Improving Altimeter Wind Speed Retrievals Using Ocean Wave Parameters

Haoyu Jiang , Hao Zheng, and Lin Mu

Abstract—Spaceborne altimeters are an important data source for obtaining global sea surface wind speeds (U10). Although many altimeter U10 algorithms have been proposed and they perform well, there is still room for improvement. In this study, the data from ten altimeters were collocated with buoys to investigate the error of the altimeter U10 retrievals. The U10 residuals were found to be significantly dependent on many oceanic and atmospheric parameters. Because these oceanic and atmospheric parameters are intercorrelated, an asymptotic strategy was used to isolate the impact of different parameters and establish a neural-network-based correction model of altimeter U10. The results indicated that significant wave heights and mean wave periods are effective in correcting U10 retrievals, probably due to the tilting modulation of long-waves on the sea surface. After the wave correction, the root-mean-square error between the U10 from altimeters and buoys was reduced from 1.45 to 1.24 m/s and the impacts of thermodynamic parameters, such as sea surface (air) temperate, became negligible. The U10 residuals after correction showed that the atmospheric instability can lead to errors on extrapolated buoy U10. The buoy measurements with large air-sea temperature differences need to be excluded in the Cal/Val of remotely sensed U10.

Index Terms—Altimeter, atmospheric instability, mean wave period, sea surface wind speed, significant wave height.

I. Introduction

SEA surface wind speed is one of the key environmental parameters in marine and atmospheric sciences. Spaceborne active microwave remote sensors, including radar altimeter, scatterometer, and Synthetic Aperture Radar (SAR), can all be used to retrieve 10-m sea surface wind speed (U10, henceforth) because the Radar Cross-Sections (RCSs) are sensitive to sea surface roughness (SSR) [1], and the SSR is closely correlated to U10. Among these remote sensors, scatterometers have the widest swath and the best overall accuracy (with a typical error of ∼1 m/s) [2], making them an irreplaceable data source of U10. Meanwhile, radar altimeters, with a typical error of wind speed of 1.5 m/s (e.g., [3], [4]), have a better accuracy in high wind speeds [1] and can provide global coverage of U10 and significant wave height (SWH) data simultaneously, making them also a unique tool for studies in wind-waves (e.g., [5]–[7]). Since 1985, more than ten satellite altimeters have been launched, which provide sufficiently long data records for studies of wind and wave climate [5].

RCSs are related to U10 through the Geophysical Model Function (GMF). For altimeters, the GMF is based on the quasi-specular scattering: The SSR is believed to be dominantly controlled by U10, and a smoother sea surface corresponds to a larger RCS and vice versa. When establishing the retrieving algorithm, however, the RCSs are usually directly mapped to U10 obtained from other instruments, such as buoys or scatterometers [4]. Although the derived GMFs generally have a good performance in measuring U10 (e.g., [1], [2], [4]), it is noted that U10 is not the only impact factor for SSR. For example, surface ocean currents and atmospheric instability can all have a direct impact on the SSR response to U10 (e.g., [8], [9]), thus impacting the wind retrieval. In addition, recent studies show that some parameters of the oceanic environment have significant impacts on the wind speed retrievals from C-band scatterometers and SARs with tilt incident angles (e.g., [10]–[12]). For example, Sea Surface Temperature (SST) can slightly change the SSR's response to U10 by impacting dynamic viscosity of water [11], [13] and by impacting the atmospheric stability [12], and ocean swells can also change this response by impacting the tilt of sea surface [10], [12]. Better accuracy of U10 may be achieved by considering these secondary responses.

Wind retrievals from altimeters may also be impacted by these effects. Among which, the impact of long-wave tilting of capillary waves has been well known (e.g., [14]) and SWH has been considered in some altimeter GMFs (e.g., [15]). Meanwhile, ocean waves may impact altimeter wind retrieval in many ways. For instance, wave crests are usually rougher than wave troughs, which is a very important effect for retrieving sea surface height termed electromagnetic bias (e.g., [16]). It may also impact U10 retrievals because the RCS is a "linear average" over the ∼7 km footprint for the 1-Hz data. Other oceanic and atmospheric

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parameters, such as wave periods, precipitation, SST, and Sea Surface Air Temperature (SSAT), might also impact altimeter U10 retrievals. This study aims to conduct a quantitative analysis of how much altimeter U10 retrievals are impacted by these parameters of the ocean environment, and a trial was made to improve the data accuracy by considering the impact of these parameters.

The rest of this article is organized as follows. The collocated dataset between altimeter and in-situ observations are described in Section II. In Section III, the differences between the altimeter and in-situ U10 data (residuals) are analyzed relative to some parameters of the ocean environment. A correction model for altimeter U10 retrievals based on the correlations in Section III is presented in Section IV. Conclusion is given in Section V.

