Acta Oceanol. Sin., 2014, Vol. 33, No. 7, P. 83–88
DOI: 10.1007/s13131-014-0500-z
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An improved wind speed algorithm for "Jason-1" altimeter under tropical cyclone conditions

QIN Bangyong[1], ZHOU Xuan[1,2]*, ZHANG Honglei[1], YANG Xiaofeng[2], LU Rong[1], YU Yang[2], SHI Lijian[3]

[1] State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China
[2] P. O. Box 5111, Beijing 100094, China
[3] National Satellite Ocean Application Service, State Oceanic Administration, Beijing 100081, China

Received 4 March 2013; accepted 6 September 2013

Abstract

Rain effect and lack of in situ validation data are two main causes of tropical cyclone wind retrieval errors. The National Oceanic and Atmospheric Administration's Climate Prediction Center Morphing technique (CMORPH) rain rate is introduced to a match-up dataset and then put into a rain correction model to remove rain effects on "Jason-1" normalized radar cross section (NRCS); Hurricane Research Division (HRD) wind speed, which integrates all available surface weather observations, is used to substitute in situ data for establishing this relationship with "Jason-1" NRCS. Then, an improved "Jason-1" wind retrieval algorithm under tropical cyclone conditions is proposed. Seven tropical cyclones from 2003 to 2010 are studied to validate the new algorithm. The experimental results indicate that the standard deviation of this algorithm at C-band and Ku-band is 1.99 and 2.75 m/s respectively, which is better than the existing algorithms. In addition, the C-band algorithm is more suitable for sea surface wind retrieval than Ku-band under tropical cyclone conditions.

Key words: altimeter; wind speed, rain effect; tropical cyclone

Citation: Qin Bangyong, Zhou Xuan, Zhang Honglei, Yang Xiaofeng, Lu Rong, Yu Yang, Shi Lijian. 2014. An improved wind speed algorithm for "Jason-1" altimeter under tropical cyclone conditions. Acta Oceanologica Sinica, 33(7): 83–88, doi: 10.1007/s13131-014-0500-z

1 Introduction

Tropical cyclones are amongst the most powerful and destructive meteorological systems on earth, which seriously threaten marine activities, human life and property. Satellite-based observations are crucial to understand tropical cyclones, forecast its track and intensity, and reduce its damage. The radar altimeter is an important tool of satellite monitoring tropical cyclones because it can provide simultaneously high resolution measurements of sea surface wind speed and wave characteristics, unlike other microwave sensors, for example, a scatterometer, which only retrieves the sea surface wind field. Although a radar altimeter measurement is limited to its nadir observation, there are presently four altimeters (HY-2A, "Jason-1", "Jason-2" and Cryosat) in orbit which greatly improves the spatial and temporal coverage.

The measurement of sea surface wind with a radar altimeter is based on the specular reflection of electromagnetic waves. The radar altimeter NRCS is determined by the sea surface roughness: the rougher the sea surface, the lower the expected NRCS (Zhao and Toba, 2003). The radar altimeter wind retrieval algorithms, which fall into two categories, empirical and analytical, are proposed by establishing the quantitative relationship between the NRCS and the sea surface wind. The most well-known empirical algorithms are Brown (Brown et al., 1981), CM (Chelton and McCabe, 1985), CW (Chelton and Wentz, 1986), MCW (Witter and Chelton, 1991), LB (Lefevre et al., 1994) and Gourrion (Gourrion et al., 2002), which are derived from the coincident scatterometer, the in situ measurement, or the numerical weather prediction data. However, their wind observation data are approximately below 20 m/s so the accuracy of these empirical algorithms decreases rapidly under high wind speed conditions. The analytical algorithms, e.g., ZT (Zhao and Toba, 2003), retrieve the wind speed by the mean square slopes of sea surface, which are calculated by integrating the wind-wave spectrums (Cheng et al., 2008). In fact, the derivation of these spectrums is based on the in situ data of middle-low sea states. Owing to the limitation of in situ data, these analytical algorithms can not be applied to high sea states conditions.

