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Comparing Satellite and Meteorological Data on Wind Velocity over the Black Sea

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Abstract—Wind-velocity data obtained from in situ measurements at the Golitsyno-4 marine stationary platform have been compared with QuikSCAT scatterometer data; NCEP, MERRA, and ERA-Interim global reanalyses and MM5 regional atmospheric reanalysis. In order to adjust wind velocity measured at a height of 37 m above the sea surface to a standard height of 10 m with stratification taken into account, the Monin–Obukhov theory and regional atmospheric reanalysis data are used. Data obtained with the QuikSCAT scatterometer most adequately describe the real variability of wind over the Black Sea. Errors in reanalysis data are not high either: the regression coefficient varies from 0.98 to 1.06, the rms deviation of the velocity amplitude varies from 1.90 to 2.24 m/s, and the rms deviation of the direction angle varies from 26° to 36°. Errors in determining the velocity and direction of wind depend on its amplitude: under weak winds (<3 m/s), the velocity of wind is overestimated and errors significantly increase in determining its direction; under strong winds (>12 m/s), its velocity is underestimated. The influence of these errors on both spatial and temporal estimates of the characteristics of wind over the Black Sea is briefly considered.

Keywords: Black Sea, wind, satellite measurements, QuikSCAT, NCEP, MERRA, ERA-Interim, in situ measurements

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INTRODUCTION

Wind velocity over the sea surface is the most important characteristic that is necessary in solving a large number of problems in the fields of meteorology and oceanology—in studying climatic processes and the atmosphere–ocean interaction, in calculating and forecasting the dynamics of flows and waves, in simulating the propagation of chemical pollutants in the marine environment, and many others.

At present, atmospheric reanalysis data obtained from calculations of both global and regional models, including the assimilation of different in-situ and satellite measurements, are most widely used in order to determine the velocity of wind. Satellite scatterometry is the most important instrument for observing wind velocity over the sea surface. Scatterometer data make it possible to determine the velocity and direction of wind over the entire ocean from measurements of the effective area of signal scattering.

However, both scatterometer and atmospheric reanalysis data contain significant errors in determining wind velocity and these errors are different for different regions of the world ocean [1, 2]. An insufficient spatial resolution (especially in the dynamically complex coastal zone) and a rough parameterization of atmospheric small-scale processes are sources of errors in determining the velocity of wind over the sea in atmospheric models [1, 3]. Scatterometer data contain errors associated with inaccuracies in determining the geophysical model function, which makes it possible to go from measurements of the effective scattering area to measurements of wind velocity at a height of 10 m [4]. The model function depends on a number of external factors—precipitation, surface temperature, wave height, and flow velocity—whose influence is still not clearly understood [4–6].

It is very important to validate and correct both scatterometer and atmospheric-reanalysis data, because underestimating or overestimating wind-velocity leads to corresponding changes in the estimates of extreme loads on hydraulic structures in the ocean, turbulent mixing, and flow velocity. The main problem in validating such data is the absence of long-term and reliable measurements of wind velocity over the sea-water area. In the open ocean, this problem was solved using wind-wave buoys whose measurement data were used for comparison in a large number of works (for example, [1, 2, 7]). The results of such a comparison showed that the errors in measuring the velocity and direction of wind amount to 1–2 m/s and 20°–30°, respectively. Moreover, the estimates of such errors significantly depend on the region under study [1, 2, 7].

Unfortunately, there are no long-term measurements of wind-wave buoys in the Black Sea. The Black Sea is a small, almost closed basin; here, the wind dynamics is sufficiently complex, and the influence of shore effects is especially strong (see, for example, [8, 9]). Up to now there have been almost no works on the validation of scatterometer data obtained for the Black Sea because of the small number of in situ measurements. The exception is the validation of wind-velocity data obtained with the Ascat and Oceansat-2 scatterometers, which was performed in [10] on the basis of their comparison with measurement data obtained at a stationary oceanographic platform (Katsiveli) located at a short distance of ~500 m from the coast with a mountainous relief. The authors of [10] suggest that the higher error estimates 3 m/s (amplitude) and ~70° (direction) are due to the vicinity of the coast. Wind-velocity data obtained for the Black Sea with the QuikSCAT scatterometer and from the NCEP reanalysis were compared in [11]. The authors of [11] show that reanalysis data may significantly differ from satellite measurements, especially in intense atmospheric formations.

At the same time, there are a number of gas and oil production platforms in the Black Sea on which meteorological parameters are regularly measured. The velocity and direction of wind at a height of ~40 m have been measured since 1996 on the Golitsyno-4 platform located on the northwestern shelf of the Black Sea at a distance of ~50 km from the coast [12]. The results obtained in [12] are used by us to validate QuikSCAT data and estimate the quality of data from the regional MM5 and global ERA-Interim, NCEP, and MERRA reanalyses.

