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Article

Satellite Altimetry of Sea Level and Ice Cover in the Barents Sea

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Abstract
Satellite altimetry data are used for investigation of the sea level variability and sea ice cover retreat in the Barents Sea in 1992-2018. The data from ERS − 1/2, ENVISAT, SARAL/AltiKa, and Sentinel-3A/3B satellites were used in this study. An increasing trend of the sea level of about 2.31 mm/yr was observed in this time period, which caused a total increase in the Barents Sea level by about 6 cm. Linear trends of the sea level change varied from 1.84 mm/yr in July to 4.29 mm/yr in September. The average velocity of the ice edge retreat along the tracks in the northeastern direction is of 10.9 km/yr for the same period. It was found that the ice edge displacement rate tends to increase by 0.30 km/yr per a degree in longitude in the eastward direction. Thus, the ice edge retreat along the "eastern" tracks goes faster than along the "western" ones, which is likely explained by a change in the water dynamics in the Barents Sea.

Key words: the Barents Sea, satellite altimetry, sea level, sea ice cover, sea ice retreat.

Introduction

About 90% of the total area of the Russian Arctic shelf, comprising 5.2–6.2 mln km^2 is located in promising oil and gas reserve areas. About 2 mln km^2 are located in the Western Arctic on the shelf of the Barents and Kara Seas (Fig. 1) (including the Ob and Taz Bays), where potential hydrocarbon resources amount to 50-60 bln m^3 (Zonn et al., 2017). Even with a little geological and geophysical exploration, eleven deposits were discovered on the shelf of the Barents Sea, including four oil reserves (Prirazlomnoye, Dolginskoye, Varandeyskoye, Medynskoye), three gas reserves (Murmanskoye, Ludlovskoye, Severo-Kildinskoye), three gas condensate reserves (Shtokmanovskoye, Pomorskoye, Ledovoye) and one oil and gas condensate reserve (Severo-Gulyaevskoye). The Shtokman gas field alone, the largest in the world, contains about 4000 bln m^3 of gas (Chuprov, 2008). Today, the development of the Arctic requires new approaches that ensure rational use of natural resources and conservation of the marine environment based on modern science and technology (Mastepanov, 2014).

Satellite altimetry is currently the only remote sensing method that allows one to study the level regime of both the World Ocean and the seas of the Arctic shelf of the Russian Federation (primarily the White and Barents Seas) (Lebedev et al., 2011). These seas are characterized by complex hydrodynamic, tidal, ice and meteorological regimes (Rodionov, Kostianoy, 1998; Kostianoy et al., 2004), which determines the specific features of processing satellite altimetry data for this region (Lebedev et al., 2011).

The Barents Sea is characterized by the following general characteristics: area - 1405–1512 thousand km^2, volume - 282–316 thousand km^3, mean depth - 186–222 m, max depth – 513 m, watershed area – 668 thousand km^2 (Dobrovolsky, Zalogin, 1982; Terziev et al., 1990; Jakobsson et al., 2004; Marchenko, 2012; Zonn et al., 2017).

Fluctuations in the level of the Barents Sea are mainly associated with tidal and surging phenomena, and in river mouths also with spring floods. Tidal phenomena in the Arctic seas are mainly determined by the tidal wave propagating from the Atlantic Ocean. Tides in the Barents Sea are caused mainly by the Atlantic tidal wave, which enters the sea from the west between the Nordkap Cape and Svalbard, and moves to Novaya Zemlya. A tidal wave from the Arctic Basin enters the northern part of the Barents Sea (Fig.1).

