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The comparison of altimeter retrieval algorithms of the wind speed and the wave period

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Abstract
With the launch of altimeter, much effort has been made to develop algorithms on the wind speed and the wave period. By using a large data set of collocated altimeter and buoy measurements, the typical wind speed and wave period algorithms are validated. Based on theoretical argument and the concept of wave age, a semi-empirical algorithm for the wave period is also proposed, which has the wave-period dimension, and explicitly demonstrates the relationships between the wave period and the other variables. It is found that Ku and C band data should be applied simultaneously in order to improve either wind speed or wave period algorithms. The dual-band algorithms proposed by Chen et al. (2002) for the wind speed and Quilfen et al. (2004) for the wave period perform best in terms of a root mean square error in the practical applications.

Key words: altimeter, wind speed, wave period, wave age, significant wave height

1 Introduction

Ocean wave is an important phenomena occurring over the ocean. It not only could lead to a lot of serious natural disasters, but also plays a key role in the air-sea exchange processes and climate change. A global measurement of ocean wave parameters is very important for ocean engineering and wave climate studies. Satellite altimeters provide global data on an ocean mean sea level, a significant wave height (SWH, H_s) and a normalized radar cross-section (RCS, σ_0) at Ku and C bands, respectively. The measurement of H_s by satellite altimeters is well established and widely accepted to be of comparable accuracy to those of in situ measurements. Thus the σ_0 at Ku and C bands as well as H_s are routinely used in the altimeter algorithms of the wind speed (U_{10}) and the wave period (T_z).

2 Brief review of wind speed and wave period algorithms

Radar altimeters receive a complex stochastic signal due to the reflection of the transmitted pulse over a 5 km radius footprint. RCS can thus be considered as a function of the statistic moment of the sea surface elevations and slopes. The most pertinent parameter of this function is the mean square slope. The short-scale slopes associated with capillary waves are mainly a function of the local wind, and large-scale slopes are mainly associated with the surface gravity waves. The smoother the sea surface is, the greater RCS will be obtained. The wind speed is traditionally supposed to be the dominant factor to control the roughness of sea surface, thus it can be derived by the correlation with the RCS. In application, however, researchers usually correlate the RCS with the wind speed directly due to the difficulty of quantitatively estimating the sea surface roughness. The common approach is to compare the RCS with the coincident observations of wind speeds from buoys, scatterometers, or numerical models (Ebuchi et al., 1992; Young, 1993; Glazman and Greysukh, 1993; Lefevre et al., 1994). A review about the algorithms that use only the Ku band σ_0 is found in Chelton et al. (2001). Before the 1990s, the effect of large-scale slopes had been neglected, and the wind speed algorithms are mostly single parameter, e.g., σ_0 at Ku band ($\sigma_{0\mathrm{Ku}}$), based (Brown, 1979; Brown et al., 1981; Chelton and McCabe, 1985; Chelton and Wentz, 1986; Witter and Chelton, 1991). By use of the coincident data of scatterometer and altimeter, Chelton

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and McCabe (1985) proposed an algorithm as a function of $\sigma_{0\mathrm{Ku}}$ (dB)

$$U_{10} = 0.943 \times 10^{(1.502-\sigma_0/10)/0.468}. \quad (1)$$

The operation algorithm for TOPEX is derived from interpolation over the look up table known as the modified Chelton-Wentz algorithm of Witter and Chelton (1991). This model directly maps $\sigma_{0\mathrm{Ku}}$ to the wind speed U_{10} in table form. The drawback for this algorithm is that it is invalid when the wind speed is greater than 20 m/s.

A goal that remains of interest for altimeter wind retrieval is the detection and correction of wind speed errors associated with longer ocean waves that are not necessarily closely coupled to the local wind field. An improvement is to consider the RCS as a function of the wind speed and a new parameter which characterizes the sea state. It has been emphasized that the influence of the sea state on radar measurements in relation to the development degree of the wind waves. The sea state can be estimated through the pseudo-wave age parameter which is a function of the wind speed and the SWH (Glazman and Pilorz, 1990; Glazman and Greysukh, 1993). Thus a number of investigators have introduced the SWH or the RCS at C band ($\sigma_{0\mathrm{C}}$) as the second parameter in their algorithms (Lefevre et al., 1994; Gourrion et al., 2002; Chen et al., 2002). An algorithm proposed by Lefevre et al. (1994) depends on both RCS and SWH at Ku band, which can be expressed as

$$U_{10} = a_{00} + a_{10}h + a_{01}\sigma + a_{11}h\sigma + a_{20}h^2 + a_{02}\sigma^2, \quad (2)$$

where $\sigma = (2\sigma_0 - 25)/15, h = (2H_\mathrm{s} - 12.5)/11.5$ are the normalized RCS and SWH, respectively, and σ_0 is the RCS in decibels, H_s is the SWH (m). The coefficients in the algorithm are listed below

$$a_{00} = 5.383, a_{10} = -0.530, a_{01} = -12.877,$$
$$a_{11} = -5.970, a_{20} = -2.350, a_{02} = 8.023. \quad (3)$$

