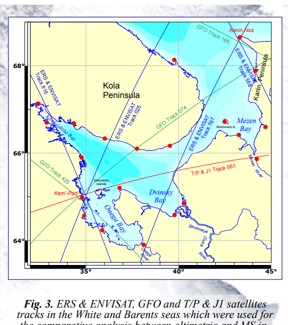

Fig. 3. ERS & ENVISAT, GFO and T/P & J1 satellites tracks in the White and Barents seas which were used for the comparative analysis between altimetric and MS in-situ data. Red circles mark locations of MSs.

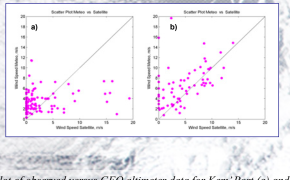

Fig. 4. Scatter plot of observed versus GFO altimeter data for Kem' Port (a) and Kanin Nos (b).

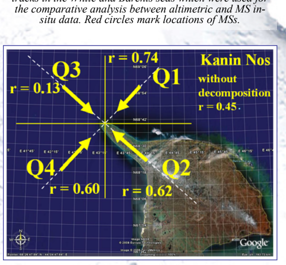

Fig. 5. Scheme of decomposition of wind directions in the four quadrants (Q1-Q4) in relation to the orientation of the coastline for the Kanin Nos case. The appropriate correlation coefficients between wind speed from altimetry and in-situ MS records are shown in the scheme. Arrows show prevailing wind direction for each quadrant.

Calibration/Validation Sea Surface Height

The consistency between altimeter sea surface height (SSH) data acquired by the satellites T/P, ERS-1/2, ENVISAT, GFO and J1, and measurements of 18 TGs located in the Barents Sea and 8 TGs – in the White Sea was investigated (Fig. 1). Processing of satellite altimetry data included calculation of sea surface height anomaly (SSHA) with using all corrections without tidal and inverse barometer correction. Then, for every cycle of the selected satellite passes, spatial coordinates of the point nearest to the concrete TG location (within 15 miles) were determined. For the Barents Sea, correlation between SSHA derived from altimetry and tide gauge data can be fairly high (> 0.85) when using ERS-1/2 and ENVISAT data. For GFO data the correlations are noticeably lower, probably due to orbit errors and inaccurate corrections. Correlations are extremely high (0.99) when ERS-1/2 and ENVISAT data are used for the comparison with Vardo and Hohhingsvarg TGs for which there are long and high quality time series. These high correlations might be explained by the tide effect, which is very significant in the Barents Sea (see above). Moreover, these TGs are located in the area where nonlinear and residual tidal phenomena are not important. For TGs in Murmansk, Polyarny, Indiga and others which are located in fjords or estuaries the correlations are small (< 0.4). Absence of 1Hz altimetric measurements in these areas or strong effect of nonlinear and residual tidal phenomena may be a cause of it. Details of SSHA comparison are shown in Fig. 6.

For the White Sea, a comparison between satellite and TG SSHA data also shows significant correlations (>0.6) for all the satellites except GFO. Greater values of correlation for TG Onega (0.76 for T/P and J1 data; 0.96 for ERS-1/2 and ENVISAT data) and TG Severodvinsk (0.97 and 0.98, respectively) are condinioned by their location. Both TGs are situated in river estuaries, thus river runoff has a strong influence on the hydrological regime in these parts of the White Sea. Correlation minimum (0.66 and 0.61, respectively) is observed at TG Kem' Port where nonlinear and residual tidal phenomena are important on shallow water. According to the results obtained, satellite altimetry SSHA data are in good consistency with TG SSHA.

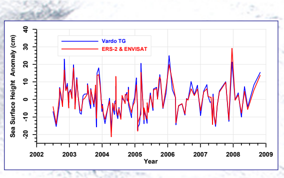

Fig. 6. Time variability of Vargo TG and ERS-2 & ENVISAT SSHA .

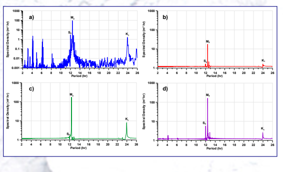

Fig. 7. Spectral density of the SSHA time series at the TG Solovki (a) and the superposition of main tidal constituents M_2, S_2 and K_2 calculated with tidal models: (b) – CSR4.0, (c) – GOT00.2 and (d) – HMRC.

Calibration/Validation Tidal Models

Peculiarities of the tidal regime in the Barents and White seas make inaccurate use of global tidal models for a processing (tidal correction) of satellite altimetry data. Therefore, to improve altimetry data processing in these regions, it is very important to use regional tidal model.

Global tidal models At present there are more than 11 global tidal ocean models. They differ by spatial resolution and procedures of assimilation of TG and satellite altimetry data. A variety of tests indicates that all these tidal models agree within 2–3 cm in the deep ocean, and they represent a significant improvement over the classical Schwiderski 1980 model. But global tidal models ignore nonlinear, residual and other tidal phenomena which inherent to coastal and shallow water area of marginal and semi-enclosed seas. In our investigation global tidal models CSR4.0 and GOT00.2 were used.