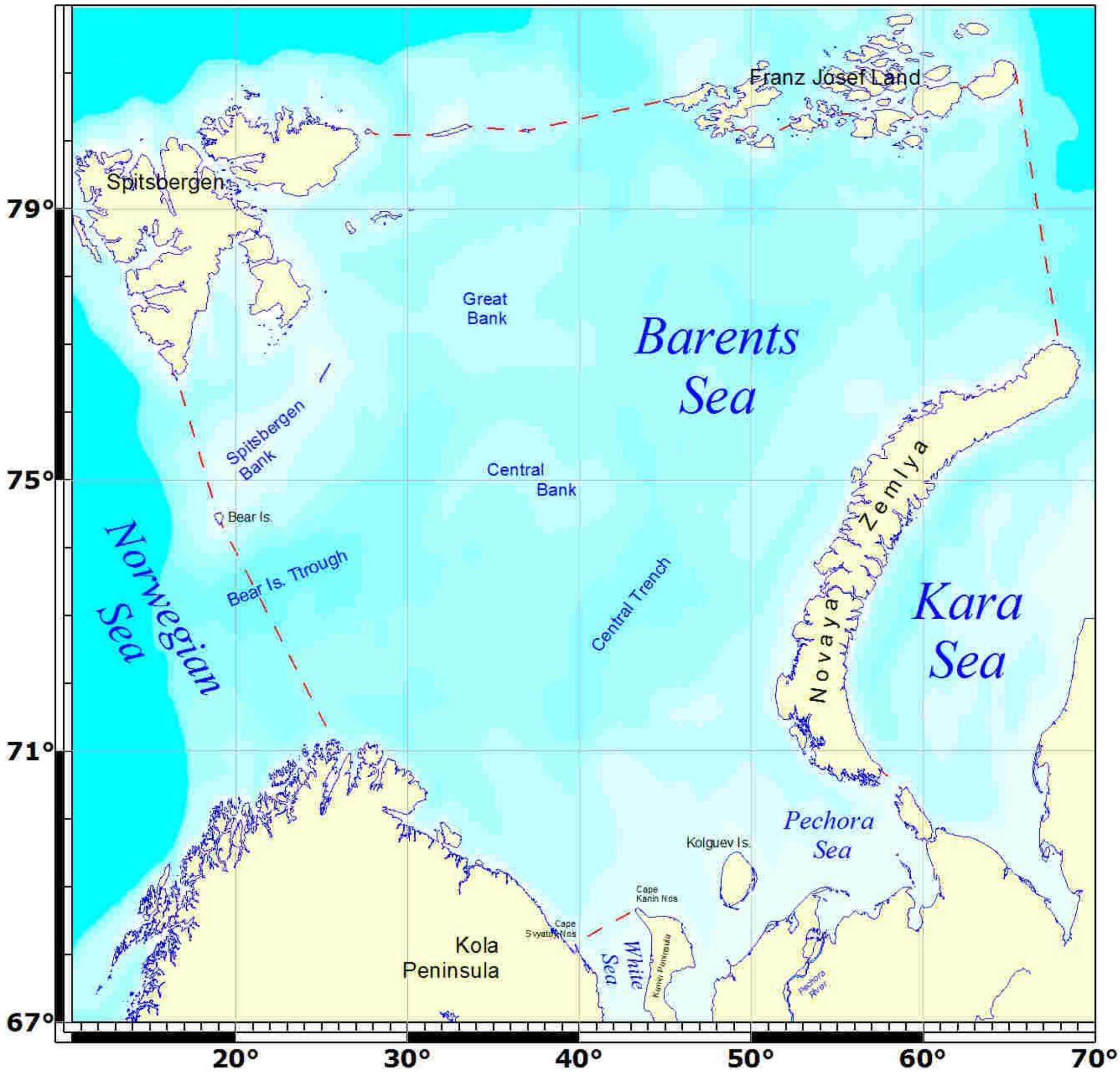

Figure 1. Map of the Barents Sea. The red dashed line shows the boundaries of the Barents Sea.

Tides usually have regular semidiurnal character. In the southeastern part of the sea, irregular semidiurnal and irregular diurnal tides are observed in some areas. The tide height in the southwestern part of the sea increases from west to east from 2.4 to 3.8 m. In the southeastern part of the Barents Sea (from Cape Kanin Nos to the Kara Gate and Yugorsky Shar), the tide decreases from 4 to 0.5 m. To the north, the tidal height decreases (at Svalbard it is of 1–2 m, at Franz-Josef Land - 20–30 cm). This is explained by the bottom topography, coastal configuration, and tidal wave interference coming from the Atlantic and Arctic oceans (Dobrovolsky, Zalogin, 1982).

As a result of the nonlinear interaction of the main tidal waves in the Barents Sea, overtones of the residual effects, long-period and short-period tidal harmonics appear. The mechanisms of occurrence of nonlinear residual tidal phenomena are associated with three types of nonlinear effects: convective nonlinearity, frictional nonlinearity due to the quadratic law of bottom friction, and shallow nonlinearity (Sgibneva, 1981). According to the results of numerical modeling (May, 2008), the total amplitude of nonlinear harmonics in the Barents Sea is equal to about 10% of the total tide height. The maximum value (more than 25%) is observed over the Central Bank, along the southeastern coast of the Barents Sea, and the southern coast of Novaya Zemlya.

Strong and prolonged winds cause surging fluctuations in the level of the Barents Sea. They are most significant (up to 3 m) along the Kola coast and Svalbard (about 1 m), smaller values (up to 0.5 m) are observed off the coast of Novaya Zemlya and in the southeastern part of the sea (Terziev et al., 1990). Waves in the Arctic seas depends on the wind regime and sea ice conditions. In general, the ice regime in the Arctic Ocean is unfavorable for the development of wave processes. Irregular coastline, the presence of numerous islands, as well as strong tidal currents have a significant influence on the propagation of wind waves and swell. The latter, in the case of waves propagating towards the flow, can increase the wave height by more than two times. Currents in the same direction, on the contrary, reduces the height to one and a half times. The Barents Sea is one of the most stormy in the World Ocean. In winter, storm events develop here, in which in the open sea the height of the waves reaches 10–11 m. The highest waves in the southeastern part of the sea are formed by northerly and northeasterly winds, their height can exceed 10 m (Terziev et al., 1990).