Instead of the SWH, Chen et al. (2002) chose $\sigma_{0\mathrm{C}}$, the RCS at C band, as the second parameter, and proposed an algorithm expressed as a set of $\sigma_{0\mathrm{C}}$ dependent linear relations between U_{10} and $\sigma_{0\mathrm{Ku}}$, which can be described as

$$U_{10} = a_i\sigma_{0\mathrm{ku}} + b_i \quad (i = 1, 2, 3, \ldots, 10), \quad (4)$$

where the coefficients a_i and b_i are related to $\sigma_{0\mathrm{C}}$ shown in their Table 3 (Chen et al., 2002).

Zhao and Toba (2003) derived an analytical relationship between the roughness of sea surface in terms of mean square slope and the RCS through a prescribed wave spectrum, in which the wave age is used to represent the wave contribution to the RCS. It can be expressed as

$$\sigma_0 = \frac{|R(0)|^2}{\alpha}\beta C_\mathrm{d}^{-\frac{1}{2}}\left\{2 + 1.5\left[\ln\frac{a + \sqrt{a^2 + 81g^2/(\beta U_{10})^4}}{9g/(\beta U_{10})^2} - \ln\frac{a + \sqrt{a^2 + k_\mathrm{d}^2}}{k_\mathrm{d}}\right]\right\}^{-1}, \quad (5)$$

where α is Toba's constant with a value between 6×10^{-2} and 12×10^{-2}; $a = \sqrt{g/\gamma} \approx 367.658$; g is the acceleration of gravity; γ is the acceleration of surface tension; C_d is the drag coefficient in which the formula of Wu (1980) is adopted; $\beta = 3.31(gH_\mathrm{s}/U_{10}^2)^{3/5}$ is a kind of pseudo-wave age indicating the development degree of wind waves, thus set $\beta = 1.2$ when it exceeds 1.2; $|R(0)|$ is the Fresnel reflection coefficient; and k_d is the cutoff wavenumber, both of them depend on the work frequency of Ku or C band. The wind speed is finally determined when the calculated σ_0 approaches to the measured σ_0. The advantage of this analytical algorithm is that it can be easily applied to both Ku and C band data by adjusting the cutoff wavenumber in the calculation of the mean square slope.

In order to describe the characteristics of ocean waves, the information of the wave period is needed in addition to the significant wave height. The sensitivity of altimeters to sea state offers an opportunity to retrieve wave period information (Glazman and Pilorz, 1990; Gommenginer et al., 2003). Since the pioneer work of Davies et al. (1997), several algorithms have been proposed relating altimeter H_s, U_{10} and σ_0 to the wave period (Hwang et al., 1998; Sarkar et al., 1998; Zhao and Ye, 2004; Kshatriya et al., 2005; Mackay et al., 2008). Compared with wind speed algorithms, however, the wave period algorithms still need a significant improvement.

Based on heuristic arguments, Gommenginer et al. (2003) postulated that the wave period is related to $(\sigma_0^{0.25}H_\mathrm{s}^{0.5})$, and obtained a linear relationship between them on the basis of buoy observations. Their algorithm is (denoted as G03)

$$T_\mathrm{z} = -0.895 + 2.545(\sigma_{0\mathrm{l}}H_\mathrm{s}^2)^{0.25}, \quad (6)$$

where $\sigma_{0\mathrm{l}}$ is the RCS at Ku band in its linear, non dB form.