DATA

In-situ Data

Instruments for hydrometeorological monitoring were installed on the Golitsyno-4 gas-production platform (45°42.5′ N, 31°52.5′ E) in 1996. In the west, the distance from the platform to the Crimean Peninsula is 63 km and, in the north, the distance from the platform to the coast of Ukraine is 58 km. This platform is a pile construction consisting of four blocks; the orientation and location of the platform are shown in [12]; here, the depth of the sea is 30 m. An M63-MP sensor to measure the velocity and direction of wind was mounted on the tower (the highest point of the platform) at a height of 37 m above sea level. All parameters were recorded with a discreteness of 3 h (1996–2002) and 1 h (2008–2009), and the velocity and direction of wind were averaged over 10 min. More detailed information on measurement errors and the resolving power of sensors that form part of the meteorological complex can be found in [13]. More than 16000 measurement runs were performed over the entire observation period. An analysis of data quality and methods for remedying faults are given in [14]. In our work, the results of measurements (since 2000) of the velocity and direction of wind (all in all, 7846 measurement runs) are considered.

Satellite Data

QuikSCAT satellite wind data obtained from 1999 to 2009 are used in this work. Scatterometers are active radars which emit microwave pulses in the direction of the ocean surface and measure the effective area of their scattering by short waves. The effective scattering area depends on the module of wind velocity and direction, which makes it possible to determine these characteristics from scatterometric measurements.

The Level2B product (Jet Propulsion Laboratory, http://prodaac.jpl.nasa.gov/) with a high spatial resolution of ~12.5 km was chosen for analysis. The velocity of wind at a height of 10 m was calculated from scatterometric data using the Ku-2011 geophysical model function [4]. For the Black Sea, such measurements were accessible two times a day (between 01:00–04:00 and 13:00–17:00 UTC). All data marked with the flag “rain” were eliminated from analysis, because the scattering from rain drops may significantly affect the results of scatterometer measurements.

The MM5 Regional Atmospheric Model

Regional atmospheric reanalysis data obtained for the Black Sea region on the basis of calculations using the MM5 mesoscale atmospheric model are used in this work. Regional reanalysis makes it possible to more accurately and, above all, in more detail describe mesoscale atmospheric and climatic features associated with the mountainous relief, coastline, and underlying surface. The horizontal spatial resolution was 18 km, and 23 levels along the vertical were chosen within the atmospheric boundary layer. Discrete time was 1 h, and the duration time was 2000–2014.

The parameterizations of physical processes, which had been used and tested over 7 years in the online forecasting for the Black Sea region, were chosen for this reanalysis [15]. Data from the GDAS archive of online analyses for 2000–2012, which had been made at the NCEP/NCAR using a global atmospheric model with a spatial resolution of 1° × 1° and with the assimilation of all available online atmospheric data, were used as initial and boundary conditions at side boundaries. The boundary condition for the underlying-surface temperature of the Black Sea water area was taken from the OISST archive of the global ocean-surface temperature with a spatial resolution of 1° × 1° and a discrete time of 1 week. In order to compile this archive, all available measurement (including satellite) data on the sea-surface temperature are used.

As the MM5 data have the highest spatial resolution, they were used to adjust the wind velocity measured at a height of 37 m on the marine platform to a standard height of 10 m with the aid of the Monin–Obukhov theory. The following parameters from the MM5 atmospheric reanalysis for the Black Sea region are used: turbulent sensible-heat flux (H), turbulent latent-heat flux (E), dynamic wind velocity (u_*), air temperature (T), and specific air humidity (q). The wind velocity obtained from the results of the MM5 reanalysis was validated.

Global Reanalysis Data

On the basis of a comparison with the results of in-situ measurements, we validated the velocity of wind at a standard height of 10 m, which was obtained from the data of the current global reanalyses:

(1) ERA-Interim [16], which was developed at the European Center for Medium-Range Weather Forecasts (ECMWF) and based on calculations using the Integrated Forecast System model, the version of 2006 (Cy31r2). The system of assimilation is based on a four-dimensional variational analysis. The spatial data resolution is 0.75° × 0.75°.

(2) Modern-Era Retrospective Analysis for Research and Applications (MERRA), which is based on the GEOS-5 ADAS system, reproduces climate in the satellite era using assimilations of different satellite data. The spatial resolution is 0.5° × 0.66° [17]. The data were downloaded from the server http://goldsmr2.sci.gsfc.nasa.gov/.