Unlike the western and central parts, the southeastern part of the Barents Sea is covered with ice. Usually, ice formation begins in the second half of October, but depending on the current weather conditions and heat reserve of the sea, the periods of ice cover formation vary greatly. The freezing process is directed from east to west; melting of ice occurs mainly in the opposite direction. Usually, ice cleansing begins in April and ends in July, although in some years this process may shift by 2-3 months. Depending on hydrometeorological conditions, the ice period lasts from 6 to 10 months. Under the influence of currents and atmospheric circulation, ice fields are in constant motion. Ice drift velocity depends on a combination of current velocity and direction, and wind speed and directions, and can reach 0.8–1 m/s (Dobrovolsky, Zalogin, 1982; Terziev et al., 1990).

Satellite altimetry allows to monitor both the sea level and ice cover on the whole area of the Barents Sea which is very important because meteo and tide gauge stations are located only on the coasts and the islands.

Materials and methods

For the analysis of the hydrological regime of the Barents Sea, the most optimal are the data from the ERS − 1/2, ENVISAT and SARAL/AltiKa satellites with a repetition period of the same tracks of 35 days and the data of satellites Sentinel-3A / 3B with a repetition period of the same tracks of 27 days (Fig. 2).

The ERS−1 satellite dataset (Gilbert et al., 2014) is a discontinuous, but the longest series of measurements in Phase C (April 1992 - December 1993) and Phase G (April 1995 - June 1996) with the possibility of its extension by ERS-2 satellite data (Gilbert et al., 2014) (April 1995 - June 2002), ENVISAT satellite (ENVISAT ..., 2007) (March 2002 - April 2012), and SARAL/AltiKa satellite (Bronner et al., 2016) (February 2013 - present). Since the orbit parameters of the Sentinel−3A satellite (February 2016 – present) and Sentinel−3B (April 2018 – present) (Along-track ..., 2019) differ from the orbit parameters of the previous satellites, their combination with the ERS − 1 / 2, ENVISAT and SARAL/AltiKa data in the same time series does not work. Combining is possible only at the crossover points of the tracks of the first and second group of satellites.

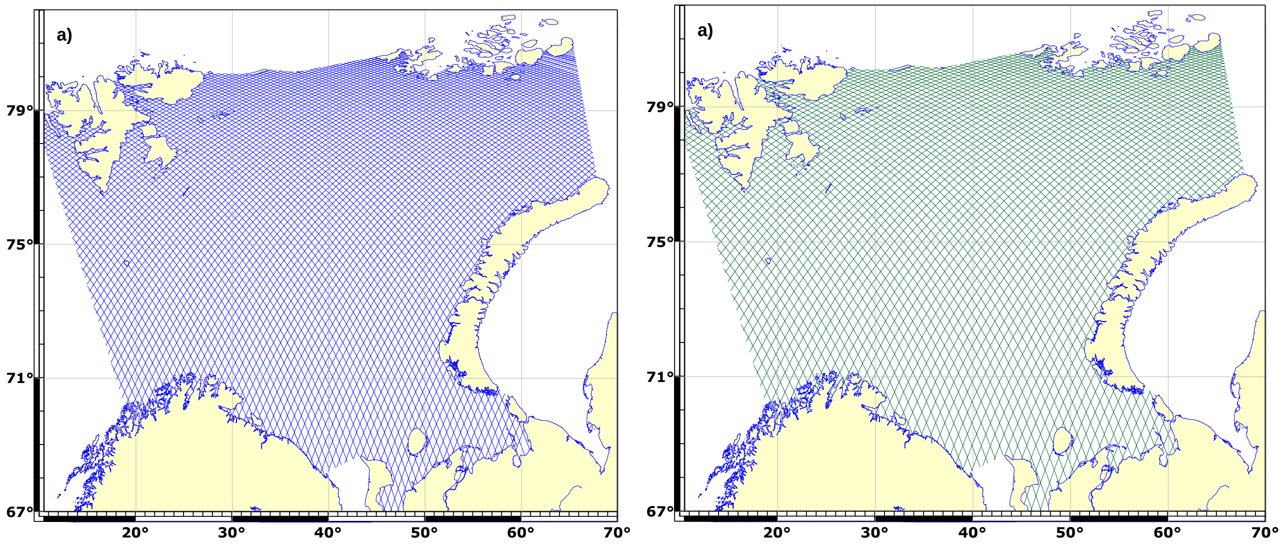

Figure 2. The position of the tracks of the ERS − 1/2, ENVISAT and SARAL/AltiKA (a) satellites with a repetition period of 35 days and the Sentinel – 3A / 3B satellites (b) with a repetition period of 27 days in the Barents Sea.

The processing of satellite altimetry data was carried out using the software of the Integrated Satellite Altimetry Database (ISAD), taking into account all the necessary data corrections: correction for a “dry” atmosphere, correction on humidity, ionospheric correction, electromagnetic bias, correction of the reverse barometer, correction on tides and bottom load, correction for tides in the earth's crust, and the pole tide correction (Lebedev, Kostyanoy, 2005; Lebedev, 2016). Anomalies in the heights of the sea surface were calculated relative to the model of average heights of the sea surface DTU13 MSS (Andersen et al., 2015).