II. DATA AND METHODS

A. Multiplatform Altimeter Dataset

Systematic calibrations and validations of simultaneous U10 and SWH data from 13 altimeter missions (GEOSAT, ERS-1/2, TOPEX, GFO, JASON-1/2/3, ENVISAT, CRYOSAT-2, HY-2, SARAL, and SENTINEL-3A) over 33 years (1985–2018) were conducted by [3] based on a previous work of [17]. Because of the joint calibration, the systematic errors of U10 and SWH between different altimeters were preliminarily eliminated. The data of the calibrated U10 from ten satellites (TOPEX, ERS-2, GFO, JASON-1/2/3, ENVISAT, Cryosat-2, HY-2, and SENTINEL-3A) over the period from 2001 to 2017 is selected in this study. The reason for using data from ten different altimeters is to obtain more collocations with buoys for better statistical significance. It was assumed that the impact of oceanic and atmospheric parameters induces a "systematic error" which is similar for all altimeters using the same frequency band (the data from Ka-band SARAL are not used here). Therefore, the different noise levels of "random errors" of different satellites should have little impact on the results. All the altimeter U10 data used in this study were retrieved from Ku-band RCS using the same GMF after removing the RCS offsets among different altimeter systems, and these U10 were then linearly calibrated against buoy data using total least-square regression, as reported in [3]. The information of SWH and RCS of other frequencies (C-band and S-band) were not taken into consideration. The data with bad quality flags or U10 > 25 m/s or SWH > 10 m were discarded. More detailed information on this dataset is available in [3].

B. Buoy Observations

The quality controlled in-situ data from the National Data Buoy Center (NDBC) were simply regarded as "ground truth" here to assess the altimeter U10 retrievals. Through not free of errors, the wind speed data from buoys are believed to be a good reference at low and moderate wind speeds. For altimeter U10 retrievals, a better comparison with buoy data can generally mean being more accurate. A total of 52 buoys more than 50 km offshore were used and the locations of these buoys are shown in Fig. 1. Most anemometers of the NDBC
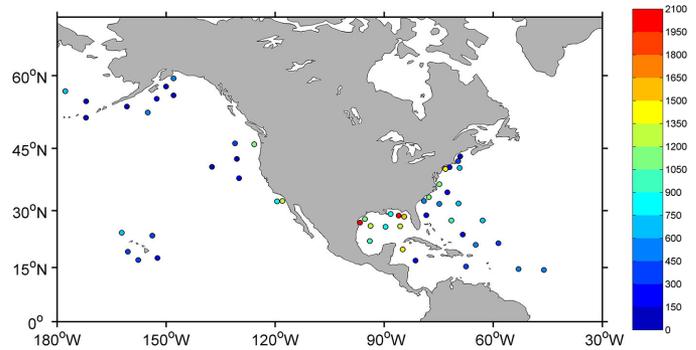

Fig. 1. Locations of NDBC buoys used in this study. The color of the dots indicates the number of collocations at each site.

buoys measure wind vectors at a height of 2–5 m above the site elevation (sea surface). To be consistent with the altimeter-retrieved U10, the buoy-measured winds were converted to 10-m neutral wind using a log-profile relation assuming that the air-sea boundary layer is neutrally stable [17], which is also widely used in other studies (e.g., [3], [10], [12], [17]). Besides wind vectors, the buoys also provide other oceanic and atmospheric information, including the SWH, Mean Wave Period (MWP), Dominant Wave Period (DWP), Mean Wave Direction (MWD), SST, SSAT, and atmospheric pressure. The SWH, MWP, and DWP are estimated from the 1-D wave spectra while the MWD is from the directional wave spectra reconstructed by the four directional Fourier coefficients [18], [19]. Detailed information about the buoy data and all the aforementioned parameters are available from the NDBC website[1].

C. Collocation

The multiplatform altimeter dataset was collocated with the NDBC buoy dataset to make comparisons between them. The spatial and temporal windows for the collocation were set to 50 and 30 min, respectively, which is a widely used criterion in previous studies (e.g., [3], [17]). When several retrievals could be collocated with a buoy in the same satellite pass, only the one that is the nearest to the buoy was used. A total of 33 404 collocations were obtained using this criterion, and the number of collocations for each buoy is shown in Fig. 1.

