*Paper presented at the 22nd Asian Conference on Remote Sensing, 5 - 9 November 2001, Singapore.*

---

# EFFECT OF WAVE STATES ON ALTIMETER WIND SPEED ALGORITHM AT HIGH WIND SPEEDS

Dongliang ZHAO[1,2] and Yoshiaki TOBA[3,4]
[1]Visiting Researcher, Earth Observation Research Center, National Space Development Agency of Japan
22F Office Tower X, Harumi Island Triton Square, 1-8-10 Harumi, Chuo-ku, Tokyo, 104-6023
Tel: (81)-3-6221-9055 Fax: (81)-3-6221-9192
E-mail: zhao@eorc.nasda.go.jp
JAPAN
[2]Associate Professor, Institute of Physical Oceanography
Ocean University of Qingdao
5 Yushan Road, Shinan-qu, Qingdao, 266003
CHINA
[3]Invited Eminent Scientist, Earth Observation Research Center, National Space Development Agency of Japan
23F Office Tower X, Harumi Island Triton Square, 1-8-10 Harumi, Chuo-ku, Tokyo, 104-6023
Tel: (81)-3-6221-9005 Fax: (81)-3-6221-9191
E-mail: toba@eorc.nasda.go.jp
JAPAN
[4]Director, Research Institute for Environmental Sciences and Public Health of Iwate Prefecture
1-36-1 Iiokashinden, Morioka, 020-0852
Tel: (81)-19-656-5666 Fax: (81)-19-656-5667
E-mail: y-toba@pref.iwate.jp
JAPAN

**KEY WORDS:** Mean square slope, Wave age, Altimeter, Wind speed, Wind-waves

**ABSTRACT:** Both empirical algorithms and those with some theoretical background for retrieving wind speeds from altimeter data have correlated radar cross sections with wind speeds only. Thus the influences of wave states or tilting effects of long waves on radar returns have usually been neglected. Although various algorithms produce comparable results in the parameter range for which they were developed, they yield very different results when extrapolated to wind speeds above 20 m/s. This paper evaluates the analytical algorithm recently proposed by Zhao and Toba (2001), which was derived by integrating wind-wave and gravity-capillary wave spectrum using radar scattering theory directly. This algorithm predicts that the magnitude of the radar cross section depends not only on wind speed but also on the development degree of wind waves. It is consistent with empirical algorithms at low wind speeds, and agrees well with the algorithm of Young (1993), which is a special algorithm for wind speeds between 20 and 40 m/s, at high wind speeds. In contrast to Hwang et al. (1998), we suggest that the tilting effect of long waves is more important at high wind speeds. Due to the existence of a theoretical upper limit to the wave slope, the upper limits of wind speeds that could be derived from altimeter strongly depend on the wave states. We indicate that the atmospheric correction to the radar cross section due to water vapor in the atmosphere, which is a function of temperature, may lead to the seasonal variations of wind speeds derived from altimeter.

## 1. INTRODUCTION

Satellite radar altimeters (ALT) were primarily developed to measure sea-surface elevation, from which such properties as the large-scale ocean circulation can be inferred. In addition, they can determine the significant wave height (SWH) quite accurately and wind speed to a lower accuracy (Fedor and Brown, 1982). The instrument of choice for the determination of surface wind speeds from an orbiting platform is generally regarded as the scatterometer (SCATT) (Chelton and McCabe, 1985). While many years of data and global coverage have been acquired by a number of ALT missions, SCATT data are still very limited. As a result, a considerable body of work has concentrated on methods for accurately determining wind speed from ALT data.