Results

The first experiments to study the possibility of using satellite altimetry data to analyze the hydrological regime of the Barents Sea showed the representativeness of the use of these remote sensing data (Andersen, 1994; Lebedev et al., 2003). Verification of satellite altimetry data was carried out by comparing the data of sea level measurements at tide gauge stations with altimetry measurements at points located on the nearest tracks, or at the crossover points of ascending and descending tracks.

For the Barents Sea, the correlation between the altimetry measurements of the ERS − 1/2, ENVISAT and SARAL / AltiKa satellites and the data at tide gauge stations is quite high (over 0.86). For example, for the stations at Vardø and Honningsvåg in Norway the correlation coefficient is of 0.992 and 0.991, respectively. These high correlations are explained by the influence of tides, which play the main role in the level regime of the Barents Sea. In addition, these stations are located in areas where non-linear and residual tidal phenomena are not so large. High correlation coefficients are also observed at the stations of Teriberka and Pechenga in Russia (more than 0.9). For stations at Iokan’ga, Bugrino, Topseda, Varandey located on the southeastern coast of the Barents Sea, the correlation coefficients are a bit lower (less than 0.881).

Interannual variability of the Barents Sea level anomalies according to satellite altimetry measurements of the ERS − 1/2, ENVISAT and SARAL / AltiKa for the period 1992–2018 is shown in Fig.3. In general, we observe an increasing trend of the sea level of about 2.31 mm/yr which caused a total increase in the Barents Sea level from 1992 to 2018 by about 6 cm. This trend is not uniform because it is modulated by seasonal variability of the sea level with amplitude of 20-30 cm and maximum sea level in winter periods. We calculated sea level variability for June, July, August, and September and calculated linear trends for these months separately (Fig. 4). Interannual variability showed different behavior of the sea level in these months when some of them showed variations in phase during some years and varied in anti-phase during other time periods. Linear trends were positive but also showed quite different values: for June

– 3.68 mm/yr, for July – 1.84 mm/yr, for August – 3.46 mm/yr, and for September – 4.29 mm/yr (Fig. 4). These differences in trends can be explained by significant changes in hydrological regime of the Barents Sea, as well as in atmospheric forcing due to regional climate change in these years.

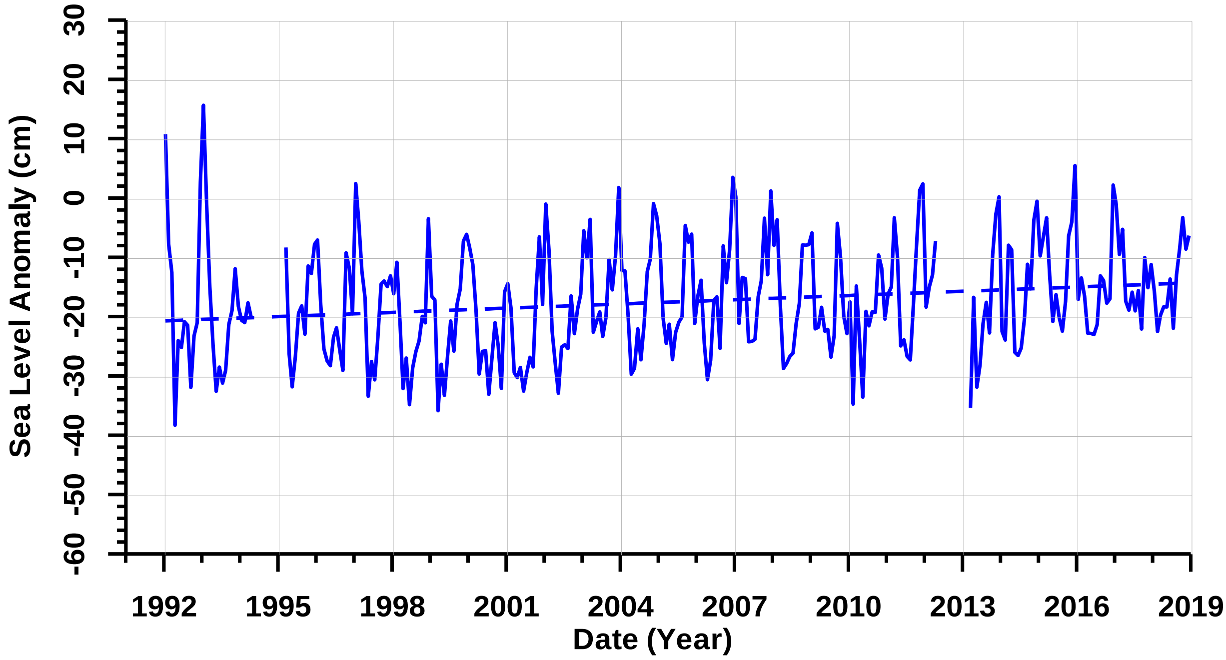

Figure 3. Interannual variability of the Barents Sea level anomalies according to satellite altimetry measurements of the ERS − 1/2, ENVISAT and SARAL/AltiKa for the period 1992–2018. Dashed line shows a linear trend.

