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Research Article

Comparison of Oceansat-2 Scatterometer Wind Data with Global Moored Buoys and ASCAT Observation

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The Oceansat-2 satellite was launched on 23 September 2009 by the Indian Space Research Organization (ISRO). In this study, the historic archived OSCAT wind vectors are compared with the global moored buoys' wind observations, including the U.S. National Data Buoy Center (NDBC), the Tropical Atmosphere Ocean (TAO), the Pilot Research Moored Array in the Tropical Atlantic (PIRATA), the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA), and Advanced Scatterometer (ASCAT) wind data in the same period of OSCAT by calculating the statistical parameters, namely, the root mean square error (RMSE), bias (mean of residuals), and correlation coefficient (R) between the collocated data. The comparisons with the global moored buoys show that the OSCAT wind vectors are consistent with buoys' wind measurements. The average errors of the OSCAT wind vectors are 1.20 m/s and 17.7°. The analysis of the OSCAT wind vector errors at different buoy wind speeds in bins of 1 m/s indicates that the accuracy of the OSCAT wind speed first increases and then decreases with the increasing wind speed. The comparisons of OSCAT wind vectors and ASCAT wind vectors show that the average RMSEs of their differences are 1.27 m/s and 20.17°. In general, the accuracies of the OSCAT wind vectors satisfy the general scatterometer's mission requirement and are consistent with ASCAT wind data. OSCAT wind vectors can be used in the global change study by the combination with other scatterometer data.

1. Introduction

Ocean surface wind is an important meteorological factor for driving seawater movement. Ocean surface wind affects almost all oceanic dynamic processes from sea surface microscale waves to ocean circulation. So, ocean surface wind is of vital importance for studies of oceanic processes and improvement of marine and weather forecasting by data assimilation in the operational prediction models [1]. Ocean surface wind is very important geophysical variable to accurately measure. Traditional anemometer winds cover the spatial and temporal domains poorly. Satellite scatterometer is a widely used technique for measuring global ocean surface winds from space synchronously. Seasat-A Satellite Scatterometer (SASS) as the first satellite scatterometer was launched in 1978; from then on, many space-based scatterometers appeared successively, such as ERS-1/2 AMI, ADEOS-1 NSCAT, QuikScat Seawinds, ADEOS-2 Seawinds, Metop-A/B ASCAT, Oceansat-2 Scatterometer (OSCAT), HY-2A SCAT, ISS-RapidSCAT, and so on. Scatterometers measure the radar cross section of the ocean surface, and numerical inversion of the geophysical model function yields the scatterometer wind measurement. Because scatterometer does not measure ocean surface wind directly and accurate observations of ocean surface wind over global oceans are required for a wide range of meteorological and oceanographic studies and global climate change study, validation of scatterometer wind vectors is necessary for the applications of the scatterometer wind data [2, 3]. For the existing scatterometers, many validation works have been carried out such as NSCAT [4], AMI [5], QuikSCAT [6], ASCAT [7], and HY-2A SCAT [8, 9] by comparing scatterometer winds with in situ measurements from buoys and vessels.

The Oceansat-2 satellite was launched on 23 September 2009 by the Indian Space Research Organization (ISRO) with a Ku-band pencil beam scatterometer (OSCAT) into a near polar sun-synchronous orbit with an altitude of 720 km, inclination of 98.25°, and the local time of equatorial crossing in the descending node at 12 noon ± 10 minutes. OSCAT experienced an irrecoverable malfunction and stopped working on 20 February 2014. The resolution of OSCAT global wind vector data is 50 km, 25 km (since July 2013), and 12.5 km. The goals of OSCAT mission were to provide wind data between 4 and 24 m/s, with an accuracy of 2 m/s and 20°. Several validation studies of OSCAT wind data are performed by using in situ data from buoys and other data. OSCAT wind vectors from November 2009 to December 2010 are compared with RAMA and TRITON buoys data in the Indian Ocean and the Pacific Ocean, and the results show the accuracies of wind speed are within the mission requirement, but the wind direction errors are higher than the mission requirement [10]. OSCAT surface winds for the monsoon period (June–September) of 2011 over the Arabian Sea were compared with two moored buoys, and the results show that the errors of wind speed and direction are less than 2.5 m/s and 20°, respectively [11]. The comparisons between surface wind vectors form OSCAT and global moored buoys during the period from November 1, 2009 to July 31, 2010 show that the RMSE of about 1.5 m/s in wind speed and about 20° in wind direction for the speed range 4–24 m/s [12]. OSCAT winds are validated using in situ buoy observations and short-term model forecasts for the monsoon in 2011, and the results show OSCAT winds are within the mission goal [13]. OSCAT ocean surface winds over the Indian Ocean were validated against the RAMA buoy winds in 2011, and the results show that the wind speeds and directions derived from OSCAT agree with RAMA buoy winds [14]. Ocean surface winds of OSCAT were validated with equivalent neutral wind observations from 87 global buoys and winds from ECMWF Numerical Weather Prediction (NWP) model using triple collocation from 1 November 2009 to 31 July 2010 [15]. OSCAT wind data in 2010 were compared with wind speeds estimated from Jason Altimeters [16]. Wu and Chen [17] validated OSCAT wind data from January 2012 to August 2013. All existing validation studies are about the parts of OSCAT wind data for the period no more than 2 years.

