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Article

Validation of Wind Speed Calculated on Satellite Altimetry Data by Measurements on Weather Stations Located Along the White Sea Coast

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Abstract
The White Sea is a southern inlet of the Barents Sea located in the northwest of European Russia. Winds are predominantly southwestern in winter with speeds of 4–8 m/s. Arctic anticyclones can change winds to the northeastern ones. The consistency between satellite altimeter derived wind speed and measurements on coastal stations of the White Sea was checked in the present study. For different parts of the coastal zone, satellites tracks were chosen to be located close to the weather station (within 10-20 km). Then, for every cycle of the selected satellite passes, corresponding values of satellite derived wind speed together with corresponding time (UT) were selected. *In-situ* wind speed data for the time nearest to the satellite pass were picked up from the databases collected at coastal weather stations. For the comparative analysis, five weather stations on the White Sea coast and tracks of TOPEX/Poseidon and Jason-1/2/3 satellites were selected. Improvement in correlation between meteo and altimeter data on wind speed can be obtained when using method of decomposition of the winds in four quadrants according to wind direction relative to local coastline orientation.

Key words: remote sensing, satellite altimetry, wind speed, validation, weather station, the White Sea.

Introduction

Information on wind speeds and direction is of paramount importance when studying the ocean and atmosphere interaction, the ocean waters circulation and their impact on the weather and Earth climate. Data on the wind speed and direction near the surface are needed to clarify weather forecasts, identify emerging hurricanes, tropical cyclones, track their paths, and calculate the intensity of storms at sea; they are used in navigation for plotting ship courses and when planning work in the offshore oil fields. Information about winds obtained from space is much cheaper and faster than that obtained by ground-based methods.

Passive microwave radiometry, scatterometry, SAR radiolocation, satellite altimetry are the main methods of remote sensing the wind parameters. The advantages of these methods are all-weather (independence from cloud cover) and frequency of repeatability (3 hours for microwave radiometry, repetition period 10–35 days for satellite altimetry). The spatial resolution varies from 75 m for SAR radiolocation to 25–35 km for microwave radiometry and scatterometry. The accuracy of the wind speed calculation is 10%, and as for wind direction (only scatterometry) are 20%.

When using wind speed data obtained by remote sensing methods, the question arises on their verification. This article presents the results of wind speed verification, calculated according to satellite altimetry data along the White Sea coast.

The White Sea

The White Sea is a semi-enclosed inland sea (Fig. 1). The sea border with the Barents Sea is a line between Cape Svyatoy Nos (northeastern coast of Kola Peninsula) and 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 receives more than a 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/year, which 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/year correspondingly (White Sea 1989; Glukhovsky 1991).