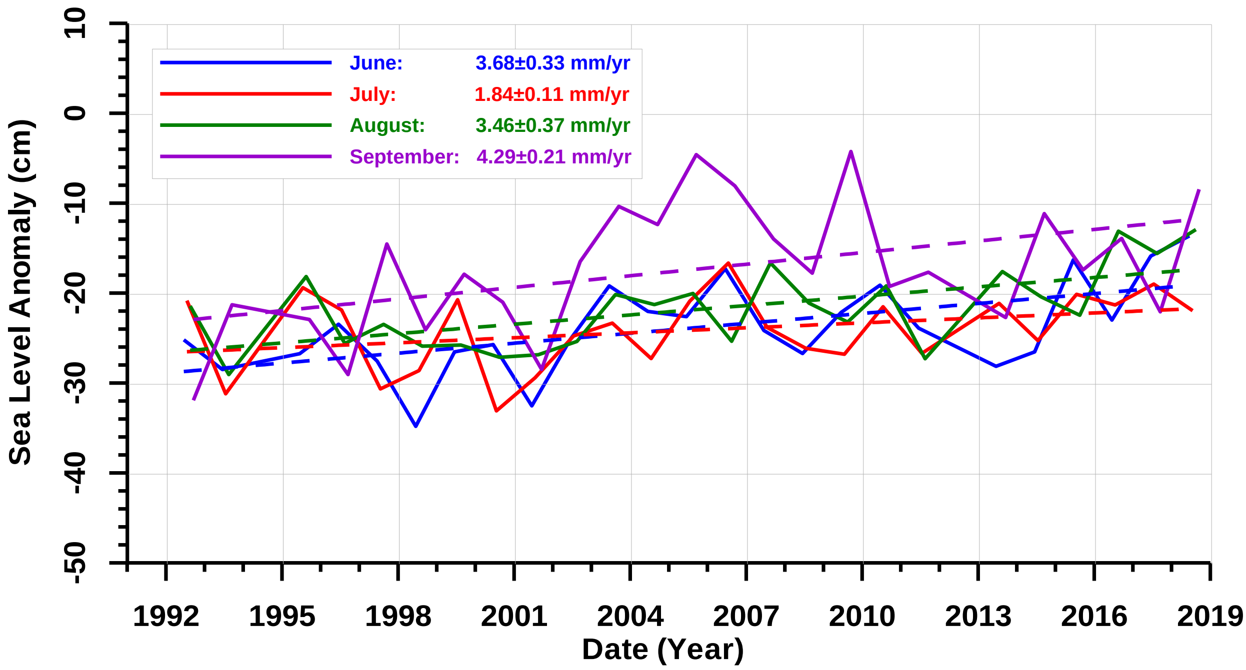

Figure 4. Interannual variability of the Barents Sea level anomalies according to satellite altimetry measurements of the ERS − 1/2, ENVISAT and SARAL/AltiKa for the period 1992–2018 for June, July, August and September. Dashed lines show linear trends.

Among the Arctic seas, the ice regime in the Barents Sea changes most dynamically under the influence of climatic changes. Traditional monitoring of sea ice cover and location of the ice edge is based on radar (SAR), optical, infrared and microwave radiometric data (Carsey, 1992; Rees, 2005; Smirnov, 2011; Shokr, Sinha, 2015). Optical and infrared methods require cloudless conditions that are rare in the Arctic.

During the polar night, the optical method also does not work. Microwave radiometric data have a spatial resolution of about 25 km. Satellite altimetry data themselves, and in conjunction with the data of a microwave radiometer located on board the satellite along with the altimeter, can also be used to identify ice cover (Lebedev, 2013; Duguay et al., 2015; Lebedev, Klyuev, 2018; Lebedev et al., 2018), its climatic variability (Kouraev et al., 2003; Kouraev et al., 2009; Duguay et al., 2015; Karetnikov et al., 2016; Lebedev, Klyuev, 2018) or the position of the ice edge (Lebedev et al., 2011).

To study the position of the ice edge in the Barents Sea, 34 descending tracks of the ERS-1 (phases C and G), ERS-2, ENVISAT, and SARAL/AltiKA satellites were selected, which are located at an optimal angle to the average climatic position of the ice edge in the Barents Sea (Fig. 5). The fact is that the sea ice retreat in the Barents Sea goes in the north-eastern direction which matches exactly with general spatial location of the satellite tracks (Fig.5). The intersection points of the tracks with the dashed line in Fig. 5 are the reference points relative to which the distance along the track to the ice edge was calculated. For the Sentinel-3, tracks of the satellite were selected as close as possible to the tracks of other satellites in distance along the reference line.