(3) Online product of the NCEP High Resolution Global Forecast System with a spatial resolution of 1° × 1° [18]. The NCEP data are based on calculations with the Weather Research and Forecasting Nonhydrostatic Mesoscale Model (WRF-NMM). The data were obtained at http://oceancolor.gsfc.nasa.gov/.

All these global reanalyses were obtained with the assimilation of a large body of different contact and satellite data, including the QuikSCAT data. In the MM5 regional model, there is no assimilation of the QuikSCAT data. The reanalysis data are available at 00:00, 06:00, 12:00, and 18:00 UTC.

ADJUSTMENT OF WIND VELOCITY TO A HEIGHT OF 10 m

The wind velocity measured at a height of 37 m on the marine stationary platform was adjusted to a standard height of 10 m with stratification taken into account according to the Monin–Obukhov theory [19]. The Monin–Obukhov scale was calculated with humidity taken into account, i.e., the total buoyancy flow expressed as a kinematic flux of virtual temperature was used. Since no direct measurements of the parameters of stratification were performed, all necessary values were taken from the MM5 regional atmospheric reanalysis.

The wind-velocity profile was determined as follows:

$$U(z) = \frac{u_*}{\kappa}\left[\ln\frac{z}{z_0} - \Psi_M(\zeta)\right],$$
$$\Psi_M(\zeta) = \int\limits_{\zeta_0}^{\zeta}\frac{1-\varphi_M(\zeta)}{\zeta}d\zeta,\quad \zeta = \frac{z}{L}, \tag{1}$$

where z_0 is the roughness parameter, $\phi_M(\zeta)$ is the universal function, L is the Monin–Obukhov scale, κ is the Kärmän constant, and $\sqrt{-\overline{u'w'}} = u_*$ is the dynamic wind velocity (friction speed).

According to the results of a large body of research, it was found that the similarity theory can be used to describe the characteristics of atmospheric turbulence over land and sea within a wide range of conditions [20, 21] ($-3 < \zeta \leq 1$). The $\phi_M(\zeta)$ functions for wind velocity and temperature are most reliably determined and, at present, have the commonly accepted forms

$$\varphi_M(\zeta) = 1 + \gamma_1\zeta,\quad \zeta \geq 0, \tag{2}$$

$$\varphi_M(\zeta) = (1 - \gamma_2\zeta)^{-1/4},\quad \zeta \leq 0, \tag{3}$$

where the values of γ have a small spread according to data in different sources: $\gamma_1 = 5$–7 and $\gamma_2 = 15$–16 [20, 21]. In our work, $\gamma_1 = 5$ and $\gamma_2 = 15$.

The form of the ψ_M functions is determined from Eqs. (1)–(3). Calculating the $\psi_M(\zeta)$ functions presents some difficulties only for $\zeta < 0$, and the Businger–Dyer formula was used instead of numerical integration [21].

The final expression to calculate the real wind velocity at a height of 10 m has the form

$$U_{10} = U_{37} + \frac{u_*}{\kappa}\left(\ln\left(\frac{10}{37}\right) + \psi_M\left(\frac{37}{L}\right) - \psi_M\left(\frac{10}{L}\right)\right). \tag{4}$$

The wind velocity determined from contact measurements will be denoted by $U_N = U_{10}$ and the direction of wind will be denoted by D_N.

VALIDATION OF QuikSCAT DATA ON WIND VELOCITY

The closest (in time and space) results of satellite and contact measurements with maximum time and space intervals of 1 h and 10 km, respectively, between them were chosen for comparison. These chosen intervals are sufficiently small so that one can expect that errors associated with the spatiotemporal disagreement of data are small. Total 1479 measurement pairs were chosen.

For the wind-velocity amplitude (U), the following statistical characteristics were analyzed: regression coefficient R_u (coefficient by which the wind velocity according to satellite/reanalysis data should be multiplied so that it could be comparable to that according to contact measurements), rms deviation S_u (corresponding to the value of measurement error), correla-

Statistical characteristics of comparison

Data array	R_u	S_u, (m/s)	K_u	B_u, (m/s)	S_d, (°)	K_d
QuikSCAT L2b (12.5 km)	0.98	**1.58**	**0.85**	–0.17	31	0.95
MM5 (18 km)	0.98	**2.24**	0.65	–0.21	32	0.94
ERA-Interim (0.75° × 0.75°)	**1.06**	1.90	0.75	**0.35**	**26**	**0.96**
MERRA (2/3° × 1/2°)	1.05	2.11	**0.69**	0.32	**36**	**0.93**
NCEP (1° × 1°)	**1.00**	1.93	0.76	**–0.01**	28	**0.96**

tion coefficient K_u, and difference in means between the contact and satellite/reanalysis data B_u. For the direction of wind (D), the rms deviation S_d and the correlation coefficient K_d were determined. The table shows the results of this comparison.