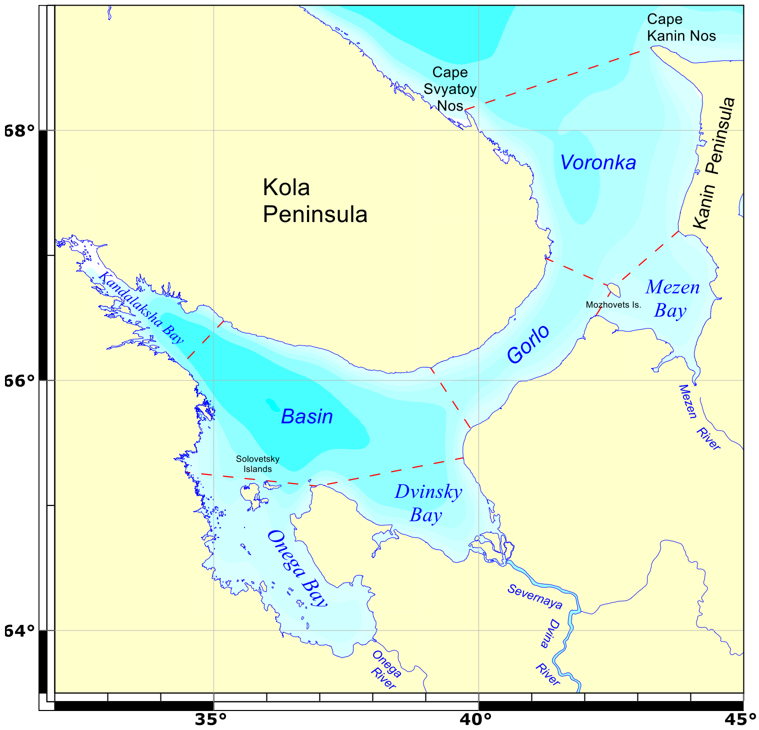

Figure 1. Maps of the White Sea. Dashed lines show boundaries of the sea and their internal parts (Lebedev et al., 2011).

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 (White Sea 1989). 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 deeply on land side, mean wind speed does not exceed 3–5 m/s during the whole year (Glukhovsky 1991).

Data and Method

For the analysis of wind speed in the White Sea, measurements from both TOPEX/Poseidon (T/P), Jason-1 (J1), Jason-2 (J2) and Jason-3 (J3) satellites were used for the following reasons. Accuracy of wind speed measurements by these satellites is 0.2 m/s.

The position of T/P, J1, J2 and J3 ground tracks (Figure 2) is optimal for analysis of wind speed variations in the White Sea. The orbital repeat period (about 10 days) enables analysis of interannual and seasonal variability of wind speed (Lebedev et al., 2011). T/P data represent the longest time-series of satellite measurements of wind speed (September 1992 − August 2002, or 1−364 cycles) with an option to extend the data series with J1 data (August 2002 − January 2009, or 1–259 cycles), J2 data (August 2008 − October 2016, or 1−303 cycles) and J3 data (February 2016 – present time) along the same ground tracks.

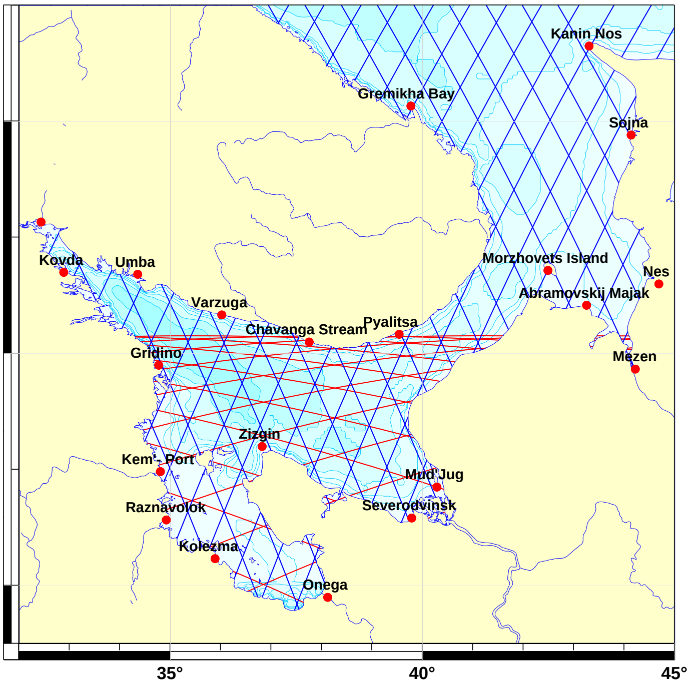

Figure 2. ERS-1/2, Envisat and SARAL\AltiKA (blue line) and T/P and J1/2/3 (red line) satellites tracks in the White Sea which were used for the comparative analysis between altimetric and weather stations (WS) *in situ* data. Red circles mark locations of WSs.