In general, it is difficult to capture the in situ sea surface wind of tropical cyclones for their destructive power. Fortunately, the sea surface wind can be estimated by entering the known parameters, such as central position, intensity and the radius of maximum wind, into tropical cyclone models. As such, some researchers proposed the altimeter wind speed algorithms at high wind speeds by comparing the NRCS with sea surface wind speed, which is generated by the tropical cyclone model. For instance, Young (1993) used the Holland tropical cyclone model to develop the Geosat altimeter wind speed algorithm at high wind speeds. But rain effects on the Geosat altimeter NRCS are not corrected in the derivation of Young's algorithm, which is an

Foundation item: The National Natural Science Foundation of China under Nos 41201350 and 41228007; the International Scientific and Technological Cooperation Projects of State Oceanic Adminstration under contact No. 2011DFA22260; the Knowledge Innovation Program of the Chinese Academy of Sciences under contact No. Y0S04300KB.
*Corresponding author, E-mail: zhouxuan@radi.ac.cn

important source of error. Although the Holland(1980) model is the ideal tropical cyclone wind speed distribution model, it may still introduce errors. Gu et al. (2011) used Yin's (2007) tropical cyclone model to propose a new wind retrieval algorithm for "Jason-1" at high wind speeds. Likewise,the rain effects and the low accuracy of wind speed estimates from the ideal tropical cyclone model are the two main sources of errors.

Heavy rain and strong wind are two important characteristics of tropical cyclones. In order to improve the altimeter wind retrieval algorithm under tropical cyclone conditions, we implement the following two processes when establishing the match-up dataset in Section 2: First, CMORPH precipitation data are introduced for correcting rain effects; Second, sea surface wind from tropical cyclone models is replaced by HRD wind, which integrates all available surface weather observations and has higher accuracy. Section 3 corrects rain effects on "Jason-1" NRCS by introducing the CMORPH rain rate into the rain correction model. An improved algorithm at high wind speeds is proposed by using the match-up dataset in Section 4. Section 5 validates the "Jason-1" wind retrieval algorithm under tropical cyclone conditions. Finally, conclusions are given in Section 6.

2 Match-up dataset

In order to derive an improved "Jason-1" wind retrieval algorithm at high wind speeds, we use "Jason-1" NRCS, the CMORPH precipitation data and the HRD wind data to establish a match-up dataset. Note that the CMORPH precipitation data is used to correct rain effects on the "Jason-1" NRCS. Here, we briefly describe data source and matching method used in this study.

2.1 *Data source*

"Jason-1" is one of the main radar altimeters in orbit and has been operating for more than ten years, which operates at C (5.3 GHz)/Ku (13.575 GHz) band and can measure the nadir NRCS of the sea surface. Its orbit repeats with a period of approximately 10 days and covers 90% of the global ocean is covered. In this study, the NRCS at C/Ku-band comes from the "b" version of the "Jason-1" geophysical data records, which is produced and distributed by the NASA Jet Propulsion Laboratory.

CMORPH produces global precipitation analyses at a very high spatial and temporal resolution. This technique uses the motion vectors derived from a half-hourly interval geostationary satellite IR imagery to propagate the relatively high quality precipitation estimates derived from passive microwave data (Joyce et al., 2004). The global three hourly CMORPH rain rate data with 0.25 degree is used to correct rain effects on the "Jason-1" NRCS in this study.

The HRD wind data is produced by the HRD real-time wind analysis system which assimilates disparate observations relative to the centre of tropical cyclone, such as reconnaissance aircraft, ships, buoys, ocean stations and satellite (Powell et al., 1998). After quality control, these observed data are processed to conform to a common framework for exposure (marine or open terrain over land), height (10 m) and averaging time (maximum sustained 1 min wind speed). For ensuring sufficient proportion of high wind speed data to derive and validate the new algorithm, we choose maximum wind speeds of tropical cyclones higher than 40 m/s in the HRD data to establish the match-up dataset.

2.2 *Matching method*

From the "Jason-1" NRCS, the CMORPH rain rate and the HRD wind speed, a temporal and spatial match-up dataset will be generated to derive an improved "Jason-1" wind retrieval algorithm at high winds. First, we include all "Jason-1" data that pass the same area within 90 min of HRD data time. In fact, tropical cyclone locations will change significantly in 90 min, which introduces errors. For eliminating match-up errors, GOES or FY-2 geostationary satellite images are used to estimate the center positions of tropical cyclones and then to calculate motion vectors (Fore et al., 2010) which are used to correct the location of HRD wind speed.