Figures 1a and 1 b show the scattering diagrams for the amplitudes of the velocity and (mathematical) direction of wind U according to QuikSCAT and contact U_N data. For the wind velocity amplitude, the regression coefficient R_u is 0.98, and the difference between the means of B_u is only –0.17 m/s; i.e., satellite data overestimate the values of wind velocity, on average, by approximately 2%. The mean error in determining wind velocity (rms deviation) amounts to 1.58 m/s.

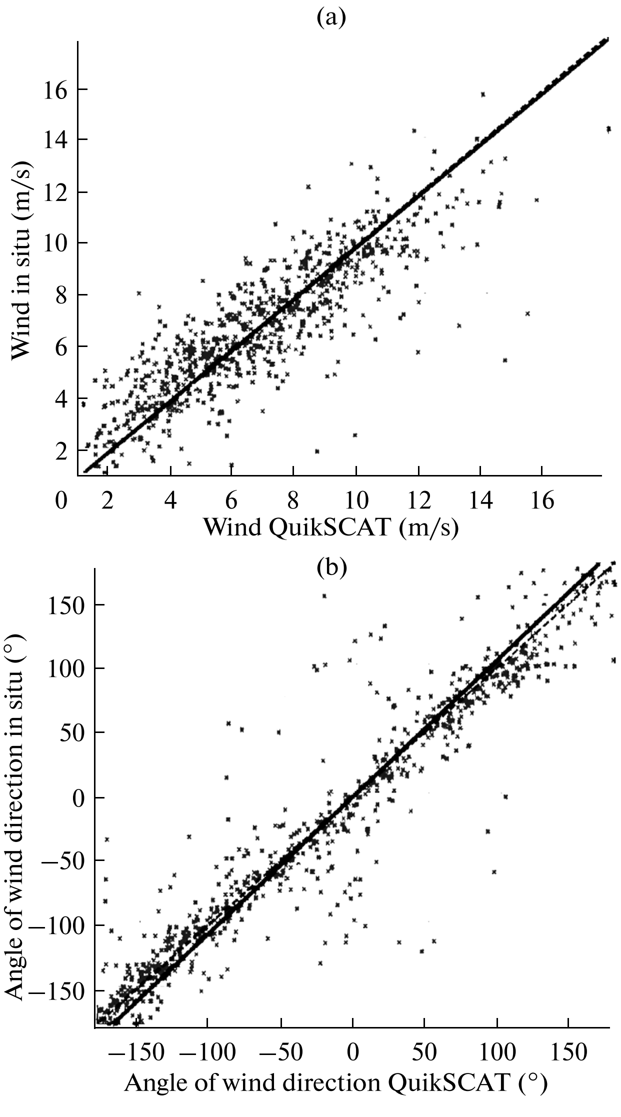

Fig. 1. Diagram of scattering for the (a) amplitudes and (b) directions of wind velocity according to QuikSCAT and in-situ data.

The difference between the means of wind velocity according to satellite and contact measurements is significantly higher for weak winds ($U_N < 3$ m/s). Within this interval, the QuikSCAT scatterometer overestimates wind velocity by 0.5–1.5 m/s (Fig. 2a). Within the wind-velocity interval (4–14 m/s), the values of B_u do not exceed 0.5 m/s, and the difference $U_N - U$ insignificantly increases with an increase in wind velocity (Fig. 2b). The value of the mean module of error in determining the direction of wind is significantly higher for weak winds $|D - D_N| = 35°–60°$ (for $U_N < 3$ m/s) and rapidly decreases with an increase in wind velocity $|D - D_N| = 10°–20°$ at $U_N = 4–8$ m/s (Fig. 2b). Under strong winds ($U_N > 8$ m/s), the error is very small and amounts, on average, to 10°. The fact that errors increase during scatterometer measurements under very weak winds is known [22]. High errors in determining the direction and velocity of wind under weak winds are associated, first with the insufficient strength of signal received by the satellite. On the other hand, determining the direction of wind under almost calm conditions is a sufficiently complicated problem. In our work, in order to decrease errors, in the cases of week winds, situations with strong stratifications ($-3 < \zeta \leq 1$) were eliminated from the consideration.

VALIDATION OF GLOBAL REANALYSIS DATA

For validation, the reanalysis data were linearly interpolated in space to the platform coordinates. Then, only such measurement pairs between which the time interval did not exceed 1 h were chosen. The table shows the results of comparison.