Short wind and capillary waves, caused by wind near the water surface, affect not only the shape of the reflected pulse, but also change the backscattering of the probe signal. Based on this effect, over the past two decades, several algorithms for calculating wind speed from altimetry measurements have been developed. They are divided into theoretical models. (Barrick, 1974; Jackson et al., 1992), semi-empirical models (Brown, 1979; Mognard, Lago, 1979; Brown et al., 1981) and empirical dependencies (Chelton, McCabe, 1985; Chelton, Wentz, 1986; Dobson et al., 1987; Witter, Chelton, 1991a).

The main semi-empirical and empirical models for calculating the wind speed at an altitude of 10 m from the sea surface are presented in Table 1.

The first semi-empirical model of the dependence of the driving wind speed at a height of 10 m from the sea surface (U_{10}) on the backscattering coefficient σ^0 was proposed (Brown, 1979), where empirical coefficients differ for different ranges. Further development of this functional dependence was proposed by Chelton and Wentz (1986) and Chelton and McCabe (1985). A more complex dependence of U_{10} on σ^0 was proposed by Chelton and Wentz (1986), which was later modified by Witter and Chelton (1991a).

Abdalla (2011) proposed an algorithm for calculating wind speed in the form of a piecewise continuous function, where the coefficients are selected so that the continuity of the function itself and its first derivative is preserved.

Table 1. Models for calculating the wind speed at a height of 10 m according to the backscatter coefficient.

Number	Formula	Application interval		Reference
		σ^0, dB	U_{10}, m/s	
1	$U_{10} = \exp\left[\left(10^{-\left(0,21+\sigma^0/10\right)} - B\right)\Big/A\right]$	$\sigma^0 < 10,9$	$2 \le U_{10} \le 18$	(Brown, 1979)
2	$U_{10} = 0,943 \cdot 10^{\left[\left(\sigma^0/10 - A\right)/B\right]}$	$10,9 \le \sigma^0 \le 10,12$	$3 \le U_{10} \le 14$	(Chelton, McCabe, 1985)
3	$U_{10} = \sum_{n=0}^{5} A_n \left(\sigma^0\right)^n$	$8 \le \sigma^0 \le 15$	$2 \le U_{10} \le 18$	(Witter, Chelton, 1991a)
4	$U_{10} = A_1 - B_1\sigma^0$	$\sigma^0 \le 10,917$	$2 \le U_{10} \le 20$	(Abdalla, 2012)
	$U_{10} = A_2 \exp\left(-B_2\sigma^0\right)$	$\sigma^0 > 10,917$		
5	$U_{10} = A\,\sigma^0 + B$	$\sigma^0 \le 8,12$	$U_{10} \ge 20$	(Young, 1993)

For two-frequency altimeters, Chen et al. (2002) proposed a more complex algorithm for calculating the wind speed from the data of backscattering coefficients at two frequencies of the *C* – band (4–8 GHz) and *Ku* – band (12–18 GHz) $U_{10} = a_i\left(\sigma_C^0\right)\sigma_{Ku}^0 + b_i\sigma_C^0$.

All proposed algorithms operate in the interval $U_{10} \le 20$ м/с. For cases of tropical hurricanes or exceeding the threshold of wind speed of 20 m/s, Young (1993) proposed a linear empirical model $U_{10} = A\,\sigma^0 + B$. In more detail, the differences between the main models for calculating the wind speed from the backscattering coefficient are presented in Figure 3.

Satellite derived wind data used in this paper were obtained from the Radar Altimeter Database System (Schrama et al., 2000). For every coastal location, satellites and their tracks were chosen so that the tracks were located close to the weather station (WS) (Fig. 2). Then, for every cycle of the selected satellite passes, spatial coordinates were determined, nearest to the concrete WS coordinates (within 10, 15 and 20 km), and corresponding values of satellite-originated wind speed together with corresponding time (UT) were selected. *In-situ* wind speed data for the time nearest to the time moment determined in such a way were picked from the databases for every coastal WS. On the basis of the derived data on date, time, coordinates, and corresponding wind speed (satellite and *in situ*) files were formed for the following data processing with the aim to evaluate capacity of satellite altimetry to give reliable information on wind speed in various regional coastal areas.