Figure 1 shows names, tracks, maximum wind speeds of tropical cyclone meeting the above conditions, and "Jason-1" passing time, corresponding tropical cyclone centre. The blue "×" represent the tropical cyclone centre at "Jason-1" passing time. Tropical cyclones meeting the conditions include Megi and Jangmi over the northwest Pacific and Isabel, Bill, Igor, Karl,

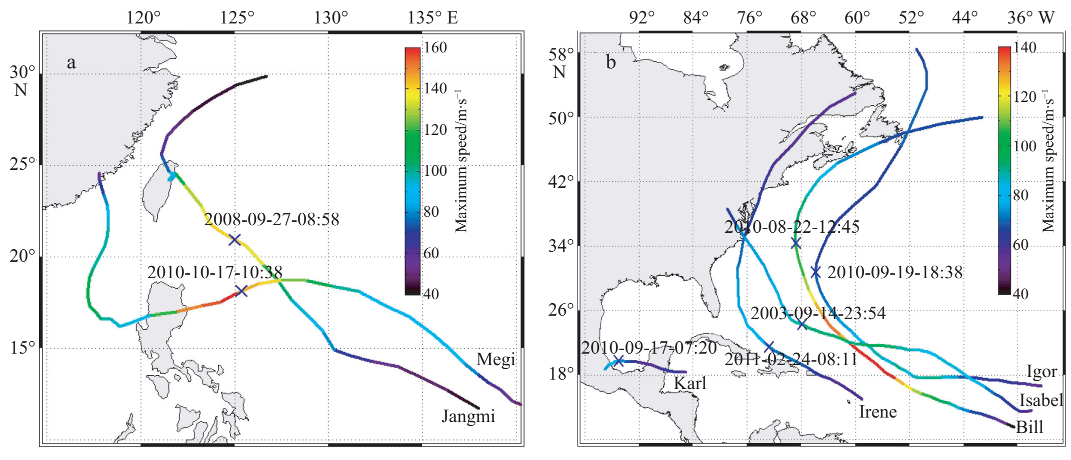

Fig.1. Names, tracks, maximum wind speeds of tropical cyclone meeting the conditions, and "Jason-1" passing time, corresponding tropical cyclone centre over the northwest Pacific (a) and the Atlantic (b)

Irene over the Atlantic. Hurricane Irene is used for validation and the other tropical cyclones are used to derive an improved "Jason-1" wind retrieval algorithm at high winds.

3 Rain corrections

Rain is one of the main sources of error in the existing algorithms. Before deriving a new algorithm, we carry out the rain correction to ensure the accuracy of the algorithm. Rain effects on the "Jason-1" NRCS include three aspects: the attenuation of altimeter signals, the volume backscattering and the sea surface perturbation by raindrops. The wind-induced surface backscatter (Zhou et al., 2013) is

$$\sigma_{\rm w}=\alpha_{\rm r}\sigma_0-\sigma_{\rm r}, \tag{1}$$

where $\sigma_{\rm w}$ is the wind-induced surface backscatter; σ_0 is the NRCS of "Jason-1" measurement; $\alpha_{\rm r}$ is the attenuation of altimeter signals by raindrops and $\sigma_{\rm r}$ is the volume backscattering and the sea surface perturbation by raindrops.

The relation between $\alpha_{\rm r}$ and the rain rate R is

$$\alpha_{\rm r}=\sum_{n=0}^{n=3}p_nR^n, \tag{2}$$

where p_n is the coefficient (see Table 1 for details).

The relation between $\sigma_{\rm r}$ and the rain rate R is

$$\sigma_{\rm r}=\sum_{n=0}^{n=3}q_nR^n , \tag{3}$$

where q_n is the coefficient (see Table 2 for details).

We correct rain effects on the "Jason-1" NRCS by inputting the CMORPH rain rate into Eq. (2). Figure 2 shows the relation between high wind speeds and the dual-frequency altimeter "Jason-1" NRCS after rain correction. The wind speed range is 15–60 m/s and the match-up dataset contains 607 data. There is a good correlation between the wind speed and the NRCS at C-band. However, at Ku-band, the distribution of data is relatively dispersive because the shorter wavelength is more responsive to raindrop or whitecap. It should be noted that most of match-up dataset are concentrated within the15–36 m/s range. Hence we will derive an improved "Jason-1" wind retrieval algorithm at high speeds by using this range of data in the following sectors.