III. CORRELATION OF THE U10 ERROR

A comparison between the multiplatform altimeter U10 and buoy U10 is shown as a scatter plot in Fig. 2. Some standard error metrics, including the root-mean-square error (RMSE), correlation coefficient (CC), and bias, are used to evaluate the data. Although the altimeter U10 has been jointly calibrated against each other and against the buoy measurements, Fig. 2(a) shows that there is a small bias of 0.14 m/s and the least-square regression line does not perfectly lie on $y = x$. This is mainly because [3] used the total least-square regression instead of the simple least-square regression. Besides, more buoy data are

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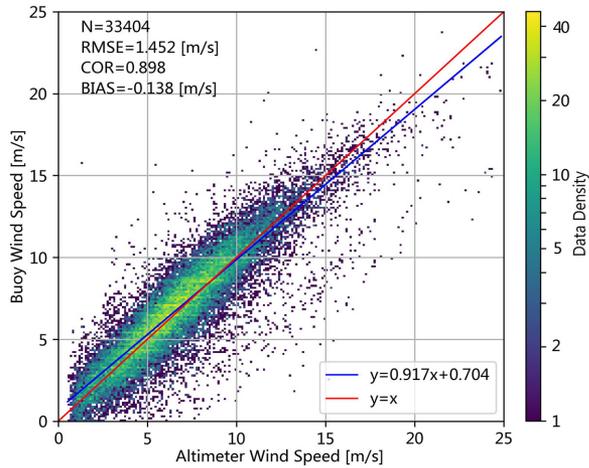[1]Online. [Available]: www.ndbc.noaa.gov

Fig. 2. Scatter plots of U10 from multiplatform altimeters versus U10 from buoys. The blue line represents the least-square regression line. The color of dots indicates the data density.

Fig. 4. Scatter plots for U10 residuals relative to (a & c) altimeter U10 and (b & d) buoy U10, (a & b) before and (c & d) after linear correction using the regression line in (a). The black solid lines show the average residuals and the error bars show the corresponding standard deviations. The red lines represent least-square linear regression.
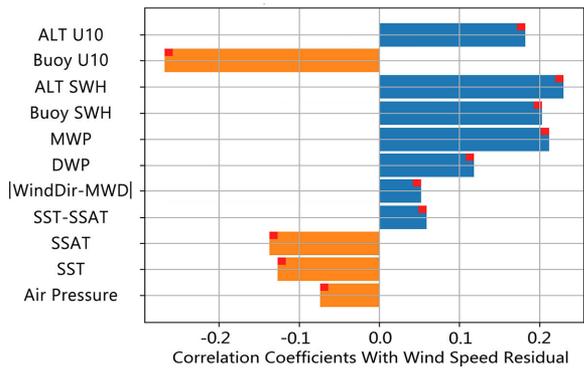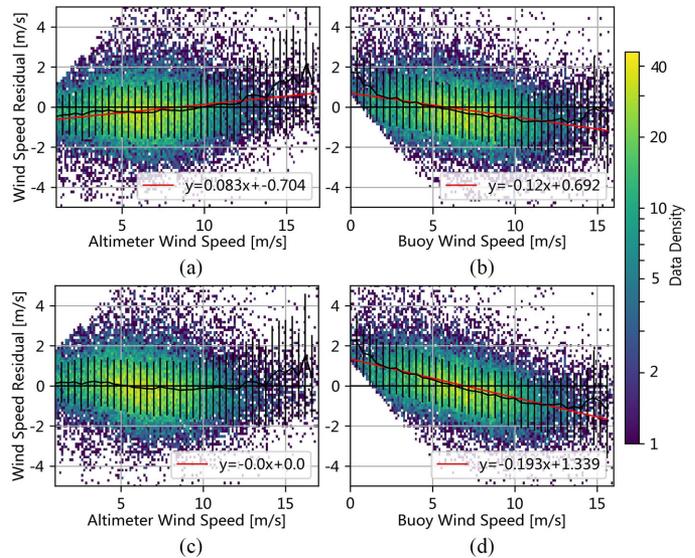

Fig. 3. Correlation coefficients between U10 residuals (altimeter U10 minus buoy U10) and geophysical parameters in collocation points. The red square in the corner of the bar denotes statistical significance at the 99% level.

used in the calibration of the dataset in [3] and there could be systematic error among different buoys. The buoy data used both here and in [3] sample only a limited number of locations in a few climate zones. Therefore, this bias does not imply that the altimeter dataset tend to overestimate the wind speed. The RMSE of the altimeter U10 retrievals is 1.45 m/s, and the CC between the two datasets is 0.90.

The residuals between altimeter and buoy U10 were computed for each collocation, and the CCs between the U10 residuals and the geophysical parameters measured by buoys were then computed with the results shown in Fig. 3. Of course, the relation between U10 residuals and geophysical parameters can hardly be perfectly linear, but the CC is helpful to give a reference as to whether the dependency between them is statistically significant. Although the CCs are less than 0.3 for most parameters, the U10 residual is significantly correlated to all the selected oceanic and atmospheric parameters at the 99% level (two-sided *t*-test, which was used for the tests of CCs throughout the article). These CCs were also computed using several single satellites, and the results were almost the same.