The regression coefficients amount to 1.00 for the NCEP data and 0.98 for the MM5 data. The mean deviations are slight for the NCEP data (–0.01 m/s), and the MM5 data overestimate the velocity of wind, on average, by 0.21 m/s. At the same time, the wind velocity in the MERRA and ERA-Interim reanalyses proved underestimated by 5 and 6%, respectively. According to these reanalysis data, the wind velocity is lower, on average, by 0.32 and 0.35 m/s, respectively. Along with this, the rms deviation is lower for the ERA-Interim (1.90 m/s) and NCEP (1.93 m/s) data and higher for the MM5 (2.24 m/s) and MERRA (2.11 m/s) calculations. The correlation coefficients are also closer to one for the ERA-Interim (0.75) and NCEP (0.76) data when compared to the MM5 (0.65) and MERRA (0.69) data. Note that the satellite QuikSCAT data are characterized by the lowest error (1.58 m/s) and a highest correlation coefficient (0.85). Thus, among all the reanalyses under consideration, the best and worst statistical characteristics of the wind-velocity amplitude were obtained for the NCEP High Resolution Global Forecast System and MERRA, respectively.

The values of errors in determining the velocity of wind depend on its amplitude (Fig. 3). Under weak winds ($U_N < 3$ m/s), all the reanalyses overestimate the wind velocity by 1–3 m/s. The highest overestimation under weak winds is noted for the MM5 reanalysis. It is likely that such an overestimation in the global reanalysis data is partially associated with the assimilation of overestimated scatterometric data

At $U_N > 6$ m/s, the wind velocity according to reanalysis data proves underestimated. In this case, for the intervals $U_N = 6$–12 m/s, the underestimation amounts to 0.5–2.0 m/s and, for $U_N = 12$–14 m/s, the error increases up to1–4 m/s. The MERRA reanalysis yields the largest underestimation of the velocity under strong winds. The NCEP wind data are characterized by the smallest errors in determining the amplitude for strong winds when compared to the rest of the reanalyses under consideration.

A somewhat different situation is observed in comparing wind-direction angles. The ERA-Interim (rms deviation $S_d = 26°$, correlation coefficient $K_d = 0.96$) and NCEP ($S_d = 28°$, $K_d = 0.96$) reanalysis data show the best agreement. In this case, these reanalyses demonstrate the best results of comparison even against the QuikSCAT data ($S_d = 31°$, $K_d = 0.95$). The largest error in determining the wind-velocity direction is noted for the MERRA reanalysis (S$S_d = 36°$, $K_d = 0.93$).

Errors in determining the direction of wind velocity also depend on its amplitude (Fig. 4). Under weak winds, the mean module of difference in wind-direction angles $|D - D_N|$ is high; it varies from 55° at $U_N <$ 2 m/s to 30° at $U_N = 4$ m/s. Within the wind-velocity interval $U_N = 5$–14 m/s, the errors in determining the direction of wind are not high and amount to 10°–25° for all the reanalyses under consideration. For $U_N =$ 5–14 m/s, the best agreement is noted for the NCEP and ERA-Interim reanalyses ($|D - D_N| \sim 10°$–15°) and the worst agreement is noted for the MERRA reanalysis (~20°).