More than 4 years OSCAT wind data are obtained during the whole lifetime of OSCAT from 23 September 2009 to 20 February 2014. These data are useful for the global ocean surface wind studies. Long-term series multisource scatterometer ocean surface wind data are also needed by the global change study and Climate Data Record (CDR) which requires the consistency of accuracy. So, it is very important to carry out data accuracy assessment of OSCAT ocean surface wind by comparing with in situ measurement of wind for the data application in the global change study. In this paper, allover archived OSCAT Level 2B ocean wind vectors in 12.5 km slice composites from 16 January 2010 to 20 February 2014 are compared with the global moored buoys and ASCAT wind data, and the accuracies of OSCAT wind data are evaluated over different oceans and in the different ranges of wind speed.

2. Data and Methods

2.1. Data

2.1.1. OSCAT Wind Data. Archived OSCAT version 2 Level 2B ocean wind vectors during 16 January 2010 to 20 February 2014 are used in this study. This level 2B dataset is produced by the Jet Propulsion Laboratory (JPL) QuikSCAT Project in cooperation with the Indian Space Research Organization (ISRO). The ocean wind vectors are provided on a nonuniform grid with the swath at 12.5 km pixel resolution. This resolution is achieved through a slice composite technique in which high resolution slice measurements from L1B data are composited into a 12.5 km wind vector cell. OSCAT is a Ku-band (13.515 GHz) pencil beam scatterometer with two differently polarized beams which scan the ocean surface in a circular manner at incidence angles of 48.9° (HH-polarization) and 57.6° (VV-polarization). This corresponds to overlapping HH and VV swaths of 1400 km and 1840 km width, respectively [18]. OSCAT has a repeat cycle of 2 days. Mission design accuracies of OSCAT wind observation are 2 m/s of wind speed and 20° of wind direction in the wind speed range of 4–24 m/s.

2.1.2. Buoy Wind Data. Wind observation data during the same period of OSCAT wind data obtained by 96 moored buoys from NDBC, 66 moored buoys from TAO/TRITON, 18 moored buoys from PIRATA, and 26 moored buoys from RAMA were used in this study. The location of these buoys is shown in Figure 1. The buoy winds are measured by averaging the wind speed and direction over 10 minutes at the different heights from the sea surface. So, the buoy winds were converted to 10 m neutral winds using the LKB model [19] to make the buoys data comparable with OSCAT.

2.1.3. ASCAT Wind Data. The Advanced Scatterometer (ASCAT) 25 km Level 2 ocean surface wind product during the same period of OSCAT data was used in this study. The ASCAT equipped on MetOp-A and MetOp-B satellite was launched on 19 October 2006 and 17 September 2012 by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), respectively. The MetOp satellite is in a circular orbit with a period of approximately 101 minutes, an inclination of 98.59°, and an orbit height of 800 km. ASCAT has two swaths 550 km wide, located on each side of the satellite track, separated by 700 km. ASCAT wind data are produced by the Royal Netherlands Meteorological Institute (KNMI) in the Ocean and Sea Ice Satellite Application Facility European Organization for the Exploitation of Meteorological Satellites (OSI-SAF EUMETSAT) projects. The validation of ASCAT wind data showed that the wind speed bias was between −0.3~0.3 m/s at different times, and average standard deviation of zonal and