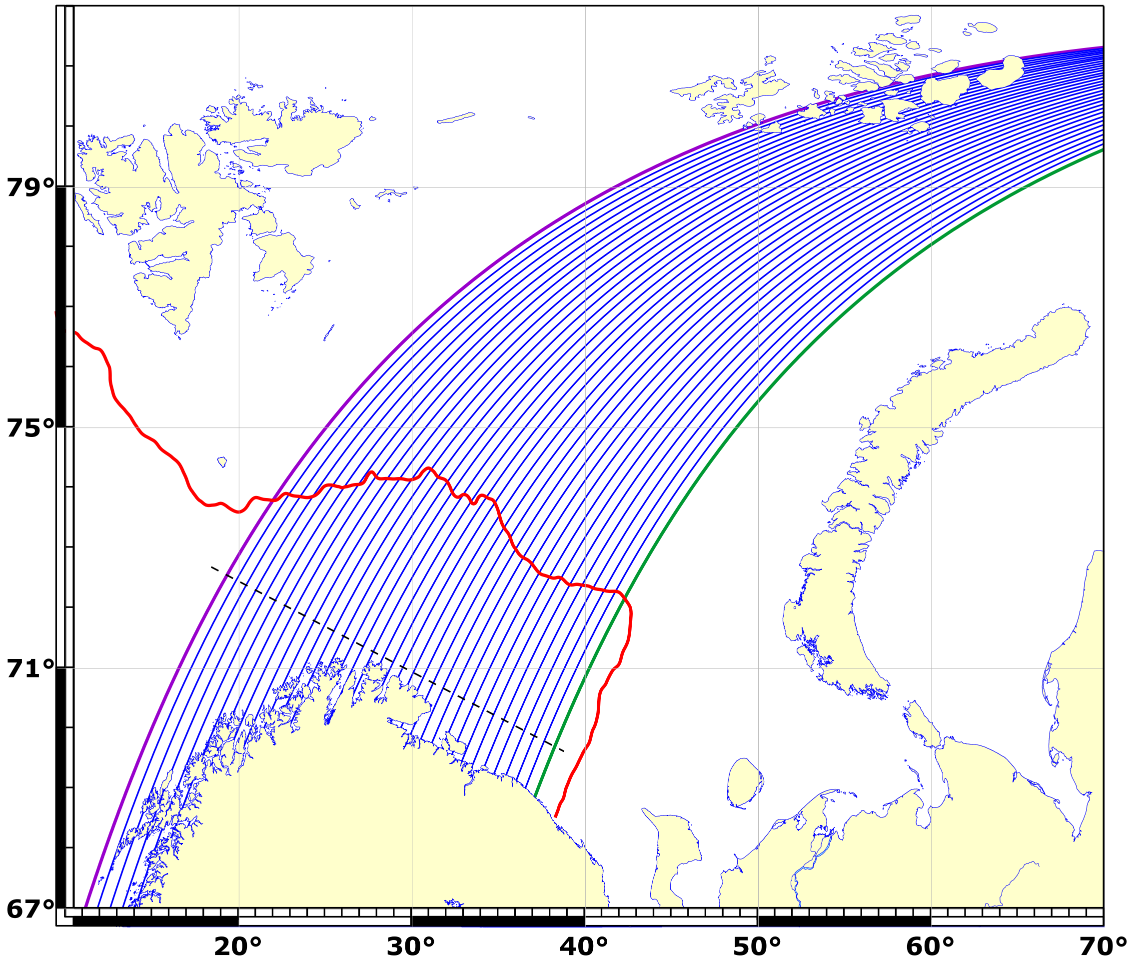

Figure 5. Location of 34 descending tracks of satellites ERS-1 (phases C and G), ERS-2 and ENVISAT, which were used to analyze the position of the sea ice edge in the Barents Sea. The red line is the average climatic position of the sea ice edge. The green line shows the position of track N444, the purple line shows the track N360. Dashed line is a reference line used for calculation the distance to the ice edge along the tracks.

Two approaches were used to identify the ice edge on the track line. The first was based on the difference in the shape of the reflected pulse from the water and ice surfaces. The reflected pulse shapes of the altimeters ERS-1/2, ENVISAT, and SARAL/AltiKA were processed using the Ice-2 analytical retracing algorithm (Gommenginger et al., 2011). However, at different time periods of the year and under different weather conditions, the width of the area of sea ice with concentration from 0% to 100%, or the area between clear water and solid ice can differ significantly. Therefore, the second algorithm for identifying the position of its middle is based on measurements of microwave radiometers with which all satellites carrying out altimetry measurements are equipped. On board the ERS-1/2, ENVISAT, and Sentinel-3A/B satellites, the microwave radiometer has operating frequencies of 23.8 and 36.5 GHz, and the SARAL/AltiKA satellite has 23.8 and 37 GHz. The middle of the region located between clear water and solid ice corresponds to the middle of the region of sharp changes in temperature and brightness. Thus, radio brightness temperatures above 230°K correspond to ice cover, and less than 170°K to pure water (Gommenginger et al., 2011).

Interannual variability of the position of the ice edge along track N118 in 1992-2018 according to altimetry measurements is presented in Figure 6. It shows that an average sea ice retreat along this track equals to 9.94 km/yr, thus during these 27 years an average ice margin has moved northeastward for more than 200 km. For example, in winters of 1996, 2003 and 2004, ice margin was located about 500 km from the reference line, whereas in winter of 2018 it was already 1000 km far from it (Fig.6).