For the spaceborne altimeters, specular reflection is the primary mechanism of radar scatter. In this mode, surface roughness causes incident waves to diffuse and scatter away from the radar reception aperture, so that the rougher the surface, the less backscattering cross section is expected. The normalized radar cross section (RCS) $\sigma_0$ can thus be considered as a function of the statistic moments of the sea-surface elevations and slopes. Due to the difficulty in quantitatively estimating the sea surface roughness, researchers usually correlate RCS with wind speed directly. In physics, this approach has neglected the effect of the large-scale slopes associated with wind-waves and has only considered the slopes related with gravity-capillary waves. Many other factors have also been regarded as contributing the radar return for the ALT. For example, water vapor in the atmosphere or rainfall degrades the radar returns. In order to evaluate this effect, a multi-channel microwave radiometer is usually carried on the ALT and could be used to perform atmospheric correction. Whitecaps are another import phenomena that occur in the ocean. The wave breaking can not only affect the roughness of the sea surface directly, but can also produce sea spray droplets into the atmosphere at the same time. The resultant effect of whitecapping on the radar return has not been investigated thoroughly.

## 2. EXISTING WIND SPEED ALGORITHMS

The most prominent sea-surface roughness parameter is the mean square slope (MSS) of the sea-surface (e.g., Jackson et al., 1992). For ALT at nadir incident angles, the relationship of RCS with MSS can be expressed as (e.g., Barrick, 1968)

$$\sigma_0(0) = \frac{|R(0)|^2}{s_{\mathrm{f}}^2} \tag{1}$$

where $|R(0)|^2$ is the Fresnel reflection coefficient, characterizing the surface reflectivity, and $s_{\mathrm{f}}^2$ is the filtered MSS, representing the portion of surface roughness elements with length scales greater than the diffraction limit. The MSS of the sea surface can be calculated by the following equation

$$s^2 = \int F(\vec{k}) k^2 d\vec{k} \tag{2}$$

where $F(\vec{k})$ is the directional wavenumber spectrum and $\vec{k}$ is the wavenumber vector. It is very difficult to directly calculate MSS from the wave spectrum, because the fourth moment of the spectrum for wind waves has not been defined in theory. For wind speed $U$ less than 20 m/s, observational data show that there is an approximately linear relationship between $U$ and $s^2$ (e.g., Cox and Munk, 1954). Using the wavenumber spectrum obtained by Hwang et al. (1996), Hwang et al. (1998) calculated the filtered MSS for the Ku-band altimeter (13.6 GHz)

$$s_{\mathrm{f}}^2 = 3.66 \times 10^{-3} U \tag{3}$$

Although they calculated MSS from the wavenumber spectrum, their result depends on wind speed only and cannot reflect the influences of the large-scale slopes associated with wind waves. Neglecting the influence of wave states, most of the geophysical model functions (GMF) used to calculate wind speeds are only related to RCS. The common approach is to compare $\sigma_0$ with the coincident observations of wind speed from in situ observations, SCATT measurements, or numerical weather prediction model, and to establish the correlation between them. The most famous GMFs that have been proposed are those of Brown, 1979; Brown et al., 1981; Chelton and McCabe, 1985; Goldhirsh and Dabson, 1985; Chelton and Wentz, 1986; Witter and Chelton, 1991; and Freilich and Challenor, 1994. Although these various algorithms produce comparable results at low wind speeds, they yield very different results at high wind speeds, especially when extrapolated to wind speeds above 20 m/s (Figure.1).

In recent years, a few researchers have recognized the effect of wave states on ALT wind speed algorithms. Monado and Dobson (1989) first suggested that the information of SWH derived from the ALT waveform should be used for wind speed determinations. The ambiguity between RCS and wind speed can be reduced when GMFs include the information of SWH (Glazman and Pilorz, 1990; Glazman and Greysukh, 1993),

$$U = f(\sigma_0, H_{\mathrm{s}}) \tag{4}$$

where $H_{\mathrm{s}}$ is the significant wave height of waves. Based on this idea, Leferve et al. (1994) developed an empirical algorithm by correlating RCS and SWH with wind speed derived from a numerical model. They suggested that their algorithm could significantly improve the results compared with those excluding the information of SWH.