By using a neural network to establish a relationship between altimeter H_s and σ_0 with buoy T_z, Quilfen et al. (2004) proposed two wave period algorithms. The first algorithm by Ku band data is (denoted as Q041)

$$T_\mathrm{z} = \exp(-17.1642a + 13.5844), \quad (7)$$

where $a = [1 + \exp(0.6573H_\mathrm{s}^{0.1084}\sigma_{0Ku}^{0.2962} - 2.2377)]^{-1}$. Their second algorithm by Ku and C bands data together is (denoted as Q042)

$$T_\mathrm{z} = \exp(5.7474 - 1.4688a + 1.7943b), \quad (8)$$

where $a = \dfrac{\sigma_{0\mathrm{Ku}}^{0.3082}}{\sigma_{0\mathrm{C}}^{0.2352}H_\mathrm{s}^{0.0981}}\mathrm{e}^{1.5068b}$; $b = 2/(1 + \mathrm{e}^{-1.8612-0.08U_{10}}) - 1$.

Kshatriya et al. (2005) proposed an empirical algorithm using the concept of wave age. Their algorithm is (denoted as K05)

$$T_\mathrm{z} = a + b\beta + cT_\mathrm{a} + d\beta T_\mathrm{a} + \mathrm{e}\beta^2 + fT_\mathrm{a}^2, \quad (9)$$

where a =–0.1130; b=0.6090; c=2.4369; d=–0.0045, e=–0.0487; f=–0.2270; and the wave age β and T_a are defined as $\beta=3.25\left(\dfrac{gH_\mathrm{s}}{U_{10}^2}\right)^{0.62}$, $T_\mathrm{a} = (\pi^2/g)^{1/2}[H_\mathrm{s}\sigma_0^{1/2}/|R(0)|]^{1/2}$.

Mackay et al. (2008) developed a two-piece altimeter wave period model for Ku-band. They showed that there is a threshold level around 13 dB above which σ_0 is no longer related to the wave period. Their algorithm is (denoted as M08)

$$T_\mathrm{z} = \begin{cases} \frac{1}{\lambda}\ln\left[\frac{1}{\tau}\left(\frac{\sigma_0-A}{H_\mathrm{s}+\gamma}\right)\right] & \text{if}\,\sigma_0 \leqslant \delta, \\ \frac{1}{\lambda}\ln\left[\frac{1}{\tau}\left(\frac{\delta-A}{H_\mathrm{s}+\delta}\right)\right] & \text{if}\,\sigma_0 > \delta. \end{cases} \quad (10)$$

For TOPEX, the coefficients stated above are A=17.11, τ=–4.504, λ=–0.1558, γ=1.658, δ=12.87.

In this paper, the wind speed and wave period algorithms are validated by using a large collocated data set of altimeter and buoy measurements. Combined the methods of Davies et al. (1997) and Hwang et al. (1998), a semi-empirical model of the wave period for both Ku and C bands is proposed using the concept of wave age. It is shown that the wind speed algorithm of Chen et al. (2002) and the wave period algorithm of Q042 perform best in practical applications in terms of the root mean square (RMS) error.

3 Collocated data set of altimeter and buoy measurements

In order to validate the algorithms, a data set of collocated buoys of the National Data Buoy Center and altimeter from 2001 to 2005 is established, in which altimeter parameters are extracted when the satellite footprint is within 50 km with the location of buoys, and the time difference between the satellite pass and buoy measurement is less than 1 h. A total of 3236 group data is obtained, which includes $\sigma_{0\mathrm{Ku}}$, $\sigma_{0\mathrm{C}}$, H_s from Ku and C bands, T_z and H_s from buoys. The comparisons of H_s from buoys and altimeter at Ku and C bands data are presented in Fig. 1.