For decreasing discrepancy between altimeter-derived and observed wind speed values, an approach was proposed on the basis of the decomposition of all wind directions observed for a certain period in four quadrants in relation to the orientation of the coastline (Lebedev et al., 2011; Ginzburg et al., 2011; Kouraev et al., 2011). *In-situ* WS data were divided into 4 quadrants, which were rotated clockwise in increments α = 10° (Figure 4). At each step, the corresponding WS data and satellite altimetry data were taken from tracks located at a distance of 10, 15 and 20 km. Then the correlation coefficient was calculated and the maximum value was selected depending on the α angle of rotation. An example of the results obtained for the meteorological station “Zhizhginsky Island” (WMO Number 22438) is presented in Figure 5

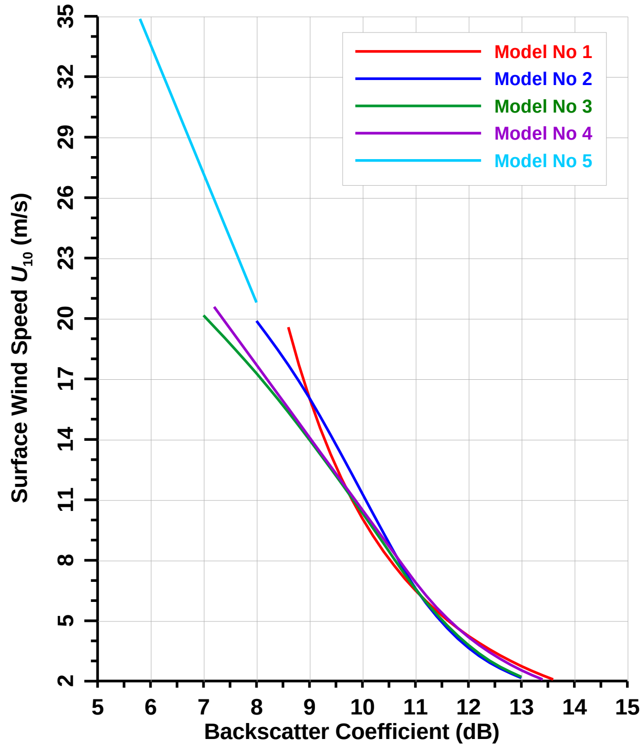

Figure 3. The dependence of the speed wind at a height of 10 m from the backscattering coefficient for the most widely used algorithms presented in Table 1.

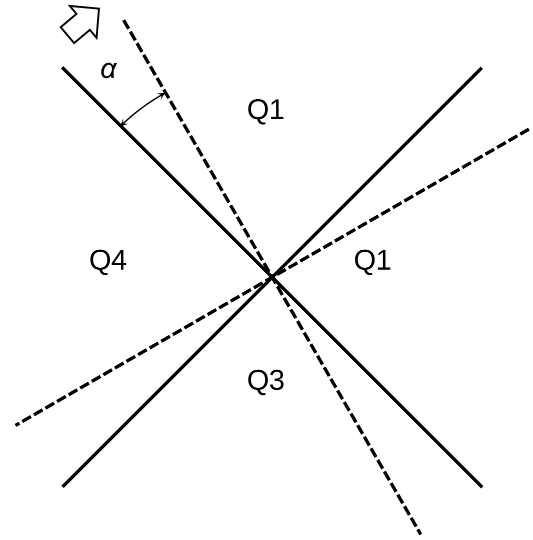

Figure 4. *In-situ* MS data breakdown scheme for a comparison with satellite altimetry data.