## 3. AN ANALYTICAL ALGORITHM

Recently, Zhao and Toba (2001) estimated MSS from a wave spectrum built on Toba (1973) and Phillips (1985) results for the gravity waves and on Toba (1973) and Mitsuyasu and Honda (1974) results for the gravity-capillary part. The resulting MSS depends on the friction velocity of air and the peak wavenumber of wind waves. These parameters are then expressed as a function of surface wind speed and wave age using classical relations. Based on Eq. (1), Zhao and Toba (2001) suggested that the RCS for ALT could be expressed as

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

where $\alpha$ is Toba's constant, $C_{\mathrm{D}}$ is the drag coefficient, $\beta = g/U\omega_{\mathrm{p}}$ is the wave age with $\omega_{\mathrm{p}}$ the spectral peak angular frequency of wind waves, $g$ is the acceleration of gravity, and $a=\sqrt{g/\gamma_{\mathrm{s}}}$ with $\gamma_{\mathrm{s}} = \Gamma/\rho_{\mathrm{w}}$. Here $\Gamma$ is the sea surface tension, and $\rho_{\mathrm{w}}$ water density. The cutoff wavenumber $k_{\mathrm{d}}$ introduced here indicates that only those facets with a radius of curvature exceeding the radar wavelength can contribute to the altimeter returns. For ALT at Ku-band (13.6 GHz), Zhao and Toba (2001) suggested that $k_{\mathrm{d}}$ can be taken as 314 $\mathrm{m}^{-1}$. In application, we proposed that $C_{\mathrm{D}}$ can be obtained by the relation given by Wu (1980), and $|R(0)|^2$ can be taken as 0.3 (e.g., Jackson et al., 1992). The results of Eq. (5) for wave ages of 0.6, 1.0 and 1.4 are shown in Figure 1.

At low wind speeds, we can see that the empirical algorithms agree well with our algorithm at wave ages greater than 1.0. Weak wind means a smoother sea surface. For fixed fetch *F*, a low wind speed corresponds to a long non-dimensional fetch $\tilde{F} = gF/U^2$. According to Wilson (1965), the wave age of wind waves with respect to $\tilde{F}$ can be expressed as $\beta = 1.31\left[1-(1+8\times10^{-3}\tilde{F}^{1/3})^{-5}\right]$. At low wind speed, $\tilde{F}$ can be regarded as infinite and the wave age approaches to 1.31, that is the fully developed sea. At high wind speeds, the curves corresponding to various wave ages separate significantly (Figure 1). It is clearly demonstrated that the development degree of wind-waves, or the tilting effect of long waves strongly affects the RCS at high wind speed. The wave ages of wind waves decrease with increasing wind speeds for fixed fetch (e.g., Wilson, 1965). A younger sea (smaller wave age) means a rougher sea surface, which would correspond to a small RCS.

Assuming the probability density of the tilting waves has a normal distribution, Hwang et al. (1998) considered the tilting effect of longer waves on modifying the local incident angles. In place of Eq. (1), they suggested the following relation should be used.

$$\sigma_0(0) = \frac{|R(0)|^2}{s_{\mathrm{f}}^2}\sqrt{\frac{s_{\mathrm{f}}^2}{s_{\mathrm{f}}^2+2\sigma_{\mathrm{t}}^2}} \tag{6}$$

where $s_{\mathrm{f}}^2$ is the filtered MSS as shown in Eq. (3), and $\sigma_{\mathrm{t}}^2 = s_{\mathrm{t}}^2 + S^2$. Here $s_{\mathrm{t}}^2$ is the tilting MSS including wind-wave slopes $s_t^2$, and $S^2$ the MSS induced by other oceanographic processes such as currents and turbulence. Hwang et al. (1998) expressed $\sigma_{\mathrm{t}}^2$ as