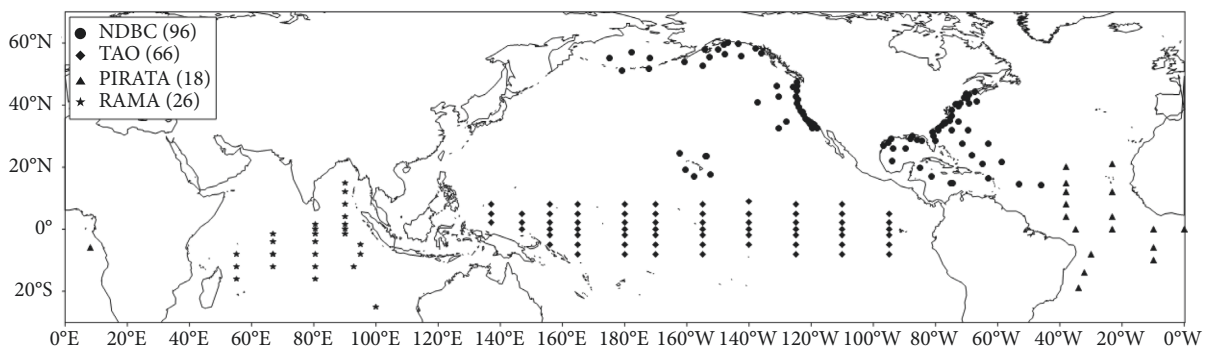

Figure 1: Distribution of the NDBC, TAO, PIRATA, and RAMA moored buoys.

meridional wind speed component of ASCAT wind data by buoy winds was less than 1.6 m/s [20].

2.2. Methods. The comparisons of OSCAT wind data with global moored buoys and ASCAT observation are mainly based on the data collocation in space and time. First, the OSCAT wind data are collocated with moored buoy and ASCAT wind data to obtain quasisynchronous collocated data. For the collocation between OSCAT and moored buoy data, the OSCAT wind vector measurement is the spatial average of the 12.5 km × 12.5 km cell, and the buoy measurement is the 10-minute average wind data at the location of the buoy. Neither of these measurements have spatial or temporal synchronization. OSCAT wind vector cells closest to the buoy locations in space (within 12.5 km) and the buoy data closest to the OSCAT observations in time (within 30 min) are chosen. For the collocation between OSCAT and ASCAT data, the spatially closest wind cells and observation within 10 min are collocated. The maximum possible distance between OSCAT and ASCAT wind vector cells is half the spatial grid size, i.e., 6.25 km. Second, according to the collocation data, statistical parameters—the root mean square error (RMSE), bias (mean of residuals), and correlation coefficient (R) [2, 3]—are computed and presented to evaluate the accuracy of OSCAT wind data through the comparison of OSCAT data with moored buoy and ASCAT wind data directly.

3. Results and Discussion

3.1. Comparison with Moored Buoys. The historical archived OSCAT Level 2B 12.5 km ocean surface wind vectors during 16 January 2010 to 20 February 2014 are compared with global moored buoys' wind data. Because OSCAT retrievals produce the 10 m equivalent neutral winds, wind speeds recorded by the moored buoys need to be converted from the observation heights to a height of 10 m in a neutrally equivalent atmosphere. Using the method mentioned in Section 2.2, the wind speed measured by the moored buoys at different heights above the sea surface is converted to the equivalent neutral wind speed at a height of 10 m. The wind direction is assumed to not change with this conversion. Data pairs totaling 49,414 from 96 NDBC buoys, 14,569 from 18 PIRATA buoys, 8001 from 26 RAMA buoys, and 39,495 from 66 TAO buoys are collocated by the method introduced in Section 2.2. The nearest collocated NDBC buoys is about 12.4 km from the coast, which is close to the spatial resolution 12.5 km of OSCAT wind vector. 14.6% of the collocated NDBC buoys offshore distance is less than 25 km. The separate comparisons of the collocated OSCAT and these buoys data show that there is no influence of land on the OSCAT wind data. The scatter diagrams of comparisons of wind speed and direction are shown in Figure 2. In general, OSCAT wind speeds and directions are consistent to those of the moored buoys except for a little overestimation of OSCAT wind speeds.

The statistical parameters of errors between OSCAT and the moored buoys are given in Table 1. The biases and RMSEs of OSCAT wind speeds compared with different moored buoys are 0.22~0.34 m/s and 1.11~1.24 m/s, and those of OSCAT wind directions are −0.61°~0.68° and 16.7°~18.4°. The overall average biases and RMSEs are 0.27 m/s and 1.20 m/s for wind speed and 0.37° and 17.7° for wind direction, respectively. The correlation coefficients show that OSCAT wind vectors and all moored buoys wind data are consistent. The OSCAT wind speed in the Pacific Ocean (area of the TAO buoys) and Atlantic Ocean (area of the PIRATA buoys) is better than that in the coastal area (area of the NDBC buoys) and Indian Ocean (area of the RAMA buoys). A possible reason for this difference is that the wind is more stable in the area of TAO and PIRATA buoys, and the land has an effect on the higher variability of wind in the area of NDBC buoys which is not sensed by OSCAT. In the comparison of the wind direction, the wind direction bias is negligibly small for all buoy observations relative to the wind direction accuracy of 2°. The positive biases indicate that the OSCAT-derived wind direction is right to the wind direction observed by buoys. In general, OSCAT wind data have similar accuracy for different oceans.