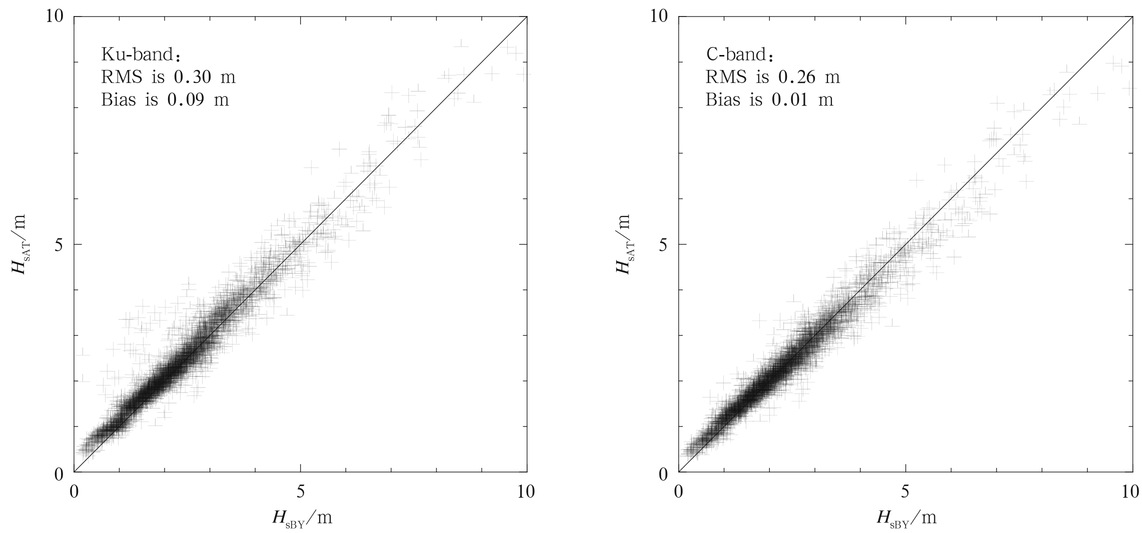

Fig.1. Comparisons of H_s from buoy with altimeter at Ku band (left) and C band (right), where BY and AT are the abbreviations of buoy and altimeter, respectively.

It can be seen that the SWH from the buoy and the altimeter is generally consistent each other in a large range of the SWH up to 10 m. With a close inspection, the SWH at C band is more approached to the in situ measurements than that of Ku band: 0.3 m (Ku) versus C band 0.26 m in terms of the RMS, and 0.09 m (Ku) versus C band 0.01 m in terms of bias. From this point of view, the H_s at C band is more suitable to be used in retrieval algorithms and wave climate studies.

4 Validation of wind speed algorithms

As mentioned above, many wind speed algorithms have been proposed up to date. Here we choose five typical algorithms in our validation. The first is the single-parameter algorithm proposed by Chleton and McCabe (1985). The second is the two-parameter empirical algorithm by Chen et al. (2002), which is regarded as the most accurate due to its consideration of σ_{0C} at the same time. The third is the single-parameter algorithm by Witter and Chelton (1991), which has been applied for operational use in all current altimeter missions. The fourth is two-parameter algorithm that is a function of σ_{0Ku} and SWH proposed by Lefevre et al. (1994). The fifth is the analytical algorithm by Zhao and Toba (2003) that can be applied by either Ku or C band data. The dual-frequency TOPEX altimeter operated at Ku and C bands, which correspond to 13.6 GHz and 5.3 GHz, respectively. It means that only the microstructure of sea surface more than 2.2 cm and 5.7 cm can be detected by the altimeter. Therefore, the cutoff wavenumbers for Ku and C bands are chosen as 284 rad/m and 111 rad/m in the algorithm of Zhao and Toba (2003). The above five algorithms are hereafter referred as C85, C02, W91, L94 and Z03, respectively. Owing to the frequency of Ku band greater than that of C band, the sea surface is supposed to be rougher for the former. As a result, σ_{0Ku} is systematically smaller than σ_{0C}. Therefore, we take $|R(0)|^2$ as 0.31 at Ku band and 0.61 at C band in Z03.

Following the common practice, the mean bias and RMS error of TOPEX and buoy winds are presented in Table 1, and the scatter diagrams of C02 and Z03 are shown in Fig. 2. It is evident from Table 1 that C02 and Z03 are significantly improved compared with W91, L94 and C85. Although C02 performs best in terms of the RMS, with a close inspection, it can be seen in Fig. 2 that it sometimes gives negative values at low wind speeds. The Z03 by C band data performs better than Ku bnad data. The result denoted by Ku plus C by Z03 is the average value of Ku and C bands, which is a little better than both of them solely. It is shown that the C band data are very important to be considered in the wind speed algorithms although it has been usually excluded in the previous studies.

Figure 3 shows the possibility distribution functions (PDF) of wind speeds obtained from the buoy measurement, as well as the altimeter estimates by C02 and Z03 from Ku and Ku plus C bands. It can be seen that the Z03 by Ku plus C band produces a PDF which is the most like the sea truth. The C02 agrees well with buoy at the wind speed less than 5 m/s, but at the high wind speed a considerable departure from buoy can be found.