The correlation of the U10 residuals is negative with the buoy U10. This means that altimeters tend to overestimate low wind speed and underestimate high wind speed compared to the buoy U10. However, the correlation of the U10 residuals is positive with the altimeter U10. This indicates that there is also an overestimation and an underestimation compared to the buoy U10 when the altimeter-retrieved U10 is high and low, respectively. This seems to be somehow contradictory, but this phenomenon can be clearly seen in Fig. 4(a) and (b), where the residuals increase with altimeter U10 but decrease with buoy U10, and larger errors occur when the buoy or altimeter U10 is high or low. Particularly, when the buoy U10 is less than 1.5 m/s, there is a systematical overestimation for 1∼2 m/s because no record of altimeter U10 < 1 m/s is even found in the altimeter dataset. This systematic error is hard to correct directly from the wind speed data themselves because increasing the residuals' CC with one U10 through linear transform will decrease the CC with the other one. Applying the regression equation of U10 residuals in Fig. 4(b) to the altimeter U10 directly will only lead to a larger overall RMSE and might cause negative retrieved U10 values. But if the dependence of residuals on altimeter U10 is corrected using linear regression, the systematic error that underestimates high winds and overestimates low winds will be magnified [see Fig. 4(c) and (d); both the slope and intercept are larger in Fig. 4(d) than Fig. 4(b), and the averaged error for no wind condition is larger than 2 m/s in Fig. 4(d)].

The wave parameters, especially SWH and MWP, are positively correlated to the residuals, and the SST and SSAT, which is consistent with the results of [12]. The SWH has the largest CC among the selected parameters, which indicate that wave parameters have large impact on the U10 retrieval of altimeters. The negative correlation of the U10 residuals on SST and
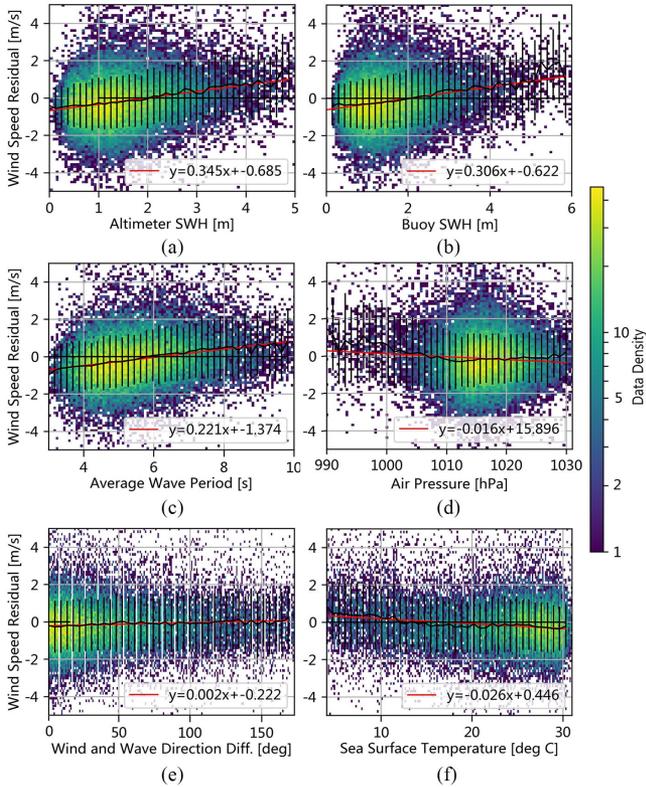
Fig. 5. Scatter plots for U10 residuals relative to (a) SWH from altimeters and (b) buoys, (c) MWP, (d) air pressure, (e) angles between wind direction and MWD, and (f) SST. The black solid lines show the average residuals and the error bars show the corresponding standard deviations. The red lines represent least-square linear regression.
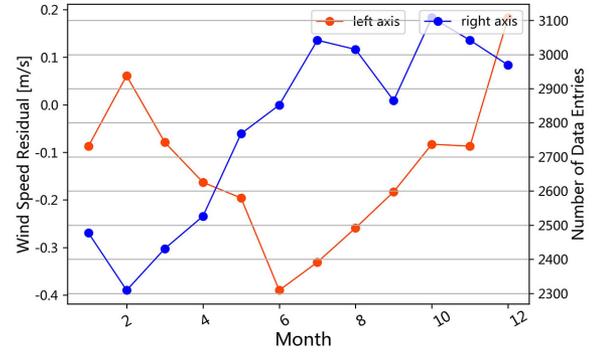

Fig. 6. Averaged U10 residuals as a function of calendar month (red lines, left axis) and the numbers of collocations as a function of calendar month (blue lines, right axis).

SSAT indicates that the change of dynamic viscosity [11] might not be important for altimeter wind speed retrieval because a higher SST corresponds to a lower viscosity, which should lead to an overestimation of the U10. The SST and SSAT might simply change the wind profiles by impacting the atmospheric instability.