Fig.5 shows that an average climatic sea ice edge in the Barents Sea has a complicated form caused by the system of warm currents entering the sea from the west (Rodionov, Kostianoy, 1998; Kostianoy et al., 2004). It is clear that the retreat of the ice edge will not be uniform on the aquatoria of the sea, as well as satellite tracks cross the ice edge at different angles in different parts of the sea. Thus, we can expect different average velocities of the sea ice retreat along different satellite tracks. This type of analysis was done for a series of satellite tracks of ERS − 1/2, ENVISAT, SARAL/AltiKA, and Sentinel-3 located on the reference line between 31^0 and 45^0E (Fig.7).

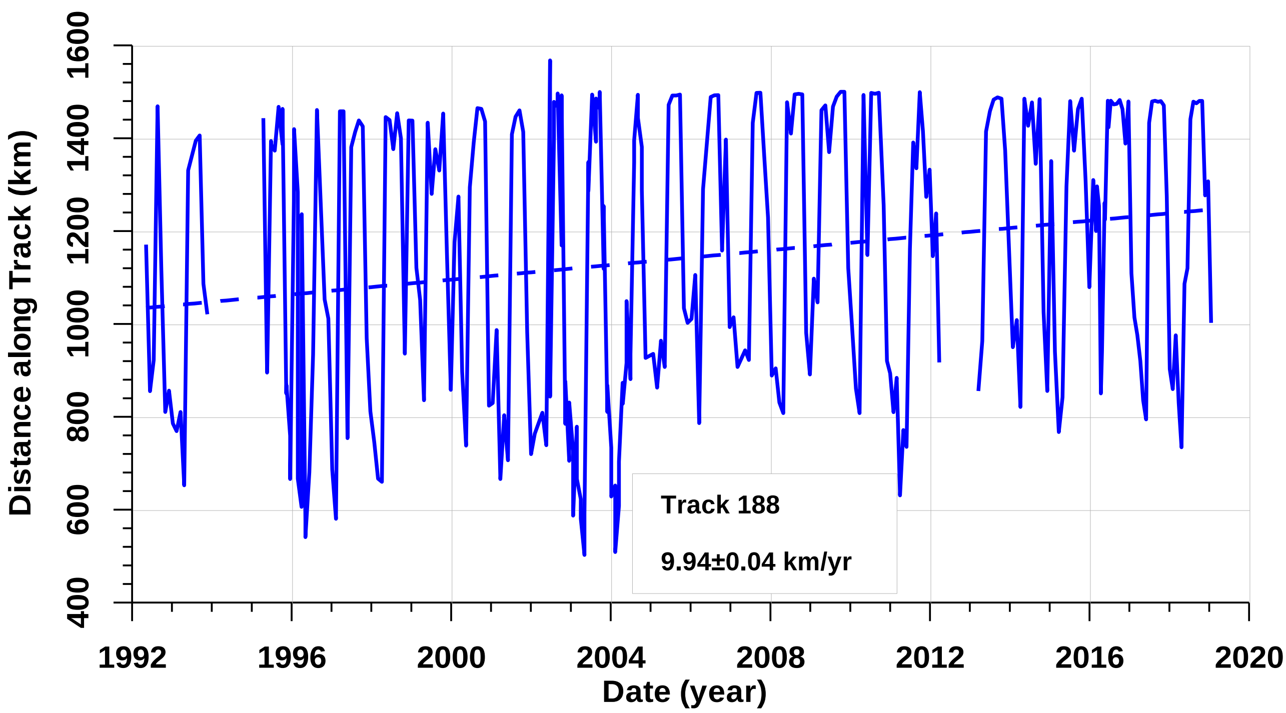

Figure 6. Interannual variability of the position of the ice edge along track N118 according to altimetry measurements of the ERS − 1/2, ENVISAT and SARAL/AltiKA satellites in 1992-2018. Dashed line shows a linear trend for the variability of the distance to the sea ice edge in the Barents Sea.

According to the obtained results, the minimum displacement of the ice edge of about 7 km/yr is observed along the 102 track, then a velocity of the ice edge retreat grows to 13.8 km/yr along the 416 track, drops to 10 km/yr along the 788 track, and grows again to 13.7 km/yr along the 158 track, and finally drops again to 10.7 km/yr along the 444 track (Fig. 7). The average velocity of the displacement of the ice edge along the tracks in the northeastern direction is of 10.9 ± 2.3 km/yr for the period 1992–2018. In general, the ice edge displacement rate tends to increase by 0.30 ± 0.05 km/year per a degree in longitude. Thus, the ice edge retreat along “eastern” tracks goes faster than along “western” ones. This is likely caused by a change in the water circulation in the Barents Sea when warm waters of the Norwegian Current branches propagates closer to Novaya Zemlya and further to the north.