In order to analyze the comparisons between OSCAT wind vectors and the moored buoy wind at different wind speeds, binwise variations of the bias, RMSE, and residuals (OSCAT minus buoy) of wind speed and direction in bins of buoy wind speed of 1 m/s are shown in Figure 3. Squares and vertical lines are biases and RMSEs in the figure, respectively. The collocated wind data are mainly distributed at the speed range of 4~12 m/s. In the case of wind speed comparisons,

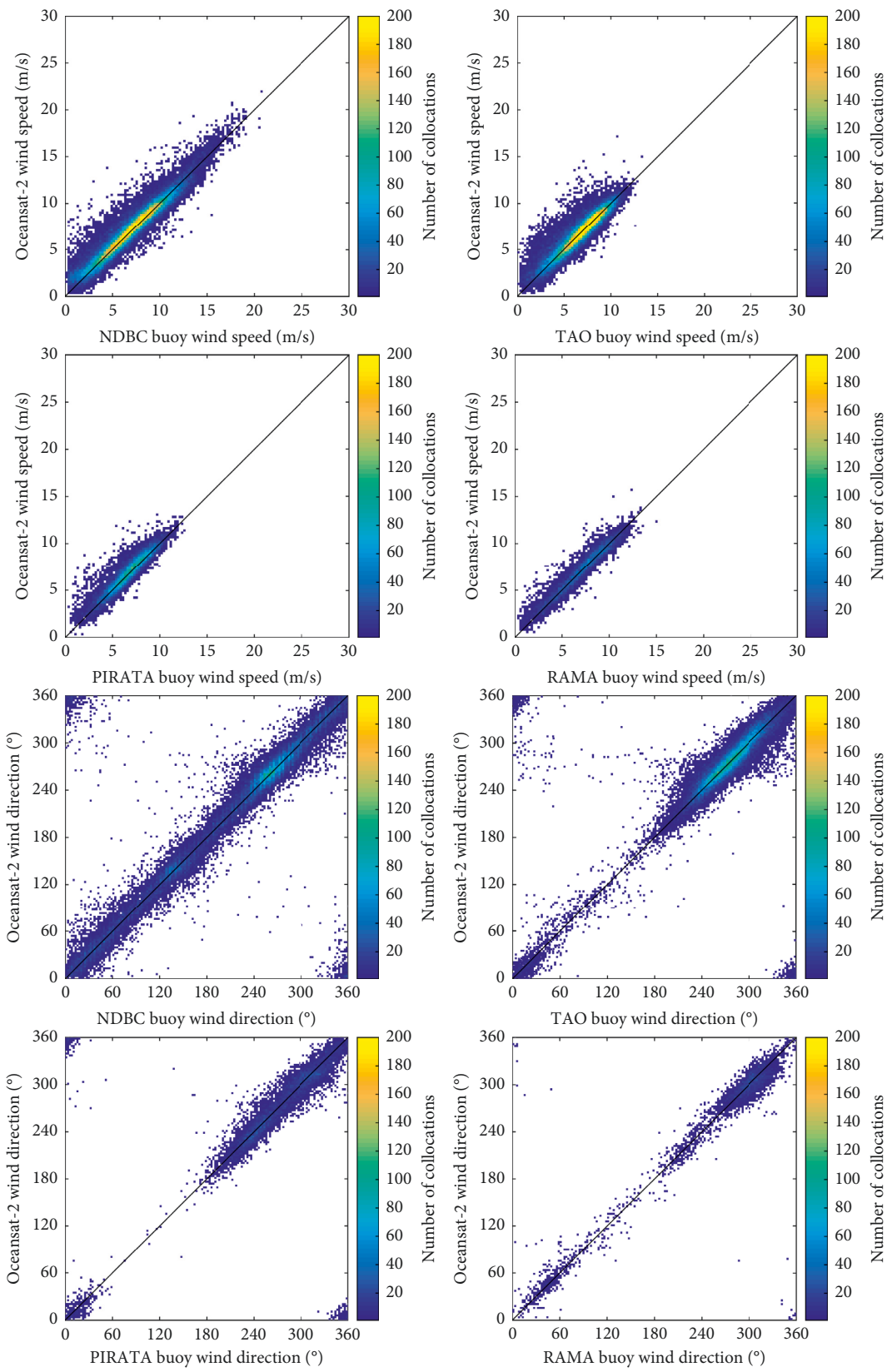

Figure 2: Scatterplots for the comparisons of wind speed and direction between OSCAT and different moored buoys.

the overall biases of wind speed are close to 0. The positive or negative biases show an overestimation or underestimation of the wind speed by OSCAT at low wind speed (less than 5 m/s) and large wind speed (more than 13~19 m/s for different buoys). The RMSEs of wind speed decrease with increasing wind speed when wind speed is lower than 9 m/s

Table 1: Error statistics of the comparison between the OSCAT and buoys wind data.