$$\sigma_{\mathrm{t}}^2 = 1.09\times10^{-3}U + 1.25\times10^{-3} + S^2 \tag{7}$$

However, because they did not know the quantitative magnitude of the ambient sea surface slopes, they gave $S^2$ a constant value of 0.02. From Eq. (7), we can see that the tilting MSS is 0.02125, which is equivalent to their filtered MSS at wind speed of 5.8 m/s, even in the case of $U = 0$. This point is also clearly shown in Figure 2, in which their modifying factor $\delta = \sqrt{s_{\mathrm{f}}^2/s_{\mathrm{f}}^2 + 2\sigma_{\mathrm{t}}^2}$ is drawn with respect to wind speed. At wind speeds of less than 10 m/s, $\delta$ increases quickly with wind speed. When the wind speed exceeds 10 m/s, $\delta$ increases very slowly with wind speed. This might be why they thought the tilting effect is more important at low wind speeds.

In contrast to Hwang et al. (1998), we show that the influence of wave states becomes stronger with increasing wind speed (Figure 1). At the same wind speed, a greater wave age means a larger RCS is received by ALT. These results can be explained as follows. The total MSS of the sea surface is small at low wind speed because the MSS of the sea surface is mainly induced by the gravity-capillary waves, which are directly related to wind speed, and the value of RCS is large. The influence of the tilting effect of longer waves on RCS is relatively small compared with the large value of RCS itself. At high wind speed, however, RCS decreases dramatically because the sea surface becomes much rougher. The influence of wave states becomes relatively important considering the small value of RCS itself. Therefore, the effect of wave states at high wind speeds must be taken into account in the algorithms. We suggest that the significant difference among those empirical algorithms at high wind speeds is also due to the influence of wave states that they have neglected.

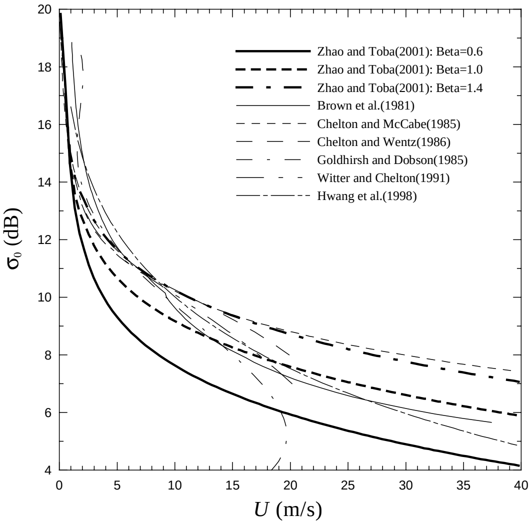

Figure 1. Comparisons of various algorithms for ALT wind speed model functions. The thin lines are the results of Zhao and Toba (2001) for different wave ages.

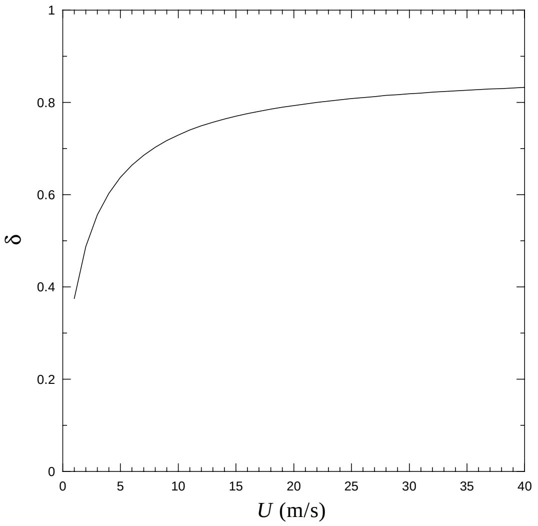

Figure 2. Modifying factor for the tilting effects $\delta = \sqrt{s_{\mathrm{f}}^2 / s_{\mathrm{f}}^2 + 2\sigma_{\mathrm{t}}^2}$ proposed by Hwang et al. (1998) versus wind speed.