To further explore the relationship between the U10 residual and the aforementioned parameters, the U10 residuals are shown in Fig. 5 as the functions of these parameters. The U10 tends to be underestimated for SWH < 2 m and overestimated for SWH > 2 m [see Fig. 5(a) and (b); it is noted that the error of altimeter retrieved SWH is very small [17]]. Waves, especially swells, could impact the remotely sensed U10 in many ways. Besides the mechanisms mentioned in Section I, swells can also change the surface wind profile by inducing the wave-driven winds [21]. Another important parameter to describe the wave state is the MWP, which is representative of the wave's horizontal scale. Fig. 5(c) shows that the U10 tends to be underestimated for MWP < 6 s and overestimated for MWP > 6 s. It is shown that sea-state bias for measuring the sea surface height is closely linked to MWP because the shape of the Stokes wave is dependent on the MWP [22]. This effect seems to also be effective for altimeter U10 retrieving. When the MWP is low (high), the shape of the wave profile is more (less) like a Stokes wave so that the area of wave troughs, which is smoother and has a smaller incidence angle than wave crests, is larger (smaller), leading to an underestimation (overestimation) of wind speed.

Compared to the SWH and MWP, the impacts of the other parameters are small. The scatter plots for residuals relative to the air pressure, the angle between wind and wave, and the SST are shown in Fig. 6(d)–(f), respectively. Although the correlation of air pressure is statistically significant, this is primarily due to the slight overestimation in a few low-pressure conditions. In the range between 1000 and 1030 hPa, the mean of the U10 residuals is not significantly different from zero (two-sided t-test at the 95% level). The dependence of the U10 residuals on the difference between wind-wave angles is also close to a linear one, which might be due to the Stokes drifts-induced relative motion of the air-sea interface that can impact the relative wind speed sensed by space-borne sensors. This dependence induces an underestimation of ∼0.15 m/s when the wind direction is in line with the mean wave direction, which is common in the wind-sea-dominated conditions. There is an underestimation of U10 (∼0.3 m/s) for the SST ranging from 12 to 30 °C and an overestimation (∼0.5 m/s) for the SST lower than 12 °C. The dependence on the SSAT is generally the same as on the SST (not shown). The low SST data are mainly from the nine buoys along the Alaska coast, thus, this error might simply be geographical errors, although the SST affecting U10 retrievals by impacting the atmospheric instability is also a plausible explanation.

Another noteworthy point is that oceanic and atmospheric parameters are often intercorrelated. Table I lists the correlation coefficient among these parameters in the collocation dataset. Most of the values in the table are significant at the 99% level. SWH is closely correlated to U10, because more than half of the collocations are located in semienclosed basins where wind-sea tends to be dominant [20], as shown in Fig. 1. Within expectation, the strongest correlation is the SST and SSAT. The three wave parameters, SWH, MWP, and DWP, also show strong correlations with each other. The parameter with the weakest overall correlation with the other parameters is the difference between SST and SSAT. The potential reason for these correlations is that these parameters have significant seasonality. The U10 residuals also show significant seasonality (see Fig. 6), which makes it difficult to separate the impacts of different parameter on the retrievals.

TABLE I
CORRELATION COEFFICIENTS AMONG DIFFERENT OCEANIC AND
ATMOSPHERIC PARAMETERS IN THE COLLOCATION DATASET

	U10 [a]	SWH [a]	MWP	DWP	$|\Delta\theta|$ [b]	ΔT [c]	SST	SSAT
SWH	0.68* [d]							
MWP	0.11*	0.70*						
DWP	0.03	0.49*	0.79*					
$|\Delta\theta|$	-0.27*	-0.10*	0.16*	0.29*				
ΔT	0.16*	0.07*	-0.03	-0.04	0.02			
SST	-0.23*	-0.36*	-0.34*	-0.31*	-0.12*	-0.06		
SSAT	-0.26*	-0.36*	-0.31*	-0.28*	-0.11*	-0.33*	0.96*	
AP	-0.25*	-0.30*	-0.13*	-0.06*	0.01	0.19*	0.15*	0.09*

The U10 and SWH data are from altimeters.
The angle between wind direction and MWP.
The difference between SST and SSAT.
The "∗" represents statistical significance at the 99% level.

IV. RETRIEVAL IMPROVEMENT

Statistically significant dependence is found between the error of altimeter wind speed retrievals and some oceanic and atmospheric parameters using altimeter-buoy collocations. Although some reasonable explanations can be given on mechanisms of the dependence on different parameters, it might be difficult to directly prove these mechanisms using the collocation data at this stage, and the inter-dependence among different geophysical quantities makes this task more difficult. Meanwhile, quantitively knowing these dependences can be useful for further reducing the error of altimeter U10 retrievals. Here, a trial was made to establish a nonparametric model for correcting altimeter U10 retrievals by considering some of the parameters. The dataset of altimeter-buoy collocations was randomly divided into two parts, one for model training (23 404 records) and the other for model testing (10 000 records). A simple three-layer back-propagation neural network (including an input layer, a hidden layer, and an output layer) was employed here to relate altimeter U10 and other geophysical parameters to the buoy U10. The neural network was realized by the MATLAB Deep Learning Toolbox TM. The RMSE between the output of the neural network and the buoy U10 was used as the cost function. The activation functions from the input layer to the hidden layer and from hidden layer to output layer were set to sigmoid function and linear ($y = x$), respectively; the Levenberg–Marquardt and the gradient descent with momentum weight and bias were selected as the training and learning functions of the neural network, respectively; the learning rate and the number of epochs were set to 0.01 and 1000, respectively, to train the model; and the number of neurons in the hidden layer was set to 21 after some tests.