Buoy	Number	Speed			Direction		
		Bias (m/s)	RMSE (m/s)	R	Bias (°)	RMSE (°)	R
NDBC	49414	0.28	1.24	0.93	0.68	18.4	0.81
PIRATA	14569	0.34	1.11	0.87	−0.60	17.6	0.80
RAMA	8001	0.27	1.24	0.90	−0.61	18.4	0.78
TAO	39495	0.22	1.17	0.87	0.53	16.7	0.79
ALL	111479	0.27	1.20	0.91	0.37	17.7	0.82

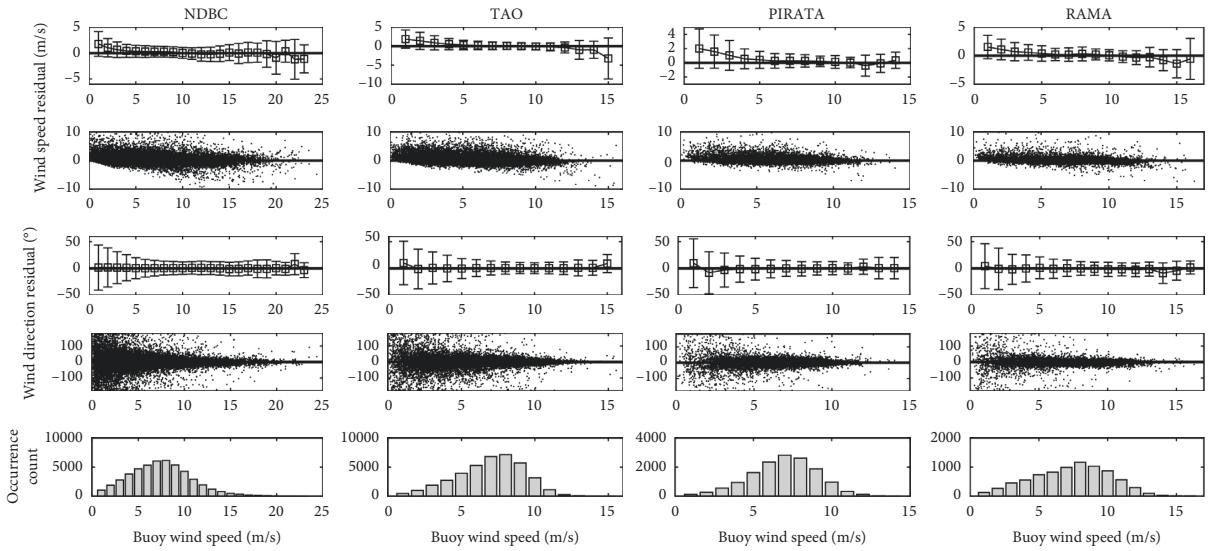

Figure 3: Dependence of statistical parameters of wind speed and direction residuals (OSCAT-buoy) on the buoy wind speed.

and then increase as the wind speed exceeds 9 m/s. The accuracy of the OSCAT wind speed first increases and then decreases with the increasing wind speed. The wind speed residuals in the coastal area (area of the NDBC buoys) are larger than that in the open sea (area of the remaining buoys). The wind speed residuals decrease with the increasing wind speed. In general, the OSCAT wind speed is higher than the moored buoy wind speed. In the case of the wind direction comparisons, the wind direction biases are very close to 0°, showing the consistency between OSCAT and buoy wind directions. The RMSE of the wind direction overall decreases with increasing wind speed. The wind direction residuals in the coastal area (area of NDBC buoys) are larger than that in the open sea (area of the remaining buoys), but it decreases with the increasing wind speed. In conclusion, the accuracy of the OSCAT wind speed generally first increases and then deceases, while the accuracy of the OSCAT wind direction generally decreases with increasing wind speed. The accuracies of the OSCAT wind data are consistent for different moored buoys. In addition, the statistical parameters of wind speed and direction residuals (OSCAT-buoy) at different times are shown in Figure 4. It is shown that the OSCAT wind data are stable over time.