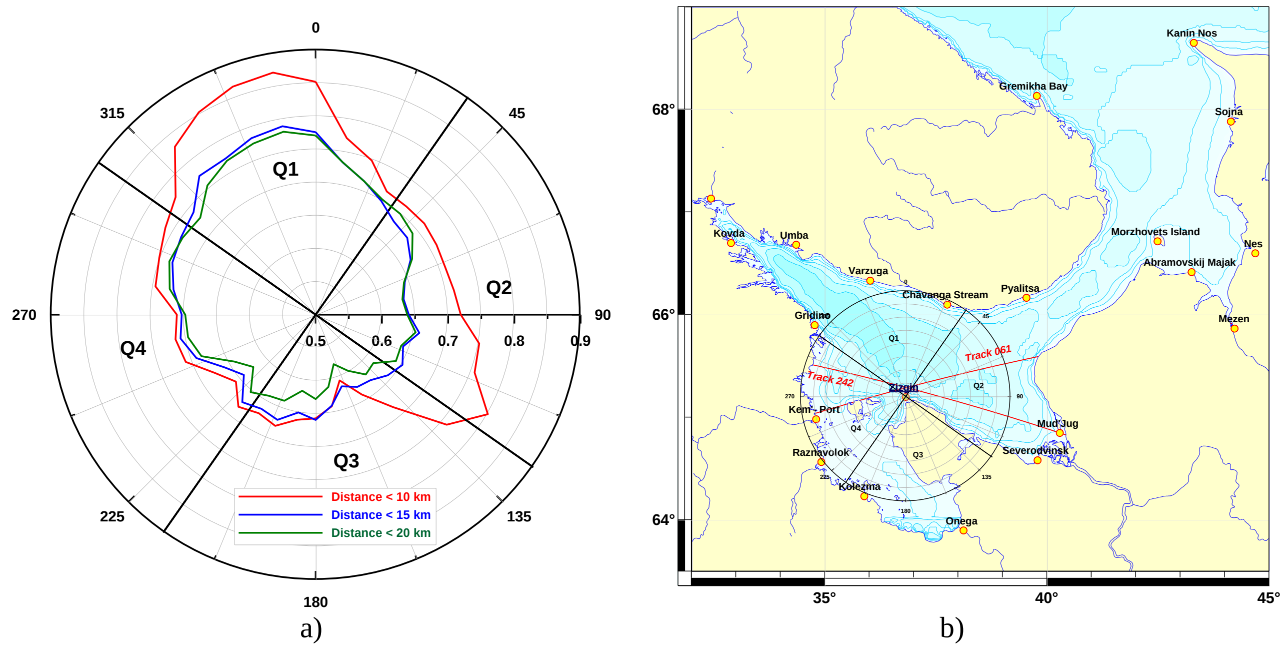

Figure 5. The dependence of the correlation coefficient between *in-situ* wind speed at the WS and remote sensing data on the orientation angle of the main quadrants (a) and their position relative to the White Sea coastline (b).

Results

The correlation coefficient between wind speed calculated from satellite altimetry along 061 and 242 tracks and measured at a WS "Zhizhginsky Island" (WMO Number 22438) changes more when the distance from the station to the satellite altimetry measurement point is less than 10 km from 0.606 to 0.871 compared to satellite measurements located on distance less than 15 and 25 km.

The island is located forty kilometers east of the Solovetsky Archipelago, and the weather station is located on its northern coast (Fig. 5b). For this reason, the correlation coefficient is always positive and varies from 0.579 to 0.871. Its maximum values correspond to the quadrants Q1 and Q2 (Fig. 5a), that is, when the wind blows from the side of the Basin (Fig. 1) and there are conditions for a maximum acceleration of the wind.

Results for other weather stations are presented in Table 2.

