An analytical algorithm with a wave age factor for altimeter wind speed retrieval

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To cite this Article Cheng, Yongcun, Xu, Qing, Liu, Yuguang, Lin, Hui, Xiu, Peng, Yin, Xiaobin, Zong, Haibo and Rong, Zengrui(2008) 'An analytical algorithm with a wave age factor for altimeter wind speed retrieval', International Journal of Remote Sensing, 29: 19, 5699 — 5716

To link to this Article DOI: 10.1080/01431160801908111

URL: http://dx.doi.org/10.1080/01431160801908111
An analytical algorithm with a wave age factor for altimeter wind speed retrieval

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(Received 24 July 2006; in final form 3 January 2008)

Based on the specular reflection theory of electromagnetic waves at rough sea surface and the wind wave spectrum model with a wave age factor, the sea surface wind speeds are retrieved from the normalized radar backscatter cross-section (NRCS) measured by TOPEX/Poseidon (T/P) Ku-band altimeter using the mean square slope (MSS) calculated from the spectrum models of the wind waves and the gravity-capillary waves. A relationship between wave age and non-dimensional wave height is applied to compute the wave age factor using the significant wave height (SWH) and wind speeds obtained from buoy or altimeter simultaneously. The study indicates that the wave age factor has a significant impact on the retrieval of altimeter wind speed. Compared with the operational algorithm for retrieving altimeter wind speed, the wind speed retrieved from the new analytical algorithm based on the wind wave spectrum model with the wave age factor, proposed in this study, can match the buoy measurements better. The effects of the wave age factor on altimeter wind speed retrieval are also shown quantitatively through a series of experiments and measurements. The comparison with the operational algorithm indicates that both the bias and root mean square error (RMSE) between wind speeds retrieved by the proposed analytical algorithm and those observed by the buoy decrease significantly. In the Gulf of Mexico, with the new analytical algorithm, more accurate altimeter wind speeds are retrieved.

1. Introduction

Although wind speed alone (without wind direction) can be obtained, altimeter-measured wind speeds have a comprehensive application in oceanographic investigations. (1) The significant wave height (SWH) and wind speed can be obtained simultaneously from altimeter observations. (2) The altimeter can provide wind speed with a higher resolution than can be obtained using a scatterometer. (3) The data of wind speed from an altimeter can be assimilated with those from

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scatterometer and microwave radiometer. Therefore, it is important to improve the altimeter wind speed retrieval algorithm.

More than a dozen wind speed retrieval algorithms have been proposed during the past two decades, as a result of continuing effort to improve altimeter wind measurements. For the TOPEX/Poseidon (T/P) altimeter, three datasets, namely normalized radar backscatter cross-section (NRCS) from Ku and C bands as well as the SWH, have been used in previous algorithms, resulting in a variety of single-, dual-, and three-parameter model functions. A detailed review of these algorithms was given by Lefevre et al. (1994) and Chen et al. (2002). The algorithm proposed by Witter and Chelton (1991) has been applied in operational products for ERS-1, ERS-2 and T/P altimeters (Chen et al. 2002). This algorithm, hereafter referred to W&C91 (Witter and Chelton 1991), will serve here as a reference to assess the new algorithm for altimeter wind speed retrieval in this study. However, the effects of wave developing stage on the altimeter radar return were not considered in the previous empirical algorithms. In addition, as the wind speed is higher than 20 m s\(^{-1}\), these algorithms are inaccurate (Zhao and Toba 2003). To solve the two problems, we will propose a new analytical algorithm for retrieving altimeter wind speed by using the mean square slopes (MSS) of sea surface, which are obtained by integrating the wind wave spectrums of gravity waves and capillary waves. By comparing the NRCS calculated by using the MSS of sea surface, with those measured by the T/P Ku band altimeter, the wind speeds are retrieved. In this study, the wave age factor is included in the wind wave spectrum model. Therefore, the effects of wave age factor on the altimeter radar return in the new algorithm for retrieving altimeter wind speed are considered. Compared with the empirical algorithm W&C91, there are smaller bias and root mean square error (RMSE) between wind speed retrieved by the proposed analytical algorithm and buoy-observed wind speed.

2. The new wind wave spectrum model

The wind wave spectrum models are widely used in various fields of ocean investigations. They play a particularly important role in the study of the remote sensing theory concerning microwave scatterometers and microwave radiometers. Within the full wavenumber range, the wind wave spectrum can be divided into long wave spectrum (gravity spectrum) and short wave spectrum (gravity-capillary spectrum). In the study of the remote sensing mechanism of microwave radiometers and scatterometers, the influence of both long and short waves must be considered. For long waves at lower frequency, Liu et al. (2003a,b) proposed a model of directional frequency spectrum \( S(\omega, \phi) \)

\[
S(\omega, \phi) = 0.0093 x_a x_w D(\phi, k) \left( \frac{\omega_p}{\omega} \right)^{2\xi - 4} \frac{g^2}{\omega^2} \times \exp \left\{ - \frac{2\xi + 1}{4} \left[ b \omega_p (1 - b) \omega_p \right] \right\} \gamma^k (1)
\]

where \( x_a \) is the wave age factor, which denotes the influence of the wave age on total energy level; \( x_w \) is the spectral width factor, which denotes the influence of spectral width on total energy level; \( D(\phi, k) \) is the directional spreading function; \( \omega_p \) is the spectral-peak angular frequency and \( \omega \) is the angular frequency; \( g \) is the acceleration of gravity; \( b \) is the directional factor; \( \gamma \) and \( \gamma \) are the spectral-peak enhancement factors; and \( \xi \) denotes the inverse spectral width. With increase of \( \xi \), the spectral
width will decrease and the wind wave spectrum will become steeper. The expression of the wave age factor $a$ is