5 A wave period algorithms using the concept of wave age

The wave age is very useful in the study of wind waves. Thus it is also supposed to be very important in the derivation of wave period from the altimeter (Davies et al., 1997). The empirical algorithm using the concept of wave age proposed by Kshatriya et al.(2005, hereafter referred as K05) is the latest of this kind, which is expressed as a polynomial of wave age. We have checked the K05 with our data set, and found that it produces negative values in the case of low wind speeds and large significant wave heights, which correspond to the large wave ages and wave periods. Thus it cannot be applied to our validation. It is also noted that the wave period is up to 13 s in our data set, but generally less than 8 s in the calculation of K05. Therefore, we try to derive an algorithm using the concept of wave age that can be applied to the

Table 1. Summary of comparison statistics of the Z03, C02, L94, W91 and C85 altimeter wind speed algorithms

Band	kd/rad·m^{-1}	$\|R(0)\|^2$	RMS/m·s^{-1}					Bias/m·s^{-1}				
			Z03	C02	L94	W91	C85	Z03	C02	L94	W91	C85
Ku	284	0.31	1.61	—	2.41	2.45	2.42	0.14	—	1.53	2.02	1.50
C	111	0.61	1.51	—	—	—		0.00	—	—	—	—
Ku plus C			1.50	1.46	—	—	—	0.07	0.48	—	—	—

Note: — denotes that the algorithm is not applicable.