From Figs. 4 and 6, it can be seen that the dependencies between the U10 residuals and oceanic/atmospheric parameters do not have strong nonlinearity. Therefore, the CC can be a good metric to quantify the dependence. Because the oceanic and atmospheric parameters are intercorrelated, the correction model was trained using an asymptotic strategy as follows to select the factors that have relatively large impact on the altimeter U10 retrievals.
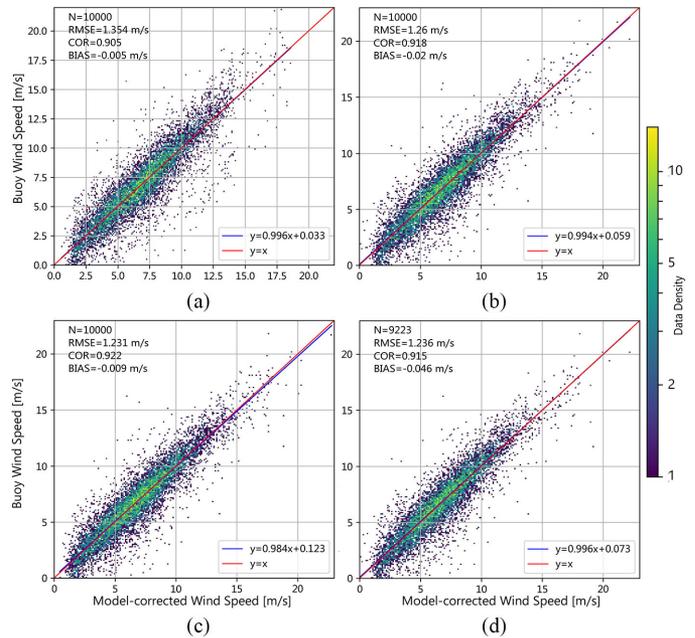

Fig. 7. Scatter plots of U10 from buoy versus U10 multiplatform altimeters corrected by models taking different parameters into account: (a) U10 and MWP, (b) U10, MWP, and SWH, (c) U10, MWP, SWH, and DWP. Subplot (d) is the same as (b), but the points with SST-SSAT difference greater than 4 °C are excluded. The blue lines represent the least-square regression lines. The color of dots indicates the data density.

1) A correction model was trained using only the original altimeter U10 as the input parameter of the neural network.
2) The RMSE of correction model output and the CCs between the U10 residuals and the aforementioned parameters were computed.
3) The parameter with the highest CC was found and a new correction model was trained by adding this parameter as another input of the neural network.
4) The 2nd and 3rd steps are repeated until the RMSE of the new correction model was not significantly lower than the RMSE of the previous one.

Using this strategy, the first four parameters that need to be taken into account are found to be the MWP, SWH, DWP, and SST-SSAT difference, respectively. Fig. 5 shows that the SWH seems to have a larger impact on U10 retrievals of altimeter than the MWP. However, SWH is closely correlated to U10 (see Table I), and some U10 residuals' dependence on SWH were corrected in the U10-only based neural network. Meanwhile, the MWP is less dependent on U10 than the SWH and CC of the MWP on the U10 residuals is only slightly reduced after the first step. This is the reason for MWP to be first considered parameter. The corresponding scatter plots after the corrections with different parameters are shown in Fig. 7. Compared to Fig. 2, the RMSE is significantly reduced from 1.45 to 1.35 m/s (1.35 m/s for the training dataset) and the CC increases from 0.898 to 0.905 (0.908 for the training dataset) after considering the dependence on MWP [see Fig. 7(a)]. The RMSE further decreases to 1.26 m/s (1.24 m/s for the training dataset) with CC
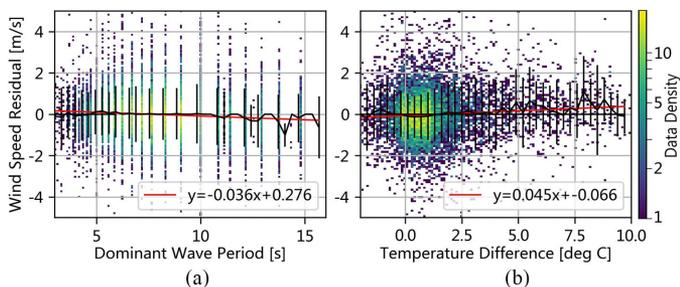
Fig. 8.   Scatter plots for U10 residuals relative to (a) DWP and (b) SST-SSAT difference after correction using U10, SWH, and MWP. Only the data from the testing dataset is used. The black solid lines show the average residuals and the error bars show the corresponding standard deviations. The red lines represent least-square linear regression.

increasing to 0.918 (0.921 for the training dataset) after considering the effect of SWH [see Fig. 7(b)]. Then, after considering DWP [see Fig. 7(c)], there is still a slight improvement on both RMSE (1.26–1.23 m/s) and CC (0.918 to 0.922), but the errors are not further reduced with adding the fourth parameter (the SST-SSAT difference, which is not shown).