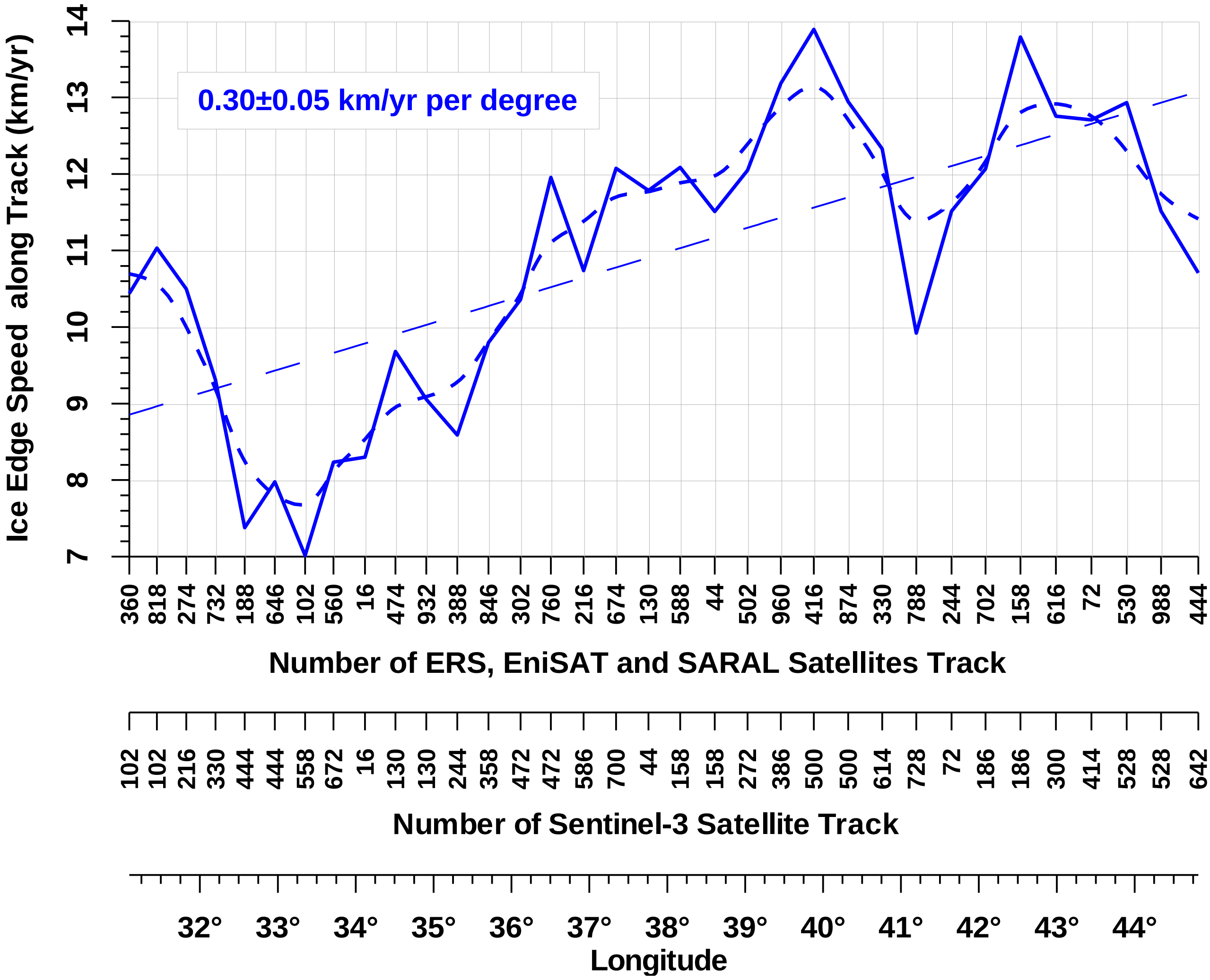

Figure 7. Variability of the velocity of displacement of the ice edge along the tracks depending on the longitude along the reference line (see Fig. 5). Straight dashed line shows linear regression. Curve dashed line shows spline approximation.

Conclusions

The present research showed that satellite altimetry is a very useful tool to monitor both sea level and ice cover in the Arctic seas due to its ability to get data in cloudy conditions and in the absence of light (polar night). Based on data acquired from ERS − 1/2, ENVISAT, SARAL/AltiKa, and Sentinel-3A/3B satellites we investigated the sea level variability and sea ice cover retreat in the Barents Sea in 1992-2018. For this time period we detected the sea level rise with an average rate of about 2.31 mm/yr, which caused a total increase in the Barents Sea level by about 6 cm. There is a significant seasonal variability of this rate of change, for instance, it varied from 1.84 mm/yr in July to 4.29 mm/yr in September. The Barents Sea experiences a serious loss of ice cover caused by regional climate change. We found that the average velocity of the ice edge retreat along the tracks in the northeastern direction is of 10.9 km/yr for the same time period. Also, it was observed that the ice edge displacement rate tends to increase by 0.30 km/yr per a degree in longitude in the eastward direction. Thus, the ice edge retreat along the “eastern” tracks goes faster (up to 14 km/yr) than along the “western” ones (a minimum of 7 km/yr), which is likely explained by a change in the water dynamics in the Barents Sea. This type of analysis can be done for the whole aquatoria of the Barents Sea as well as for other Arctic and Sub-Arctic seas.

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