Table 2. Results of verification of meteorological observations and remote sensing data

Distance	Correlation coefficient			
	WS "Zhizhginsky Island" (WMO Number 22438)			
	Q1	Q2	Q3	Q4
	305°–35°	35°–125°	125°–215°	215°–305°
< 10 km	0.831	0.714	0.682	0.657
< 15 km	0.773	0.681	0.629	0.642
< 20 km	0.754	0.691	0.618	0.623
	WS "Mezen" (WMO Number 22471)			
	20°–110°	110°–200°	200°–290°	290°–20°
< 10 km	0.195	0.032	-0.068	0.093
< 15 km	0.080	0.118	-0.079	0.112
< 20 km	0.089	0.128	-0.118	0.145
	WS "Kem' Port" (WMO Number 22520)			
	280°–10°	10°–100°	100°–190°	190°–280°
< 10 km	0.139	-0.054	-0.042	0.010
< 15 km	0.147	0.018	0.032	0.157
< 20 km	0.138	0.051	0.045	0.156
	WS "Arkhangelsk" (WMO Number 22550)			
	10°–100°	100°–190°	190°–280°	280°–10°
< 10 km	0.530	0.145	0.249	-0.240
< 15 km	0.217	0.094	0.201	0.087
< 20 km	0.315	0.011	0.011	0.0784
	WS "Onega" (WMO Number 22641)			
	90°–180°	180°–270°	270°–0°	0°–90°
< 10 km	0.341	0.140	-0.272	-0.687
< 15 km	0.516	0.377	0.008	0.026
< 20 km	0.116	0.159	0.153	0.222

Negative correlation coefficients are observed when comparing WS data and remote sensing data located at a distance < 10 km. This is due to the peculiarity of the wind regime over the White Sea. So according to Korobov and Zavernina (2009), wind speeds at a WS and on the ship have an inverse correlation coefficient. When the wind speed increases on the coastal WS, then in the open sea it decreases.

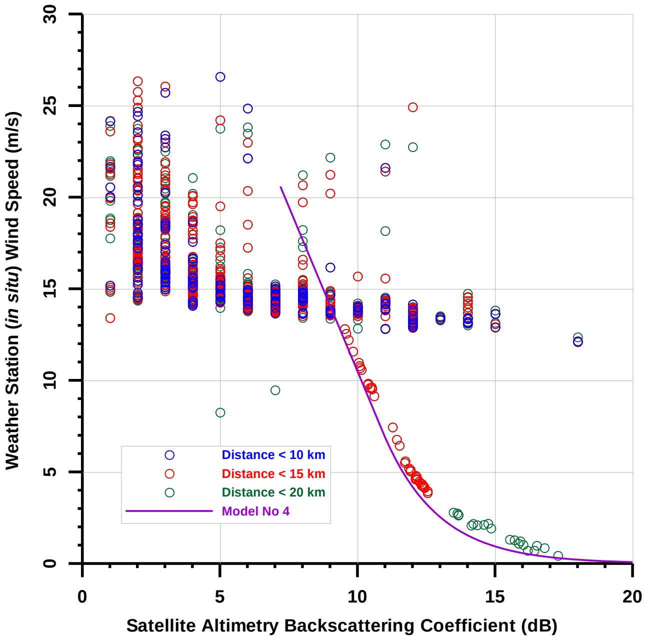

Figure 6. Dependence of wind speed at weather stations on the satellite altimetry data backscattering coefficient. Purple line shows model calculations (Abdalla, 2012).

This difference in data is due to the fact that the models for calculating the wind speed (Table 1) do not work when the distance from the coastline exceeds 15 km (Fig. 6). This suggests that the retracking algorithms used in processing of satellite altimetry data in the coastal zone give a big error, in particular, in calculating the backscatter coefficient. In this case, a new algorithm should be developed, for example, as in (Troitskaya et al., 2012: Troitskaya et al., 2013).

Conclusion

Verification of wind speed calculated from satellite altimetry data by WS data shows that for an island WS good correlation is observed when remote sending measurements have distance > 15 km. As concerns the coastal zone, it is necessary to develop new retracking algorithms, i.e. to improve the calculations of the backscattering coefficient, and also to develop new algorithms for wind speed calculation by satellite altimetry data.

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