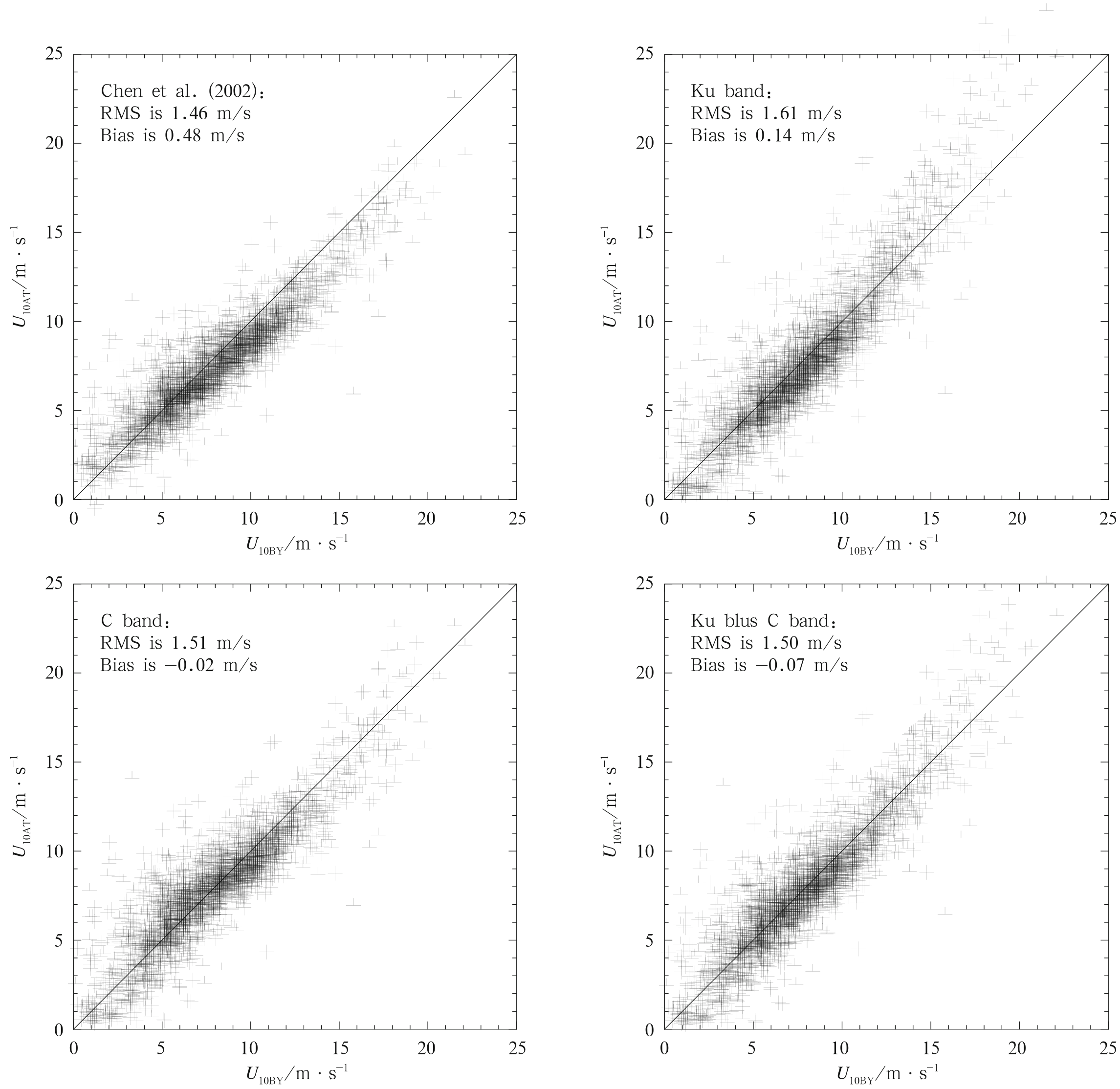

Fig.2. Scatter diagrams of TOPEX versus buoy wind speeds. The C02 and Z03 by Ku, C and Ku plus C bands data are applied form deriving TOPEX wind speed. A perfect line is also overlaid on each subplot.

general conditions.

According to the geometrical optics theory, the reflection of radar signal by the ocean surface at small incidence is supposed to be proportional to the PDF of surface wave slopes. If the sea surface is further assumed to be a random, Gaussian surface, then the RCS is related to the mean square slope (MSS) of the sea surface that can be written as

$$\sigma_0 = |R(0)|^2/s^2, \tag{11}$$

where s^2 is the MSS of the sea surface; and $|R(0)|$ is the Fresnel reflection coefficient for the normal incidence. On the other hand, MSS can be directly calculated by spectral moment of ocean wave spectra (Phillips, 1977),

$$s^2 = \frac{(2\pi)^4}{g^2} m_4, \tag{12}$$

where $m_n = \int f^n S(f) \mathrm{d}f$, is the nth spectral moment of frequency spectrum S(f) of wind waves, f is the frequency; and m_4 is the 4th spectral moment. The 0th spectral moment of wind wave m_0 is related to the SWH by

$$m_0 = H_{\mathrm{s}}^2/16. \tag{13}$$

Thus spectral moment m_0 and m_4 can be estimated directly by altimeter SWH and RCS data.

Two currently used wave periods are the crest-to-crest period T_{c} and the zero-upcrossing period T_{z},

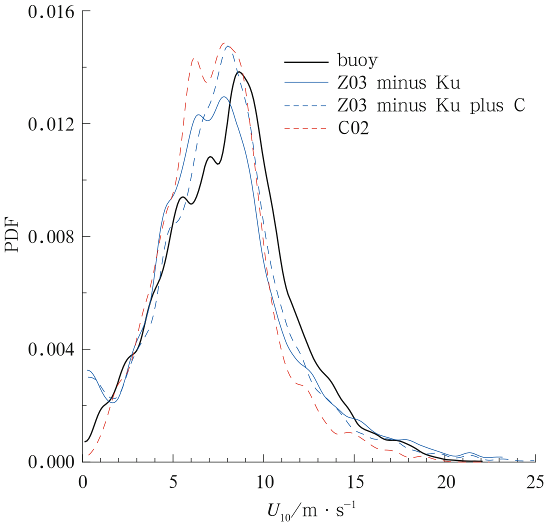

Fig.3. Possibility distribution functions of wind speeds by buoy, C02 and Z03 from Ku and Ku plus C bands.

which are defined by the spectral moments as

$$\left.\begin{array}{l} T_c = (m_2/m_4)^{1/2} \\ T_z = (m_0/m_2)^{1/2} \end{array}\right\}. \tag{14}$$

In general, only T_z is a standard output of the buoy, and T_c is usually used in the theoretical study. In order to compare with buoy observations, T_z is traditionally adopted in the retrieval of wave period from altimeter data. It can be written as a function of T_c

$$T_z = (m_0/m_2)^{1/2} = \left(\frac{m_0}{m_4}\right)^{1/2}\left(\frac{m_4}{m_2}\right)^{1/2} = (m_0/m_4)^{1/2}T_c^{-1}. \tag{15}$$

Substituted Eqs (11), (12) and (13), Eq.(15) can be expressed as

$$T_z = \frac{(2\pi)^2 H_s \sigma_0^{1/2}}{4g|R(0)|}T_c^{-1}. \tag{16}$$

The question now becomes how to determine T_c by altimeter data. Wave age β is a dimensionless parameter which is defined as the ratio between the phase speed of wind wave at the peak of the spectrum $gT_p/2\pi$ and the wind speed U_{10}, where T_p is the peak wave period that is widely used in wind-wave studies. Because the altimeter does not measure the wave spectrum, it is necessary to relate wave age β with H_s and U_{10} through wind wave growth relationships (Hwang et al., 1998). Many relationships have been developed based on in situ wave measurements. The relationship proposed by Zhao and Toba (2003) is adopted in this study. It can be written as

$$\beta = \frac{gT_p}{2\pi U_{10}} = 3.31\left(\frac{gH_s}{U_{10}^2}\right)^{0.6}. \tag{17}$$