To understand the abundance of the collocated data for an entire possible range of ocean surface wind, probability distribution functions (PDFs) of the collocated data are plotted for wind speed and direction as shown in Figure 5. The distribution behavior of PDFs of OSCAT and buoys for wind speed and direction implies their consistencies, and they have the similar characteristics. The wind speed histograms of OSCAT and buoys at speeds less than 10 m/s have a slight offset for NDBC, PIRATA, and RAMA buoys, which indicates the positive biases of OSCAT wind speed. OSCAT overestimates the buoy wind at low wind speed as proofed above.

3.2. Comparison with ASCAT. In order to analyze the accuracy of OSCAT wind vectors on the global oceans area where there are no in situ wind observations, OSCAT wind vectors are compared with ASCAT wind vectors which has been proved to be highly accurate during the period from 16 January 2010 to 20 February 2014. The collocated data pairs of OSCAT and ASCAT wind vectors by the method introduced in Section 2.2 are more than 1.4 million, and they locate on high latitude areas as shown in Figure 6, and the scatterplots of comparisons are shown in Figure 7.

It is shown in Figure 7 that wind speed and direction derived by OSCAT are consistent with those of ASCAT. Scatterplots of wind direction comparison show that there are some differences of 180° between OSCAT and ASCAT wind direction. The reason for 180° difference is the existence of 180° ambiguities in some derived wind directions by scatterometer. The 180° ambiguity of wind direction means the wind direction retrieved by scatterometer is opposite to

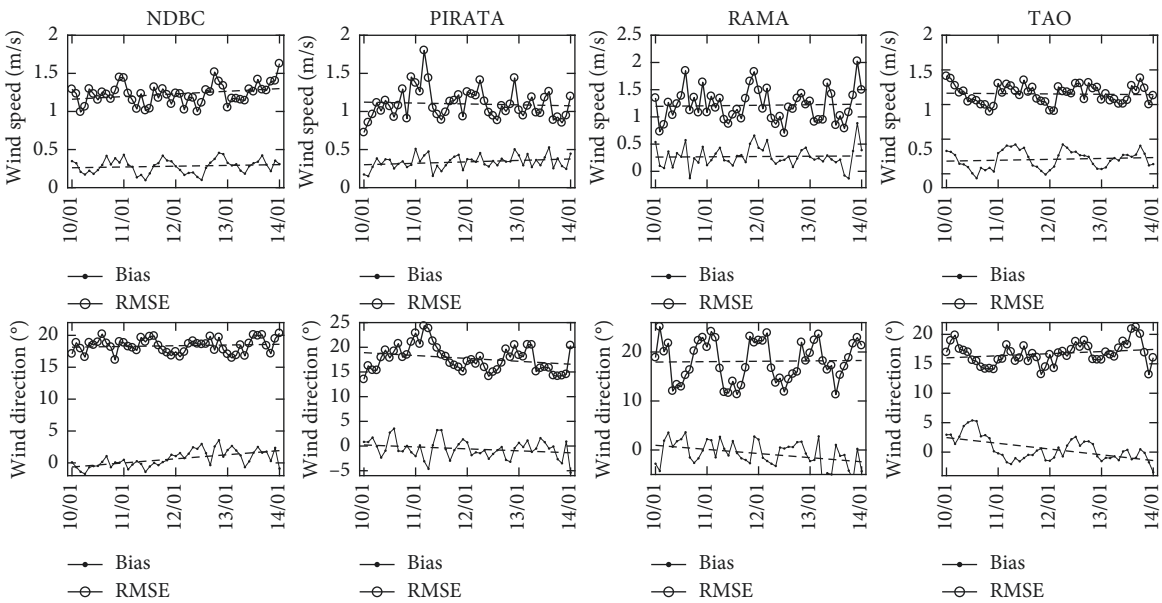

Figure 4: Statistical parameters of wind speed and direction residuals (OSCAT-buoy) at different times.