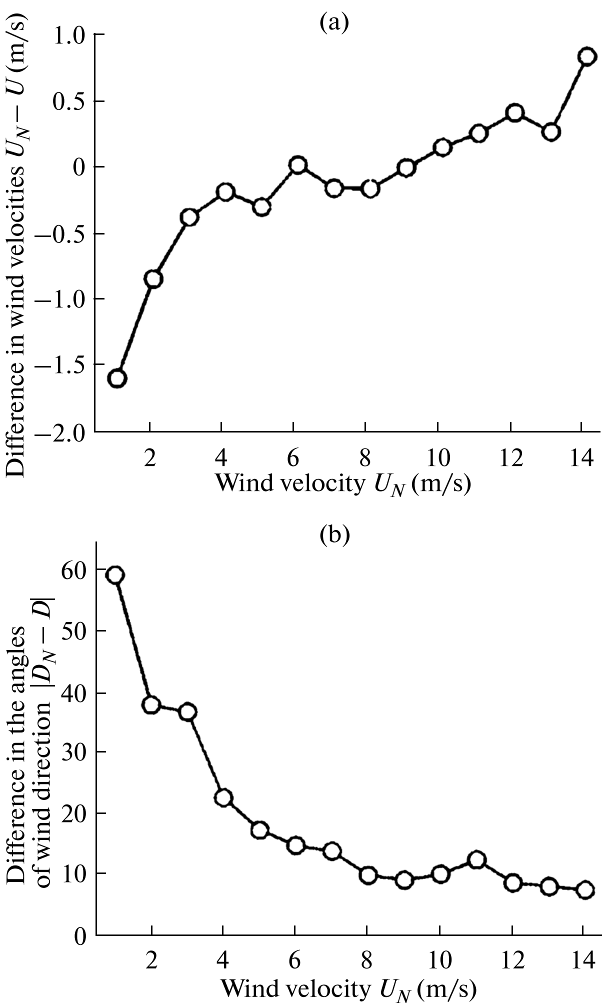

Fig. 2. Dependence of the mean differences in (a) the amplitudes ($U_N - U$) and (b) directions $|D - D_N|$ of wind velocity between data obtained on the platform and aboard the QuikSCAT satellite on the amplitude of wind velocity U_N from in-situ measurements.

DISTRBUTION OF EXTREMELY WEAK AND STRONG WINDS OVER THE BLACK SEA

The results of our analysis showed that, in current wind-data sources, the highest errors are observed under weak ($U < 4$ m/s) and strong ($U > 12$ m/s) winds. In this case, according to both satellite and reanalysis data, the wind-velocity module is overestimated under weak winds and underestimated under strong winds. Let us consider the Black Sea regions, in which the contribution of both weak and strong winds ($U < 4$ m/s and $U > 12$ m/s) is most significant. To this end, we plot the seasonal variability and spatial distribution of the probability of occurrence of these two wind-velocity groups according to the QuikSCAT data for 2000–2009 (Fig. 5). Note that the statistics of extreme winds with velocities of more than 20 m/s over the Black Sea was analyzed earlier in [23]. Over the entire observation period, the probability of recording weak winds

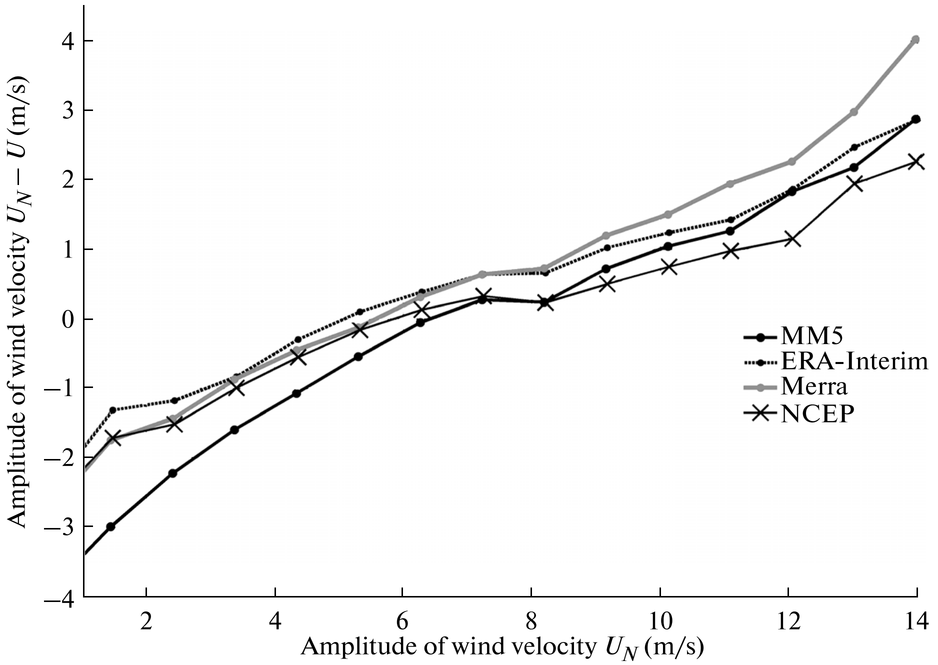

Fig. 3. Dependence of the difference in the amplitudes of wind velocity ($U_N - U$) between data obtained from measurements on the platform and from reanalyses on its amplitude U_N from in-situ measurements.