Thus T_p can be determined by altimeter data, in which U_{10} is supposed to be known through wind speed algorithms mentioned above. It is reasonable to assume that $T_p = \alpha T_c$, where α is a constant that will be specified by collocated altimeter and buoy observational data. Substituted Eq.(17) into Eq.(16), T_z can be expressed as

$$T_z = \alpha\frac{\pi H_s \sigma_0^{1/2}}{2|R(0)|U_{10}\beta}. \tag{18}$$

Unlike the previous algorithms, Eq.(18) has the dimension of wave period. It is clearly shown the relationships of wave period with SWH, RCS, wind speed, and wave age.

6 Validation of the wave-period algorithms

Substituted the Fresnel coefficient $|R(0)|$ for Ku and C bands specified above (Table 1) into Eq.(18), the corresponding α can be determined as 3.83 and 3.65, respectively, when the RMS of wave period reaches its minimum based on the collocated altimeter and buoy data set.

The results of RMS and bias for the wave period calculated by this new algorithm and those of G03, Q041, Q042 and M08 are summarized in Table 2, and the scatter diagrams are presented in Fig. 4. The algorithm using the concept of wave age by Kshatriya

Table 2. Summary of RMS and bias of wave period algorithms of this study (Z11), M08, Q041,Q042 and G03

Band	α	RMS/s					Bias/s				
		Z11	M08	Q041	Q042	G03	Z11	M08	Q041	Q042	G03
Ku	3.83	0.91	0.72	1.24	—	0.91	0.01	−0.34	−0.35	—	−0.19
C	3.65	0.90	—	—	—	–	0.02	—	—	—	—
Ku plus C		0.89	—	—	0.64	—	0.01	—	—	0.03	—

Note: — denotes that the algorithm is not applicable.