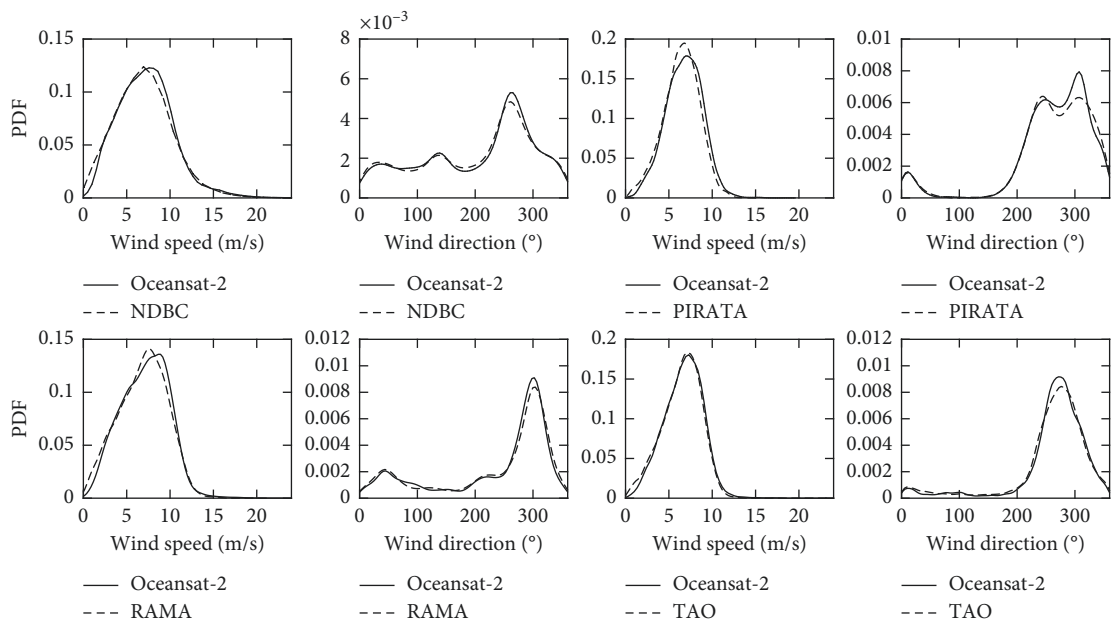

Figure 5: PDFs of the collocated OSCAT and moored buoy wind speeds and directions in the bin of 1 m/s and 10°.

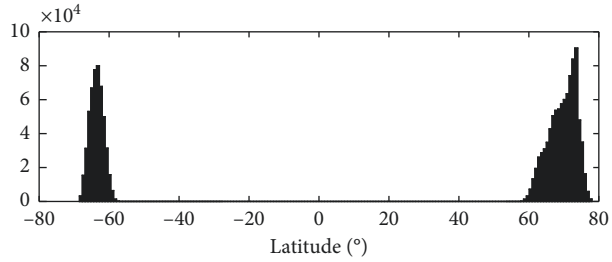

Figure 6: Number distribution of collocated data between OSCAT and ASCAT on the latitude.

the true wind direction. The differences between OSCAT and ASCAT wind vectors (OSCAT minus ASCAT) in different months are shown in Figure 8.

The biases and RMSEs of wind speed between OSCAT and ASCAT are −1.23~−0.17 m/s and 0.62~1.71 m/s and those of wind direction are −10.00°~16.23° and 17.56°~22.94°. The overall average biases and RMSEs of wind speed and direction are −0.64 m/s, 1.27 m/s and 2.87°, 20.17°, which basically satisfies the mission specification of less than 2 m/s and 20°. The negative wind speed bias means that OSCAT wind speed is less than that of ASCAT, which is

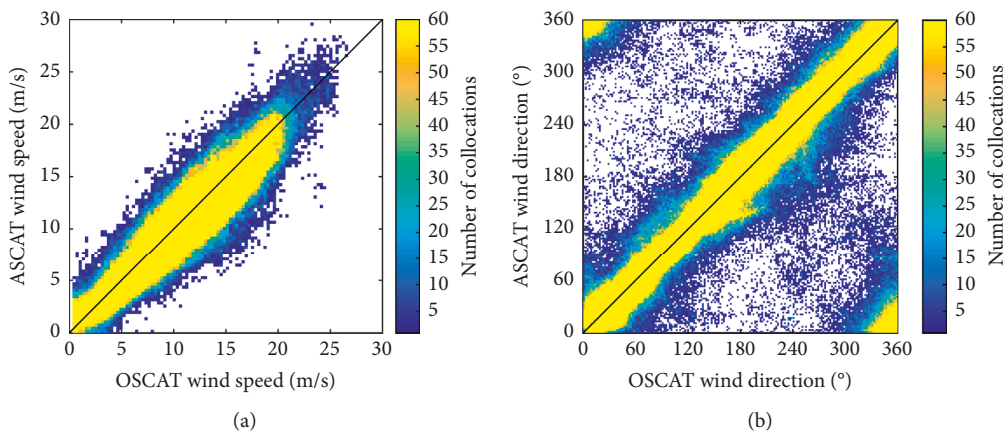

Figure 7: Scatterplots for wind speed and direction of the comparisons between OSCAT and ASCAT.