The three most effective parameters to improve wind speed retrievals are all surface wave parameters, which indicates that the impact of ocean waves is much more important than the impact of other ocean and atmospheric parameters. In the three wave parameters, the SWH is the one that has been widely used for wind speed retrieval in previous studies (e.g., [10], [12], [15]) as it is directly available from the altimeter. In addition, algorithms have been presented to use U10, SWH, and MWP to correct sea-state bias in measuring sea surface height (e.g., [22]). This study shows that MWP is also an effective parameter in improving the accuracy of altimeter U10 retrieval. Some algorithms have been established on retrieving wave period information from altimeter data (e.g., [23]–[25]). However, the algorithms in most of these studies are established based on the empirical relation assuming that the wave period is a function of U10 (or RCS) and SWH, which is not very helpful for improving U10 retrievals (as it does not increase the input information). Another source of independent MWP information is the numerical wave model. Contemporary numerical wave models can have a fairly good performance on simulating many wave parameters including MWP (e.g.,[26]), which can be used in this correction model.

Fig. 8(a) shows the U10 residual as a function of DWP after being corrected using MWP and SWH. The mean U10 residual is not statistically different from zero when the DWP is shorter than 12 s, but there is an underestimation of the altimeter U10 when the DWP is longer than 12 s, which means the sea is swell-dominated. When the sea is either overwhelmingly dominated by wind-seas or swells, the wave spectrum can be regarded as a unimodal one so that the value of MWP should be close to DWP so that the DWP becomes a redundant parameter. When the sea state is bimodal or multimodal, the DWP can be very different from the MWP. However, it is noted that including DWP is still insufficient to describe this complex sea-state, and DWP is not a stable wave parameter when spectral densities of the two highest peaks are close to each other. Therefore, the improvement of

U10 retrieval after considering DWP is marginal. Due to these reasons, a correction model using simply U10, MWP, and SWH seems to be more practical.

It is noted that the U10 from the buoy was obtained using a logarithmic wind profile under the assumption of neutral atmospheric stability. Therefore, the variation of atmospheric stability can lead to deviation from this profile and then lead to an error of the buoy U10. Previous studies found the dependencies of remotely sensed U10 residuals on air pressure and SST/SSAT (e.g., [11], [12]), and attributed these dependencies to the impact of atmospheric instability and dynamic viscosity. However, after the correction using MWP and SWH, the U10 residuals' CCs with air pressure and wind-wave angle becomes insignificant (at 95% level) and error dependencies on SST and SSAT become much less than the dependence on their SST-SSAT difference (not shown). This indicates that some of these dependencies might simply be due to the universal intercorrelation of geophysical parameters as they all have seasonality. Even if the impacts of air pressure, SST, and SSAT are through some physical processes, such as changing dynamic viscosity, they can also be largely corrected by using some wind and wave parameters.

Meanwhile, this does not mean that the atmospheric instability is not important for the Cal/Val of remotely sensed U10. The most direct indicator for atmospheric stability among the selected parameters is the SST-SSAT difference, which is also the parameter relatively independent of other ones (see Table I). The wave boundary layer will be in an unstable state when the sea is warmer than the air, and vice versa. Although considering the SST-SSAT difference does not help for a better algorithm here, the correlation of the U10 residuals with the SST-SSAT difference is significant (0.08, which significant at the 99% level) for the results in Fig. 7(b) and (c). To further explore this dependence, the U10 residual as a function of SST-SSAT difference is shown in Fig. 8(b). The air-sea temperature difference for around 90% of the data is within ± 2.5 °C, and the bias of U10 is negligible in this range. However, when the difference becomes higher, which means the sea is warmer than the air above (unstable condition), the altimeter systematically overestimate the U10 for about 0.5 m/s. In this case, the buoy U10 obtained from the logarithmic profile of neutral stability itself is overestimated, and the buoy data are not a good U10 reference anymore because it is difficult to determine whether this error comes from the remote sensors or the buoys. Therefore, we suggest that buoy U10 with high air-sea temperature difference should not be used for the Cal/Val and error analysis of remotely sensed U10. After excluding the "bad-quality" buoy data with an SST-SSAT difference greater than $+4$ °C (777 points), it is found that the altimeter U10 can have a slightly better comparison with the buoy U10 with an RMSE of 1.24 m/s [see Fig. 7(d)].