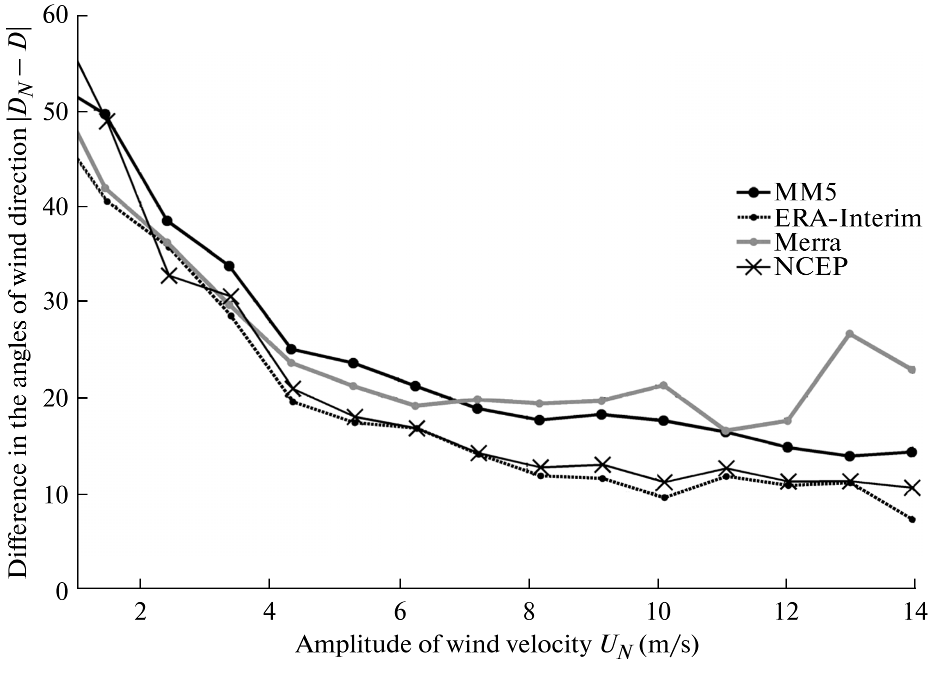

Fig. 4. Dependence of the module of the mean difference in the angles of wind direction $|D - D_N|$ between data obtained from measurements on the platform and from reanalyses on the wind-velocity amplitude U_N.

over the Black Sea amounts to, on average, approximately 30% (Fig. 5a). Moreover, weak winds are most often observed in the southeastern region of the basin, in which these winds occur, on average, in 60% of all cases. Under both southern and eastern large-scale winds, the southeastern sea region surrounded by the Caucasus Mountains in the east and the Pontic Mountains in the south proves within the wind-shadow zone. Seasonal variations are manifested in the recurrence of weak winds: the probability of occurrence of weak winds reaches 50% in May and decreases to 20% in December (Fig. 5b). Thus, in the southeastern region of the Black Sea, during spring and summer, one can expect the highest errors associated with over-