Table 1. The fitting coefficients of $\alpha_{\rm r}$ and rain rate for Eq. (2)

Band	p_0	p_1	p_2	p_3
C	1.00	8.98×10^{-4}	2.38×10^{-4}	2.32×10^{-5}
Ku	1.05	9.90×10^{-3}	4.16×10^{-3}	5.40×10^{-4}

Table 2. The fitting coefficients of $\sigma_{\rm r}$ and rain rate for Eq. (3)

Band	q_0	q_1	q_2	q_3
C	0.945	−0.249	-6.68×10^{-2}	-5.38×10^{-3}
Ku	0.819	0.287	0.275	-1.68×10^{-2}

4 Wind retrieval algorithm

After rain correction, the relationship between the "Jason-1" NRCS and the wind speed can be derived from the match-up dataset. However, tropical cyclones often bring heavy rains. In this section, we will remove rain effects by using the Ku/C rain-free relationship and propose a flow of "Jason-1" wind retrieval under tropical cyclone conditions.

4.1 *The relationship between "Jason-1" NRCS and wind speed*

Figure 3 shows the "Jason-1" NRCS at C/Ku-band varying with the HRD wind speed under no-rain conditions. The number of match-up dataset is 569. The "Jason-1" NRCS at C/Ku-band decreases slowly with the increase of HRD wind speed. We use a second-order polynomial to fit their relationship by the least squares method.

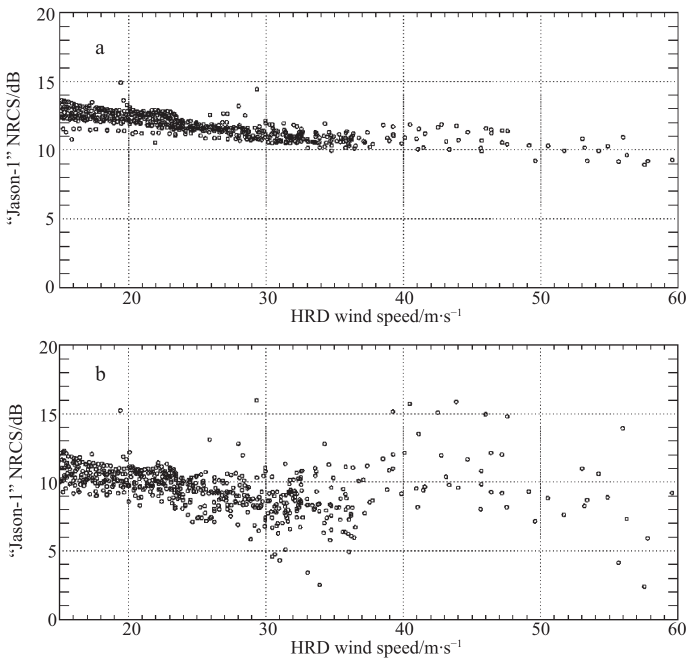

Fig.2. Scatter plot of "Jason-1" NRCS at C-band (a) and Ku-band (b) versus HRD wind speed.