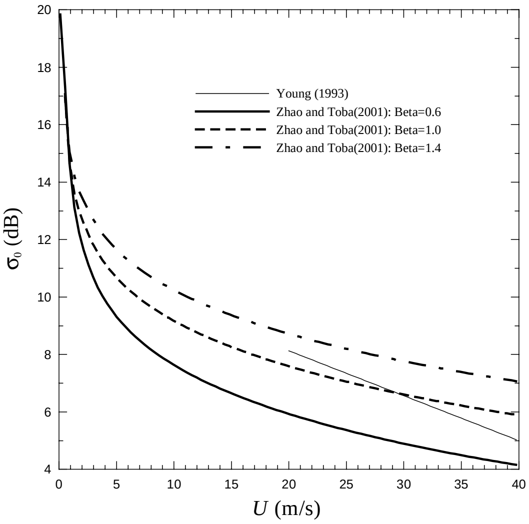

Figure 3. Analytical algorithm of Zhao and Toba (2001) versus the algorithm of Young (1993) for wind speed greater than 20 m/s.

Table 1. The effect of wave states on the maximum wind speeds derived from ALT, assuming the upper limit of MSS is 0.08.

| $\beta$ | $U_{\max}$ |
|---|---|
| 0.2 | 6.90 |
| 0.4 | 12.7 |
| 0.6 | 20.9 |
| 0.8 | 30.7 |
| 1.0 | 41.7 |
| 1.2 | 53.6 |
| 1.4 | 66.5 |

As mentioned above, the proposed empirical algorithms for ALT cannot be applied in the case of high wind speeds due to their limit of the parameter range for which they were developed. Young (1993) developed a wind speed algorithm valid for wind speeds between 20 and 40 m/s by comparing Geosat altimeter values of the RCS with model predictions of the surface winds during satellite overpasses of tropical cyclones. The linear dependence of the RCS on wind speeds is proposed

$$U = -6.4\sigma_0 + 72 \tag{8}$$

where $U$ has units of meters per second and $\sigma_0$ has units of decibels. Figure 3 compares the algorithm of Zhao and Toba (2001) with that of Young (1993). We can see that the algorithm proposed by Young (1993) is consistent with our algorithm at a wave age of 1.0. Here, we try to explain this as follows.

Under the strong wind actions, the wind-waves quickly develop until the wind and wind-waves have attained a local balance by highly nonlinear self-adjustment processes. This is the concept of the "wind-waves in local equilibrium with the wind" (e.g., Toba, 1998). In this case, the wave height and wave period of individual waves cannot adopt arbitrary values, but satisfy the 3/2-power law. The increasing wind speed will decrease $\tilde{F}$ and reduce wave age at the same time (e.g., Wilson, 1965). Unlike in the case of saturated states of low wind speeds, the wave ages of wind waves in local equilibrium are usually around or less than 1.0. This is why the algorithm of Young (1993) agrees well with our algorithm at wave age of 1.0.

## 4. DISCUSSION

By integrating the wave spectrum including wind-waves and gravity-capillary waves, we have obtained an analytical algorithm for ALT. This new algorithm depends not only on the wind speed but also on the wave age, which represents the development degree of wind waves or wave states. We have shown that the effect of wave states on deriving wind speed from ALT is more important for high wind speeds. This property can also be used to explain why the empirical algorithms significantly differ at high wind speeds, though they agree well at low wind speeds. However, as discussed below, there are also other factors that will affect the accuracy of deriving wind speeds from ALT.

### 4.1 Upper limit of wind speed derived from ALT

In general, higher wind speeds produce rougher sea surfaces. The sea-surface roughness is parameterized by the MSS, which can be used to estimate wind speed based on Eq.(1). However the MSS cannot be increased with wind speed infinitely. Based on the argument that the momentum flux from wind to waves should not exceed the wind stress, Plant (1982) has proposed an upper limit to the wave slope. Jackson et al. (1992) have expressed this limit in terms of MSS as less than 0.08. The existence of such a limit implies an upper limit to wind speeds at which ALT can provide useful data at a fixed wave age. Based on our explicit expression of MSS in Eq. (5), we can estimate the upper limit of wind speeds obtained by ALT. Table 1 shows the various wave ages versus the maximum wind speeds that ALT can measure. It is clear that the wave states are very important in determining the upper limit of wind speed from ALT since wave age is a key parameter. This calculation also confirms that the wave age of wind-waves should exceed 1.0 if we expect ALT to provide reliable data up to 40 m/s. When the wind speed is greater than 40 m/s, the wind-waves associated with the wind field will dominate the wave field, and the influence of swells can be neglected. In general, we cannot expect that wave age will be greater than 1.0 at such a high wind speed. Thus, we suggest that the maximum wind speed detected by ALT is around 40 m/s.