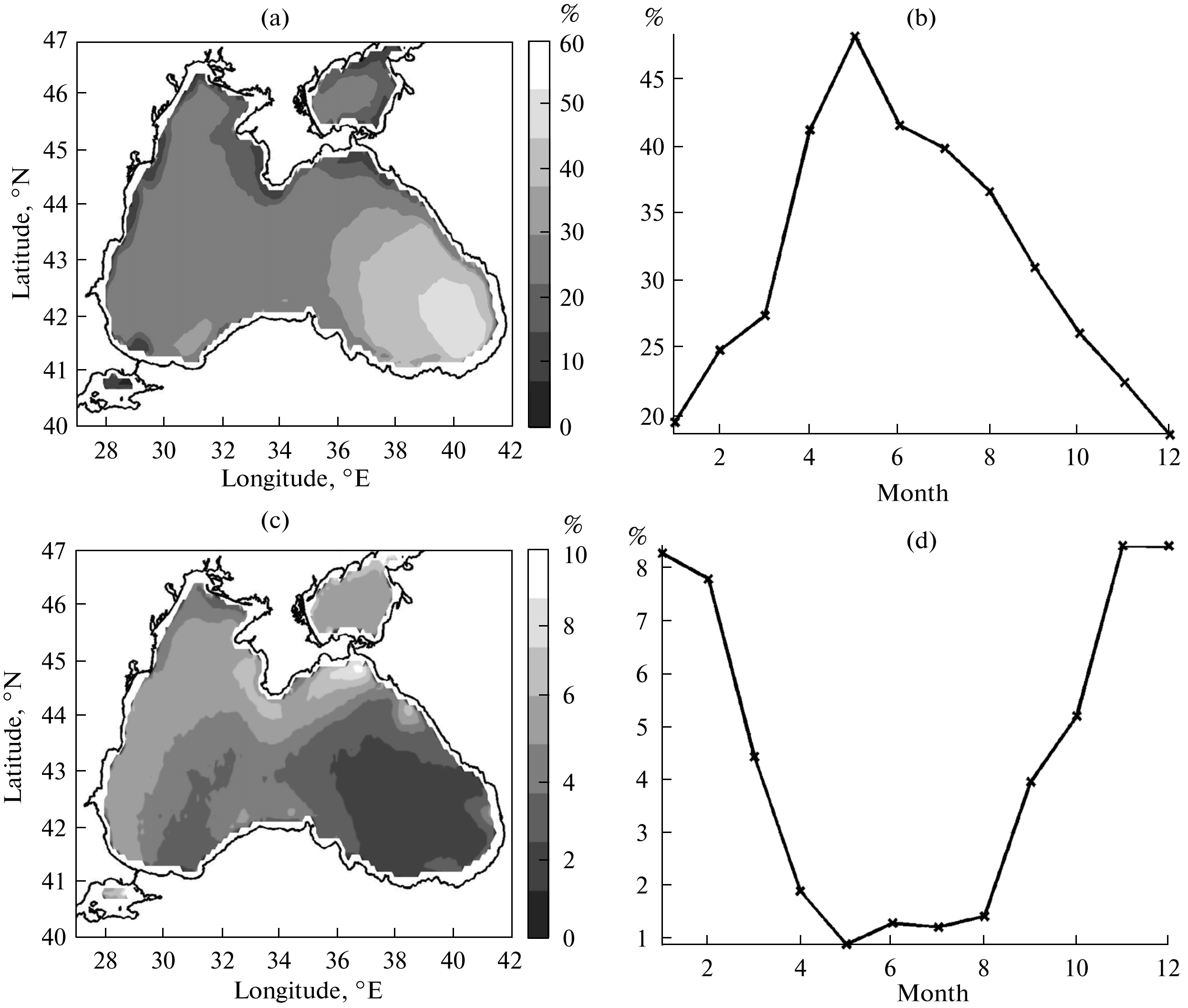

Fig. 5. Spatial distribution of the probability of occurrence of (a) weak winds (<4 m/s) and (c) strong winds (>12 m/s) according to QuickSCAT data for 2000–2009. Seasonal variability of the probability of occurrence of (b) weak winds (<4m/s) and (d) strong winds (>12 m/s) according to QuikSCAT data for 2000–2009.

estimated wind velocities. Such errors may result in overestimated turbulent mixing in the sea [24].

Strong winds occur much less frequently (on average, in 5% of cases) (Fig. 5c). Winds with velocities of more than 12 m/s are observed mainly in the cold season from November to February (~8%). The spatial distribution of the probability of occurrence of strong winds shows that they are most frequently observed in the western, northwestern, and northeastern regions of the sea (~6–8% of cases). In winter, according to atmospheric reanalysis data, it is expected that the module of wind velocity may be underestimated, which, in turn, may lead to inaccurate calculations and forecasts of the wind-wave characteristics of the Black Sea.

CONCLUSIONS

The data obtained from in situ measurements on the Golitsyno-4 marine stationary platform, with the QuikSCAT scatterometer, and from several atmospheric reanalyses are compared in this work. This comparison showed that the satellite data more accurately determine the characteristics of wind over the Black Sea when compared to global reanalysis data: the regression coefficient of the amplitude of wind velocity is 0.98, the difference in the means of wind velocity is 0.17 m/s, the rms deviation is 1.58 m/s, the correlation coefficient for the module of wind velocity is 0.85, and the rms deviation of wind direction is 31°.

The data of atmospheric reanalyses are in sufficiently good agreement with those obtained from in situ measurements. The errors for the reanalyses under consideration are low: the regression coefficient varies from 0.98 to 1.06, the rms deviation of the wind-velocity amplitude varies from 1.90 to 2.24 m/s, and the rms deviation of wind direction varies from 26° to 36°. The variability of the amplitude of wind velocity and direction is most adequately described in both NCEP and ERA-Interim reanalyses. The real wind variability is described slightly worse in the MERRA reanalysis.

Errors in determining the velocities of wind significantly depend on its amplitude. Under strong winds (>12 m/s), the data of the global reanalyses underestimate the velocity of wind, on average, by 1–4 m/s. Under weak winds (<4 m/s), these data overestimate the wind-velocity amplitude, and the error in determining the direction of wind significantly increases. Weak winds rather frequently occur over the Black Sea (~30% of cases), especially during the warm season in its southeastern region. Thus, one can expect that atmospheric reanalysis data for the warm half-year overestimate the velocity of wind, which may significantly affect the accuracy of calculations. Strong winds most frequently occur in the western, northwestern, and northeastern regions of the sea, in which their recurrence may reach ~6–8%. And, for the winter period, the wind-velocity module is expected to be underestimated for these regions, which may lead to inaccurate calculations and forecasts of the wind-wave characteristics of the Black Sea.

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