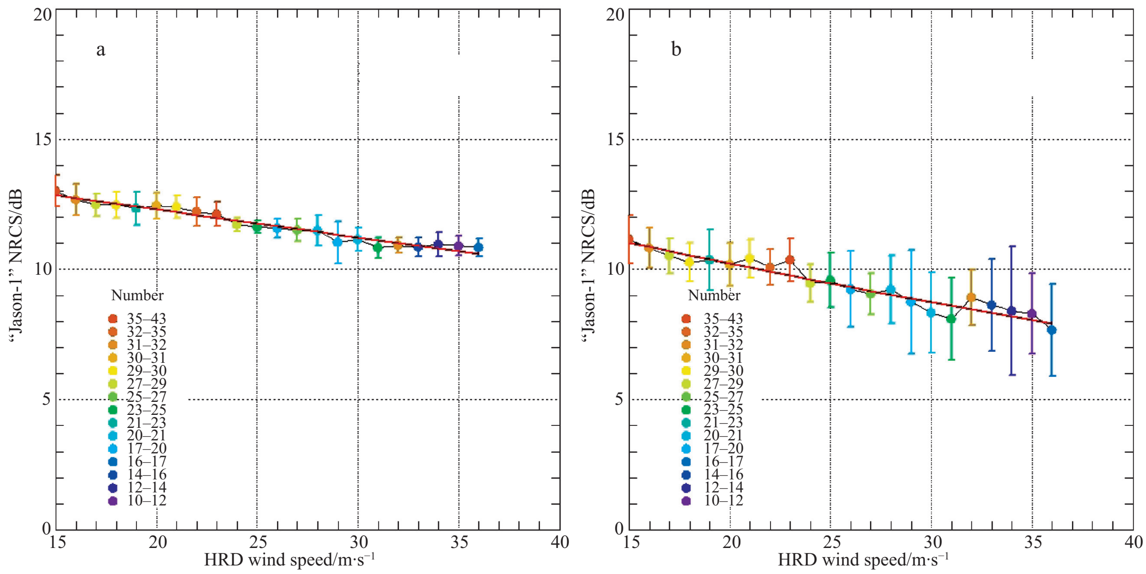

Fig.3. "Jason-1" NRCS at C-band (a) and Ku-band (b) verse HRD wind speed. Wind speed has been binned using a bin interval equal to 1 m/s. Color of the error bars symbolizes the amount of datasets and their length's standard deviations. The solid circle in the middle of the error bars represents the mean. The red solid line represents a second-order polynomial fit as a function of HRD wind speed.

At C-band,

$$\sigma_C = \sum_{n=0}^{n=2} p_n U_{10}^n \,, \tag{4}$$

where σ_c is the "Jason-1" NRCS at C-band and U_{10} is the 10 m wind speed over the sea surface; p_n is the fitted coefficient, where p_0=14.5, p_1=–0.11 and p_2=4.92×10^{-5}.

At Ku-band,

$$\sigma_{Ku} = \sum_{n=0}^{n=2} q_n U_{10}^n \,, \tag{5}$$

where σ_{Ku} is the "Jason-1" NRCS at Ku-band and q_n is the fitted coefficient; where q_0=13.7, q_1=–0.191 and q_2=8.56×10^{-4}.

4.2 *Wind speed retrieval under tropical cyclone conditions*

Equations (4) and (5) provide the relationship between the "Jason-1" C/Ku-band NRCS and the 10 m sea surface wind speed over the sea surface at high wind speeds under no-rain conditions. But in general, tropical cyclones are often accompanied by heavy rains. Therefore, the "Jason-1" NRCS should be corrected for rain before wind speed retrieval. The microwave radiometer on "Jason-1" operates at three frequencies (18.7, 23.8 and 34.0 GHz) and can measure water vapor content but the rain rate in the atmosphere. Consequently, we correct rain effects by using the Ku/C rain-free relationship at high wind speeds, which is derived from Eqs (4) and (5).

$$\sigma_C - \sigma_{Ku} = \sum_{n=0}^{n=2} s_n U_{10}^n \,, \tag{6}$$

where s_0=8.00×10^{-2}, s_1=8.10×10^{-2} and s_2=–8.07×10^{-4}.

Figure 4 shows the flowchart of the "Jason-1" wind retrieval

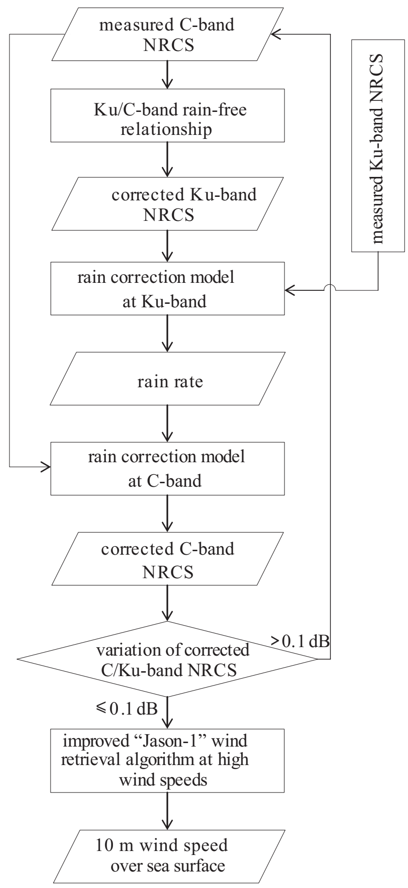

Fig.4. Flowchart of "Jason-1" wind retrieval algorithm under tropical cyclone conditions