### 4.2 Effect of water vapor on the radar return

The importance of wet tropospheric range correction for satellite altimetry has been well established in earlier studies (e.g., Tapley et al., 1982). The wet tropospheric range correction is proportional to the water vapor present in the atmosphere. Emery et al. (1990) have shown that atmospheric water vapor degrades the radar return and hence reduces the observed values of $\sigma_0$. It is therefore important to provide the best possible estimates of global water vapor for correcting RCS. Emery et al. (1990) found that the highest values of water vapor are around the equator either in the Pacific or in the Atlantic (their Figures 5 and 6), which means the water vapor depends mainly on temperature. If these data are used to apply atmospheric correction to the original RCS for ALT, we can assume that the RCS for ALT in summer would be greater than their original value. Thus, a relatively lower wind speed would be derived from the corrected RCS. Interestingly, Chen et al. (2000) compared the coincident wind speeds derived from TOPEX altimeter by empirical algorithms and JMA buoy wind speeds from January 1993 to December 1998 and pointed out that the wind speeds from ALT are always lower than those from buoy observations during summer. Is this seasonal variation of wind speed related to the atmospheric correction of RCS? At high wind speeds, whitecaps are a well-known surface signature of the breaking waves and air entrainment processes. The existence of foam after wave breaking affects the sea-surface reflectivity and will increase the microwave radiation into the atmosphere. At the same time, whitecaps are also accompanied with the ejection of sea spray droplets into the atmosphere. Up to date, the water vapor associated with whitecapping has not been considered in the atmosphere correction. These issues are to be investigated in the future.

## 5. CONCLUSION

Our new analytical algorithm incorporating wind speed and wave age agrees well with the empirical algorithms at low and high wind speeds. The influence of wave states on the RCS is more important at high wind speeds. The upper limit of reliable wind speeds derived from ALT depends heavily on the wave age.

## References

Barrick, D.E., 1968. Rough surface scattering based on the specular point theory. IEEE Trans. Antennas Propag., AP-16, pp.449-454.

Brown, G.S., 1979. Estimation of surface winds using satellite-borne radar measurements at normal incidence. J. Geophys. Res., 84, pp.3974-3978.

Brown, G. S., H. R. Stanley and N. A. Roy, 1981. The wind speed measurement capability of spaceborne radar altimetry. IEEE J. Oceanic Eng., OE6, pp.59-63.

Chelton, D. B. and P. J. McCabe, 1985. A review of satellite altimeter measurements of sea surface wind speed: With a proposed new algorithm. J. Geophys. Res., 90, pp.4707-4720.

Chelton, D. B. and F. J. Wentz, 1986. Further development of an improved altimeter wind speed algorithm. J. Geophys. Res., 91, pp.14250-14260.

Chen, G., H. Lin and J. MA, 2000. On the seasonal inconsistency of altimeter wind speed algorithms. Int. J. Remote Sensing, 21(10), pp.2119-2125.

Cox, C.S., and W. Munk, 1954. Statistics of the sea surface derived from Sun glitter. J. Mar. Res., 13, pp.198-227.

Emery, W. J., G. H. Born, D. G. Baldwind and C. L. Norris, 1990. Satellite-derived water vapor corrections for Geosat altimetry. J. Geophys. Res., 95, pp.2953-2964.