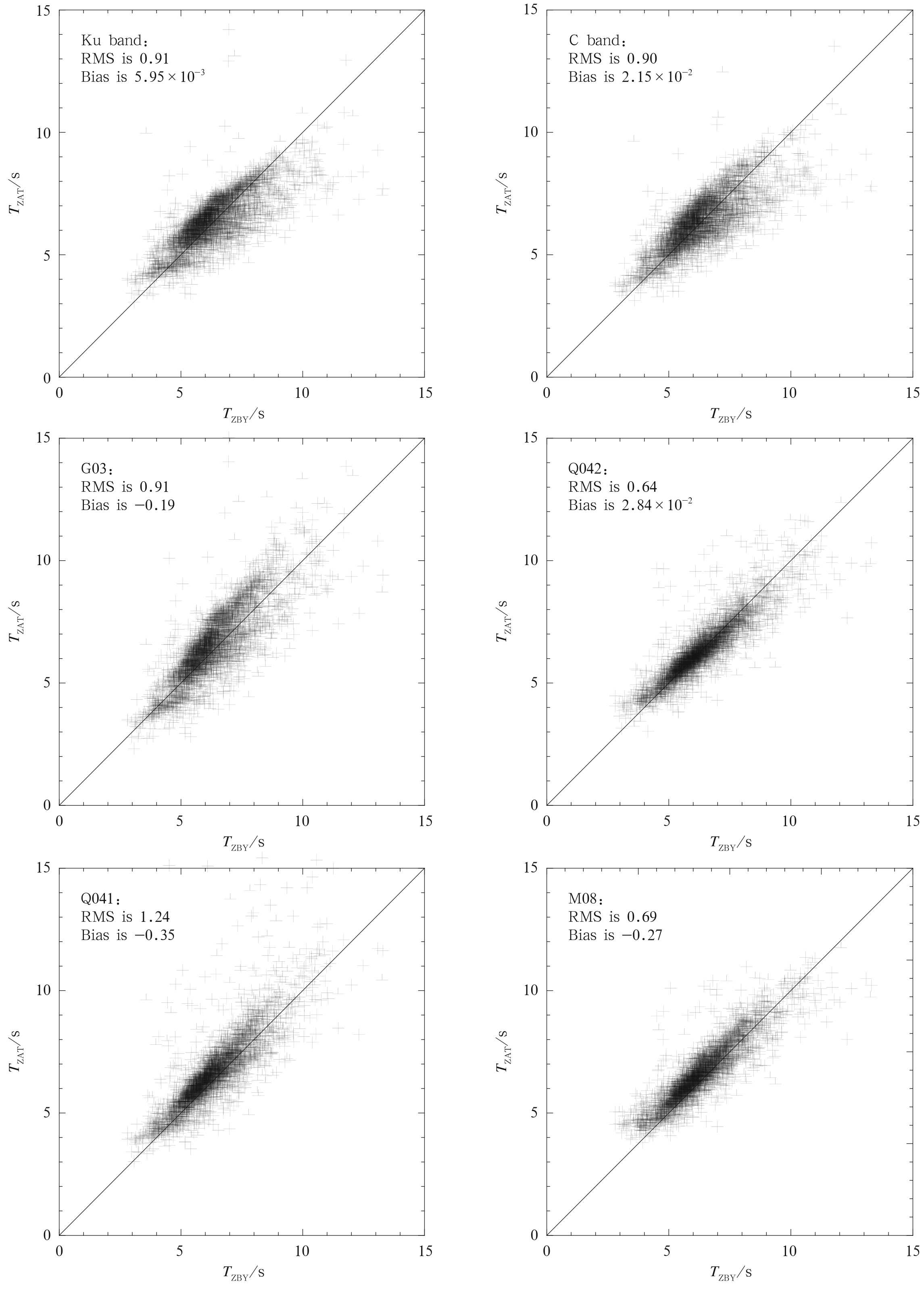

Fig.4. Scatter diagrams of TOPEX altimeter versus buoy wave periods. The algorithms of Z11, M08, Q04 and G03 are used for deriving altimeter wave period. A perfect line is also overlaid on each subplot.

et al. (2005) is also calculated for comparison. It is found that this algorithm sometimes gives extremely large wave periods which are obviously unreasonable. Thus its result is not shown in Fig. 4. In terms of the RMS, the performance of our wave-age dependent algorithm (the top two subplots of Fig.4) proposed in this study (hereafter referred as Z11) produces an equivalent result to G03. With Z11, the wave period derived from C band data is closer to the buoy measurement than Ku band data. The result can be improved by simple average of the wave period obtained from Ku and C bands data by Z11, and the RMS reduces to 0.89 s (not shown in Fig. 4). Either Ku or C bands data, Z11 gives very smaller bias as compared with the other algorithms. By the use of Ku and C bands data together, Q042 algorithm reduces the RMS to 0.64 s, which is less than those of the Ku-band algorithms of M08, Q041 and G03. It is obvious that the Ku and C bands data should be simultaneously taken into account in order more accurately to derive the wave period from the altimeter in the future.

The comparisons of PDF of the wave period by the buoy and the altimeter are presented in Fig. 5. It can be seen that M08 overestimates the wave period as a whole. The PDFs of Q042 and Z11 by C band data agree well with those of buoy measurements.

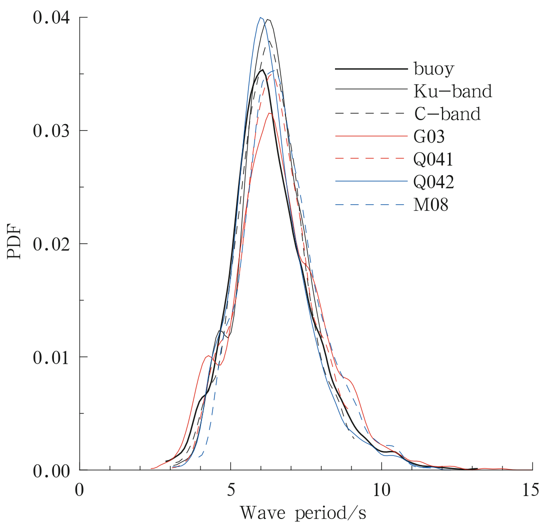

Fig.5. Possibility distribution functions of wave period calculated by the TOPEX/buoy collocation data set.

7 Conclusions

The typical wind speed and wave period algorithms are validated by a large collocated TOPEX/Buoy data set. It is shown that the Ku and C bands data should be considered simultaneously in the derivation of either wind speed or wave period. The algorithm of wave period using the concept of wave age proposed in this study can be applied to Ku and C bands, in which the latter gives more reasonable results. The advantage of this algorithm is that it has the dimension of wave period, and explicit relationship with the other variables. The wind speed algorithm of C02 and the wave period algorithm of Q042 are best performed in terms of RMS.

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