algorithm under tropical cyclone conditions. The expected Ku-band NRCS is derived from the 10 m wind speed over the sea surface of C-band algorithm and the Ku/C rain-free relationship at high wind speeds using Eqs (4) and (6). A rain rate estimate is then deduced by putting the measured and expected Ku-band NRCS into Eq. (1). Although rain effects on C-band NRCS are smaller than on Ku-band NRCS, it can not be ignored (Yang et al., 2008). Thus the corrected C-band NRCS is obtained by putting a rain rate estimate into Eq. (1). The process is iterated until the corrected NRCS reaches stable values within 0.1 dB (Quilfen et al., 2006).

5 Validations

The improved "Jason-1" wind retrieval algorithm under tropical cyclone conditions is validated by the 2011 Atlantic Hurricane Irene. Figure 5 shows HRD wind speed and "Jason-1" ground track across Hurricane Irene.

Our algorithm, Gu's algorithm (Gu et al., 2011) and Gourrion's algorithm (the "Jason-1" operational algorithm) (Gourrion et al., 2002) are used respectively to retrieve the sea surface wind under tropical cyclone conditions. Figure 6 shows the HRD wind

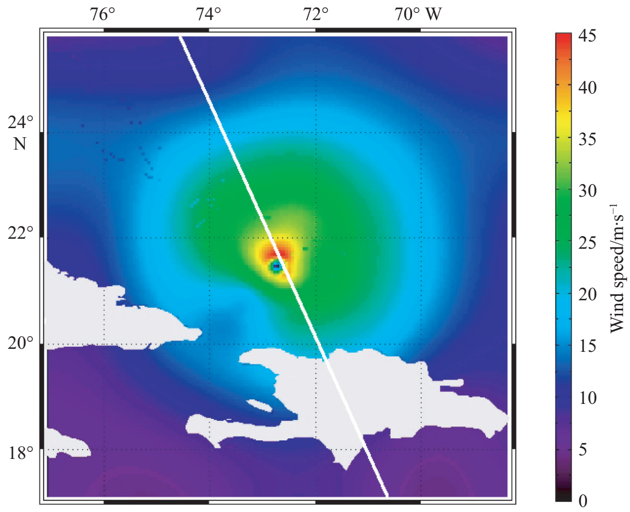

Fig.5. The HRD wind speeds and "Jason-1" ground tracks across Hurricane Irene. The white solid line represents "Jason-1" ground track