Fedor, L.S., and G.S. Brown, 1982. Wave height and wind speed measurements from the Seasat radar altimeter. J. Geophys. Res., 87, pp.3254-3260.

Freilich, M.H., and P.G. Challenor, 1994. A new approach for determining fully empirical altimeter wind speed model functions. J. Geophys. Res., 99, pp.25051-25062.

Glazman, R.E. and S.H. Pilroz, 1990. Effects of sea maturity on satellite-borne altimeter measurements. J. Geophys. Res., 95, pp.2857-2870.

Glazman, R.E. and A. Greysukh, 1993. Satellite altimeter measurements of surface wind. J. Geophys. Res., 98, pp.2475-2483.

Goldhirsh, J. and E. B. Dobson, 1985. A recommended algorithm for the determination of ocean surface wind speed using a satelliteborne radar altimeter. Rep. JHU/APL SIR-85-U005, Johns Hopkins Univ., Appl. Phys. Lab., Laurel, Md.

Hwang, P.A., S. Atakturk, M.A. Sletten, and D.B. Trizna, 1996. A study of the wavenumber spectra of short waves in the ocean. J. Phys. Oceanogr., 26, pp.1266-1285.

Hwang, P.A., W.J. Teague, G.A. Jacobs, and D.W. Wang, 1998. A statistical comparison of wind speed, wave height, and wave period derived from satellite altimeters and ocean buoys in the Gulf Mexico region. J. Geophys. Res., 103(C5), pp.10451-10468.

Jackson, F. C., W. T. Walton and D. E. Hines, 1992. Sea surface mean square slope from Ku-band backscatter data. J. Geophys. Res., 97, pp.11411-11427.

Lefervre, J. M., J. Barckicke and Y. Menard, 1994. A significant wave height dependent function for TOPEX/POSEIDON wind speed retrieval. J. Geophys. Res., 99, pp.25035-25049.

Mitsuyasu, H., and T. Honda, 1974. The high frequency spectrum of wind-generated waves. J. Oceanogr. Soc. Jpn., 30, pp.185-198.

Monaldo, F.M., and E.B. Dobson, 1989. On using significant wave height and radar cross section to improve radar altimeter measurements of wind speed. J. Geophys. Res., 94, pp.12699-12701.

Phillips, O.M., 1985. Spectral and statistical properties of the equilibrium range in wind-generated gravity waves. J. Fluid Mech., 156, pp.505-531.

Plant, W.J., 1982. A relationshipbetween wind stress and wave slope. J. Geophys. Res., 87, pp.1961-1967.

Tapley, B.D., J. B. Lunderg and G. H. Born, 1982. The Seasat altimeter wet tropospheric range correction. J. Geophys. Res., 87(C5), pp.3213-3220.

Toba, Y., 1973. Local balance in the air-sea boundary processes III. On the spectrum of wind waves. J. Oceanogr. Soc. Jpn., 29, pp.209-220.

Toba, Y., 1998. Wind-forced strong wave interactions and quasi-local equilibrium between wind and windsea with the friction velocity proportionality. In: Nonlinear Ocean Waves (Adv. Fluid Mech. Vol. 17), edited by Perrie, W., Comp. Mech. Pub., Southampton, pp.1-59.

Witter, D. L. and D. B. Chelton (1991): A Geosat altimeter wind speed algorithm and a method for altimeter wind speed algorithm development. J. Geophys. Res., 96, 8853-8860.

Wilson, B.W., 1965. Numerical prediction of ocean waves in the North Atlantic for December, 1959. Dt. Hydrogr. Z., 18, pp.114-130.

Wu, J., 1980. Wind-stress coefficients over sea surface near neutral conditions—A revisit. J. Phys. Oceanogr., 10, pp.727-740.

Young, I. R. (1993): An estimate of the Geosat altimeter wind speed algorithm at high wind speeds. J. Geophys. Res., 98, 20275-20285.

Zhao, D., and Y. Toba, 2001. A spectral approach for determining altimeter wind speed model functions. (to be published).