Data from ten different altimeters were used to train the correction model to get a better statistical significance. Therefore, an assumption during the analysis was that the impacts of the aforementioned geophysical parameters on the U10 retrievals are generally the same for different satellites. To test the validity of this assumption, the U10 errors for each satellite before and after the correction (considering the U10, MWP, and SWH) are described in Table II. The results show that the accuracies

Altimeter Name	N_{col} [a,b] Total	Bias [b] (m/s)	CC [b]	RMSE [b] (m/s)	N_{col} [c] Test	Bias [c] (m/s)	CC [c]	RMSE [c] (m/s)
TOPEX	1586	-0.20	0.88	1.47	427	-0.02	0.89	1.27
ERS-2	2760	-0.12	0.90	1.48	749	-0.01	0.92	1.27
GFO	1355	-0.14	0.90	1.41	369	0.02	0.93	1.24
JASON-1	4291	-0.13	0.91	1.39	1173	-0.01	0.93	1.21
JASON-2	6174	-0.13	0.90	1.46	1652	-0.02	0.91	1.23
JASON-3	2184	-0.07	0.89	1.48	605	-0.03	0.93	1.21
ENVISAT	3399	-0.13	0.90	1.49	913	-0.01	0.91	1.25
Cryosat-2	5682	-0.16	0.89	1.45	1532	-0.01	0.92	1.21
Sentinel-3A	1971	-0.16	0.89	1.44	539	-0.08	0.92	1.20
HY-2	4678	-0.16	0.90	1.47	1264	0.02	0.92	1.27

N_{col}: Numbers of collocations.
Data before the correction.
Data after the correction.

for different altimeters are similar, and the improvements for different altimeters are also similar after the correction (with RMSEs reduced for ∼0.2 m/s for all ten satellites). This result indicated that the assumption is valid and the correction model is applicable for all Ku-band altimeters.

V. CONCLUSION

Spaceborne altimeters can provide nadir wind speed information because the RCS is strongly dependent on U10. Although the U10 is the most important impact factor of the RCS, the RCS can also have some secondary response to other oceanic and atmospheric parameters, such as the SWH, MWP, SST, and SSAT, which has been confirmed by previous studies using scatterometer and SAR data (e.g., [10]–[12]). In this study, the impact of these secondary responses on altimeter U10 retrievals was analyzed using the colocations between ten satellite altimeters and 52 NDBC buoys. These collocations allow an assessment on the performance of altimeter U10 retrievals and a detailed description of the dependency between the altimeter U10 residuals and some oceanic and atmospheric parameters obtained by the buoys.

After the joint calibration [3], the U10 from the multiplatform altimeters generally show a good agreement with the buoy U10 with an RMSE of 1.45 m/s. Meanwhile, the U10 residuals are found to be weakly but significantly correlated to many oceanic and atmospheric parameters, which means some of the errors of the altimeter U10 retrievals are systematic and can be corrected using these parameters. Because oceanic and atmospheric parameters are usually intercorrelated, an asymptotic strategy is used to establish a correction model of altimeter U10. The results indicated that the altimeter U10 retrievals are the most significantly impacted by the SWH and MWP. A reduced RMSE of 1.24 m/s can be obtained using the correction model taking ocean waves into account. The impacts of many other parameters, such as air pressure, SST, SSAT, become insignificant

after the wave correction. Using the dependency between the SST-SSAT difference and residuals of corrected U10, it is also found that the atmospheric instability can lead to some errors on the buoy extrapolated U10. Thus, another conclusion that can be drawn is that the cases with large SST-SSAT differences should be excluded in the comparison between remote sensed and in-situ wind speed.

In this study, the correction was based on the collocation between buoys and ten satellites for a better statistical significance. The altimeter U10, which has been jointly calibrated was used as an input term of the correction model. Operational altimeter missions may use a different GMF than the multiplatform satellite dataset. Therefore, the correction model derived from the collocations in this study may not be directly applicable to them. However, the same idea can also be used in establishing operational altimeter GMFs with Ku/Ka-band RCS, SWH, and MWP (from numerical wave forecast/hindcast), which can be a direction for the future study. Some altimeters, such as TOPEX, Jason-1/2/3, HY-2A, and Sentinel-3A, use the Ku-and-C dual-frequency setup, which can also be used to improve U10 accuracy [27]. A recent study showed that the difference between the RCS of the two bands is related to ocean wave information [28]. Therefore, further study can also be made to investigate whether this wave correction is redundant for the dual-frequency U10-retrieving approach.

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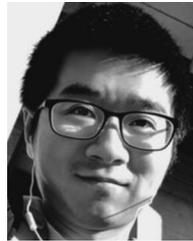
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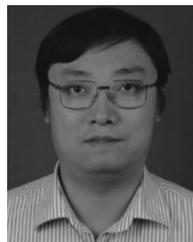
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