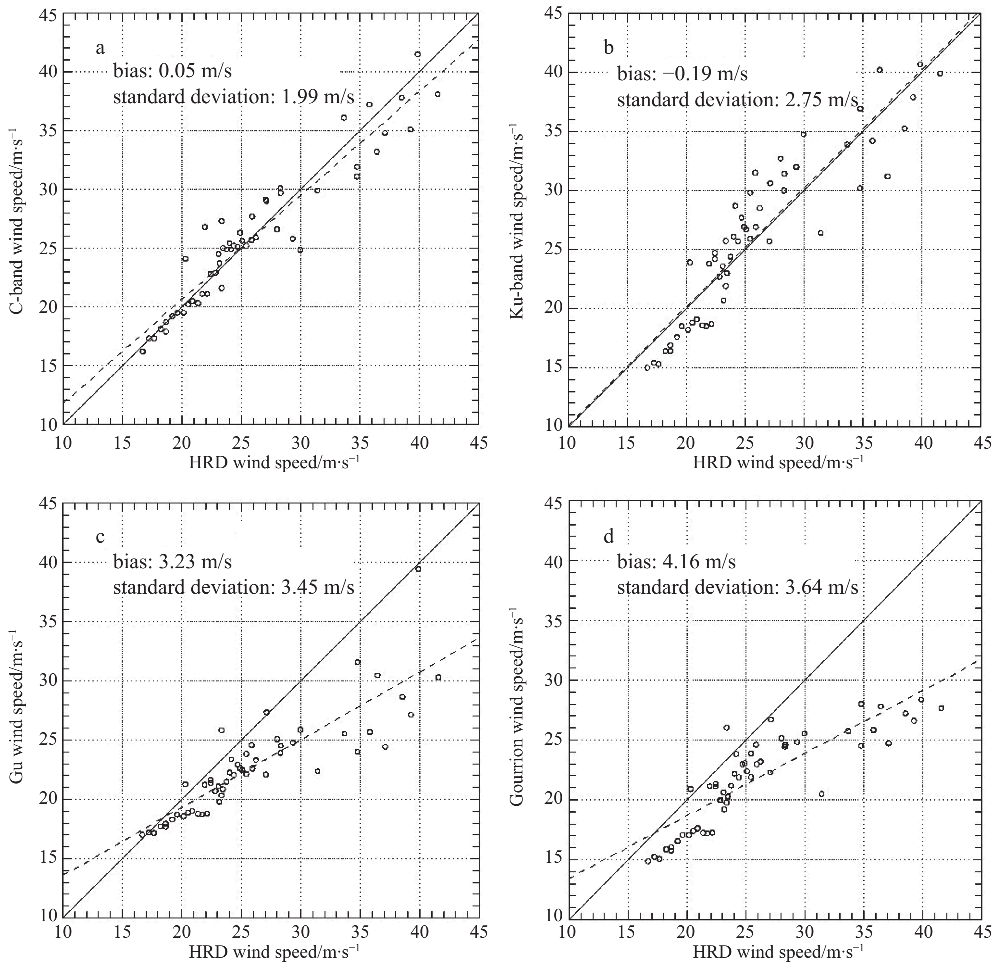

Fig.6. The improved "Jason-1" wind retrieval algorithm at C-band (a) and Ku-band (b), Gourrion's algorithm(c) and Gu's algorithm (d) versus HRD wind speed. The dashed line represents a linear fit as a function of HRD wind speed.

speed versus wind speed retrieved by different algorithms at high wind speeds (>15 m/s). The number of match-up dataset is 54. The standard deviation (STD) and bias of the HRD wind speed minus the C-band wind speed, which is estimated from the improved "Jason-1" wind retrieval algorithm at C-band, are 1.99 and 0.05 m/s in Fig. 6a.Because of the shorter wavelength, Ku-band is much more affected by raindrop or whitecap under tropical cyclone conditions. As shown in Fig. 6b, the STD and bias at Ku-band are 2.75 and –0.19 m/s, respectively, and the accuracy of the improved "Jason-1" wind retrieval algorithm at Ku-band is lower than at C-band.

Figure 6c shows that the STD and bias of Gu's algorithm are 3.45 and 3.23 m/s, respectively, and its accuracy is clearly lower than our algorithm's at either the C-band or Ku-band. The rain effects and tropical cyclone model errors may be the cause. Gourrion's algorithm is suitable for middle-low sea states and there is a larger error than with other algorithms. As shown in Fig. 6d, the STD and bias of Gourrion's algorithm are 4.16 and 3.64 m/s, which are greater than the values obtained with our algorithm and Gu's algorithm.

The above comparison and analysis show that the accuracy of the improved "Jason-1" wind retrieval algorithm under tropical cyclone conditions is better than Gu's algorithm and Gourrion's algorithm. It is noted that our algorithm at C-band is more suitable for the sea surface wind retrieval than Ku-band under tropical cyclone conditions because C-band has a lower sensitivity to raindrop or whitecap.

6 Conclusions

Due to its destructive power, the in situ wind of tropical cyclones is difficult to obtain. Thus the wind speeds of tropical cyclone models are frequently used to substitute for the in situ data and compared with the altimeter NRCS to develop the altimeter wind algorithms at high wind speeds. Tropical cyclone models will inevitably introduce errors. In addition, the existing algorithms do not consider the effects of rainfall in the derivation process, which also introduce errors.

To improve the accuracy of the "Jason-1" wind retrieval algorithm under tropical cyclone conditions, we firstly combine the HRD wind speed, which has a higher accuracy than the wind speeds of tropical cyclone models, CMORPH rain rate and "Jason-1" NRCS to establish a match-up dataset. Then we correct rain effects by using CMORPH rain rate and derive an improved wind retrieval algorithm for high wind speeds under no-rain conditions. However the tropical cyclones often bring heavy rain. Therefore, we use the Ku/C band rain-free relationship to remove rain effects and present a flow of "Jason-1" wind retrieval under tropical cyclone conditions. Finally, we carry out an experiment to validate the presented algorithm. The experimental results indicate that our algorithm significantly improves the accuracy of "Jason-1" wind retrieval under tropical cyclone conditions.

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