Regional tidal model Three dimensional baroclinic model with free surface was developed in Laboratory of Sea Applied Research at HMRC of Russian Federation. For the Barents and White seas, only M_2 S_2 and K_2 main tidal components were used in calculation. Mean temperature and salinity fields, as well as atmospheric fields from the NCEP/NCAR Reanalysis project were used in calculation of the Barents Sea level and currents for 1948-2008. In contrast to global models results of the HMRC model represent fields of total tide height for each time moment with a given time step.

For comparison of global and regional tidal models spectral density of sea level was calculated for all TGs and for different main tidal constituents – M_2, S_2 and K_2 with time step of 1 hour. Analysis of SSHA was based on the results of harmonic analysis of temporal series. Spectral density of TG Solovki (Fig. 7) includes main tidal constituents (M_2, S_2 and K_2), their nonlinearly interference (see peaks with period less than 8.5 hours) and periods related to synoptic dynamics.

Long-Term Variability of Sea Level

The trend of the Barents Sea level estimated from TG observational data is -0.05 ± 0.05 cm/yr after all corrections. It may be supposed that negative value of the Barents Sea level trend is a result of a slow rise of Fennoscandia and Novaya Zemlya. Coast of Kola Peninsula of the Barents and White seas uplifts with a rate of 4-8 mm/yr. Rate of ascend of Earth's crust in the region of Novaya Zemlya Island is 1–2 mm/yr. For interpretation of climatic sea level change it is desirable to keep in mind that the Barents Sea shelf is sagging.

With the end of investigating long-term variability of sea level, SLA (sea level anomaly) was calculated with regional tide HMRC model in three points (Fig. 8). Points A and B are located near Scandinavia and Kola Peninsula. Their position coincides with isoline 2 cm of climatic dynamic topography field obtained with hydrodynamic model HMRC without account for tide-generating force. Third point C is located on the boundary between the Barents and White seas. Altimetric data from the satellites ERS/ENVISAT and GFO-1 were used for processing. Analysis of temporal SLA variations in the point A shows that SLA increases in March 1998 – May 1999, May 2001 – August 2001 and June 2005 – September 2007 with a rate of 4.58 cm/yr, 9.62 cm/yr and 2.00 cm/yr, respectively (Fig. 9). Ice cover in these time periods is less than in the following years. So it is possible that this phenomenon was associated with intensification of the Norwegian Coastal Current.

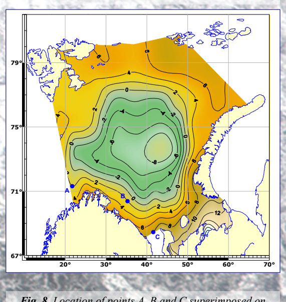

Fig. 8. Location of points A, B and C superimposed on climatic dynamic topography field obtained with hydrodynamic HMRC model for time period 1958-2008.

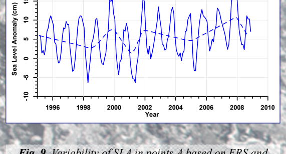

Fig. 9. Variability of SLA in points A based on ERS and ENVISAT data.

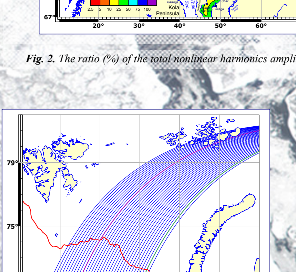

Fig. 10. Ground tracks of 34 descending ERS-2 and ENVISAT passes which are used for analysis of alongtrack sea ice edge position. Red line is mean climatic sea ice edge position. Green line shows position of 988 track and purple line – of 932 track.

Interannual Variability of Sea Ice Edge Position

Traditional research of Arctic ice cover and ice edge location are based on infrared and microwaves radiometry data. But satellite altimetry data may be also used to estimate ice cover extent or rather position of ice edge.

For this purpose 34 descending tracks of the satellites ERS-2 and ENVISAT have been chosen (Fig. 10). These tracks are located under the optimal angle to mean climatic sea ice edge position. Significant SSH records along the satellite tracks over the sea surface and over the ice fields strongly differ. This point of the signal change located on the track was identified as an ice edge. Some temporal variations of ice edge position along tracks are shown in Fig. 11. From 1995 to 2008 sea ice edge didn't reach its mean climatic position along 988 track. For 932 track sea ice edge observed in the winters of 1996, 2003 and 2004 was displaced southwestward by 60 km, 40 km and 53 km, respectively, from its mean climatic position. For both tracks the 2000 and 2007 winters were very warm.

According to our calculations, interannual trends of sea ice position northeast-ward along 988 and 932 tracks were 13.2±0.6 km/yr and 10.7±0.4 km/yr, respectively. For summer months, similar trends were 24.8±1.2 km/yr and 8.2±0.5 km/yr, respectively. Averaged velocity of the ice edge along track displacement for all tracks was 11.8±0.5 km/yr.

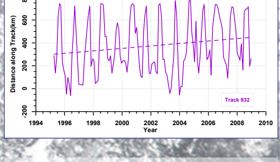

Fig. 11. Temporal variability of sea ice edge position along 932 (descending ERS-2 and ENVISAT tracks. Dashed line shows interannual trend. Zero corresponds to the mean climatic sea ice edge position.

Acknowledgements

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