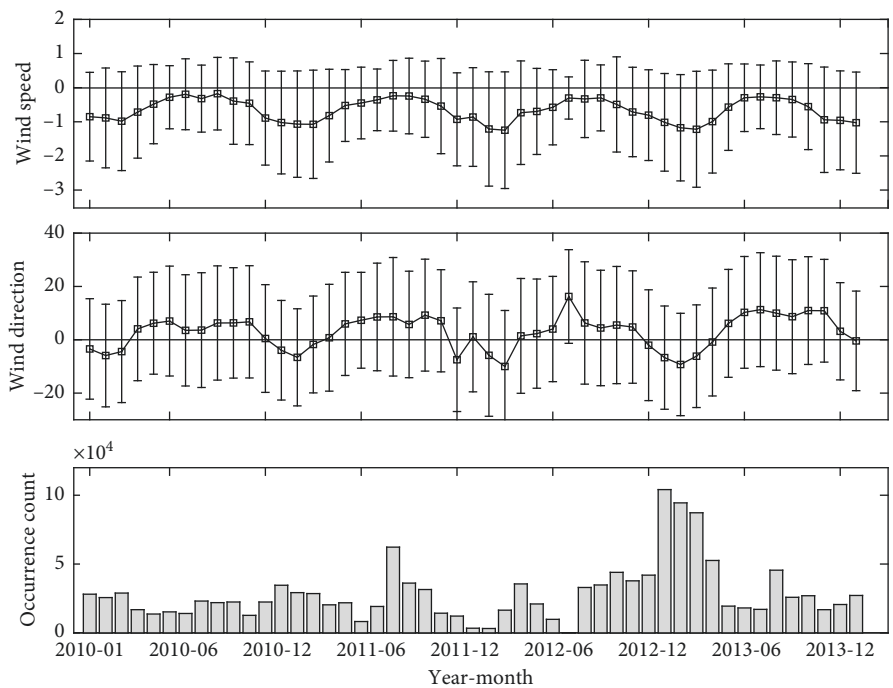

Figure 8: Statistical parameters of difference between OSCAT and ASCAT wind vectors at different months from January 2010 to February 2014.

because of the sea surface temperature effects on the OSCAT Ku-band wind retrievals. Ku-band radar backscatter is known to be sensitive to SST, and this results in lower retrieved wind speeds over colder ocean areas [21] (OSCAT-ASCAT collocated data locate on high latitude areas). These indicate the consistency of OSCAT and ASCAT wind vectors, and they have the same accuracies of wind vectors. The biases of wind speed and direction difference between OSCAT and ASCAT at different months show that there is an annual periodic signal regarding the wind speed and direction errors, as shown in Figure 8. The possible reasons for these results are the annual cycle variation of ocean winds causing the annual error variations.

4. Conclusion

Satellite scatterometry is one of the important means to achieve quasisynchronous acquisition of the global ocean surface wind, and long-term sequence global ocean surface wind data are one of the important data sources for global climate change research. OSCAT can provide global ocean surface wind vectors. Validation of OSCAT wind data is important to the data application. This study comprehensively evaluates the overall historical archived OSCAT wind vectors from 16 January 2010 to 20 February 2014 by comparing global moored buoys and MetOp-A/B ASCAT wind data. Firstly, OSCAT wind vectors are compared to 206

global moored buoys (96 NDBC buoys, 18 PIRATA buoys, 26 RAMA buoys, and 66 TAO buoys) wind data, and more than 110,000 data pairs are collocated within the spatial and temporal scales of 12.5 km and 30 min. The results show that the overall average biases and RMSEs of wind speed are 0.27 m/s and 1.20 m/s and those of wind direction are 0.37° and 17.7°. This indicates that the consistency between OSCAT wind vectors and buoy wind data. The analyses of OSCAT wind vector errors in the different buoys' wind speeds show that the accuracy of the OSCAT wind speed first increases and then decreases with the increasing wind speed. Secondly, OSCAT wind vectors are compared with ASCAT wind vectors within the spatial and temporal scales of 12.5 km and 10 min. More than 1.4 million data pairs of OSCAT and ASCAT wind data are collocated. The differences (OSCAT minus ASCAT) are analyzed at the different months from January 2010 to February 2014. The results show that the overall average biases and RMSEs of wind speed and direction difference are between −0.64 m/s and 1.27 m/s and 2.87° and 20.17°, respectively. This indicates the consistency of OSCAT and ASCAT wind vectors.

In general, comparisons of OSCAT wind vectors with moored buoy wind data and ASCAT wind vectors show that OSCAT wind vectors satisfy the general scatterometer mission requirements (<2 m/s and 20°), and they are consistent with ASCAT wind data. Consequently, OSCAT wind vectors can be used in the oceanic numerical forecast and the global change study by the combination with other scatterometers' data.

Data Availability

The Oceansat-2 scatterometer, ASCAT, and buoy data and their collocation data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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