$$ a = \omega_p^{0.55} $$

where $\omega_p$ is the inverse wave age. The relation of the spectral-peak angular frequency $\omega_p$ with the inverse wave age $\omega_p$ is

$$ \omega_p = \sqrt{\frac{g}{1.2U_{10}}} $$

and the spectral-peak angular frequency in the direction of $\phi$ is

$$ \omega_{p\phi} = 0.95\omega_p \sqrt{\frac{g}{1.2U_{10}\text{sech}(1.2375\phi)}} $$

where $U_{10}$ denotes the wind speed at a height of 10 m in a neutrally stable atmosphere, and ‘sech’ denotes hyperbolic secant.

For fully developed wind waves, the inverse wave age $\omega_p = 1.0$, and the spectral-peak angular frequency $\omega_p = g/1.2U_{10}$. Therefore, $g/1.2U_{10}$ denotes the spectral-peak angular frequency of fully developed wind waves. If $\omega_p > 1.0$, the wind waves are in developing stage. This is why $\omega_p$ is named as the ‘inverse wave age’.

The relationship between the spectral width factor $a_w$ and the inverse wave age $\xi$ is

$$ a_w = 3 + 2 \sin \left[ (\xi - 3) \frac{\pi}{2} \right]. $$

The spreading function $D(\phi, k)$ is

$$ D(\phi, k) = \sec^2(\beta\phi) \int_{-\pi}^{\pi} \sec^2(\beta\phi) d\phi $$

where the expression of parameter $\beta$ is

$$ \beta = 10 \left[ -0.4 + 0.8393 \left( \frac{k}{k_p} \right)^{-0.567} \right] \quad k/k_p > 2.56 $$

$$ \beta = 1.2375 \quad k/k_p \leq 2.56 $$

where $k$ is wavenumber and $k_p$ is the wavenumber at the spectral peak. A simplified expression of the directional factor $b$ is

$$ b = \left( \frac{\omega_{p\phi} - \omega_p}{\omega_{p\phi}} \right)^{0.35}. $$

The expressions of the spectral-peak enhancement factors $\gamma$ and $\Gamma$ are

$$ \gamma = \left( 1.225 + 6 \log \omega_p \right) \left( \frac{\xi}{2} \right)^{-2} $$
respectively, where \( \sigma = 0.08 \) is the spectral-peak width parameter.

Based on a balance of the wind input, the spectral flux divergence, the viscous dissipation, and the modulation from the wave–drift interaction, Liu and Yan (1995) proposed a form of spectrum of wind-induced gravity-capillary waves. Later, Liu et al. (2003a, b) improved the model as follows

\[
S(k, \phi) = \frac{1}{320} k^{-4} \left[ \frac{u_\ast - \delta}{c} \right]^2 D(\phi) D_d D_e r_p
\]

where the threshold wind friction velocity \( \delta = 0.03\sim0.05 \text{ m s}^{-1} \) and \( u_\ast = U_{10}\sqrt{10^{-3}(2.717/U_{10} + 0.142 + 0.076 U_{10})} \). The spreading function is

\[
D(\phi) = \sec^2 (1.3\phi).
\]

The dissipation factor, caused by the modulation of large-scale long waves to small-scale short waves, is

\[
D_d = 1 - \exp \left[ - \frac{c^2}{(x_1 \cos^2 \phi + x_2 \sin^2 \phi) U_{10}^2} \right]
\]

where \( x_1 \) is the modulation coefficient of long waves to short waves, \( x_1 = 0.001 \) if the riding waves are located on the windward (\( \phi = 0^\circ \)) side of background waves, and \( x_1 = 0.0002 \) if they are in the leeward (\( \phi = 180^\circ \)) side; and \( x_2 = 0.00005 \) is the modulation coefficient for cross-wind (\( \phi = 90^\circ \)) direction.

The capillary wave enhancement factor is

\[
\Gamma_p = \exp \left[ - \frac{(k/900 - 1)^2}{2\sigma_p^2} \right]
\]

where \( \sigma_p = 0.6 \) for \( k < 900 \text{ rad m}^{-1} \) and \( \sigma_p = 1.5 \) for \( k > 900 \text{ rad m}^{-1} \). Another wave enhancement factor is

\[
\begin{align*}
  r_p &= 1 & U_{10} \leq 2.2 \text{ m s}^{-1} \\
  r_p &= 3 \log U_{10} & 2.2 < U_{10} \leq 10 \text{ m s}^{-1} \\
  r_p &= 3 \left( \frac{10}{U_{10}} \right)^{1.5} \log U_{10} & U_{10} > 10 \text{ m s}^{-1}
\end{align*}
\]

The eddy dissipation factor caused by the micro-scale turbulence in the wind-drift layer is

\[
D_e = \exp \left[ - \alpha_c k^{2.5} (u_\ast - \delta)^{-0.75} \right]
\]

where \( \alpha_c = 0.0011 \text{ (rad cm}^{-1})^{-2.5} \text{ (cm s}^{-1})^{-0.75} \). When compared with the measurements from ‘laser sloping gauge’ and ‘imaging optical technical and digital image processing’, \( \alpha_c \) is taken as 0.0011 and 0.018, respectively, to simulate the cut-off of capillary waves. At present, it is not clear about what caused the difference
of the cut-off with different measurement equipment and methods, even if the measurements are carried out simultaneously (Cheng et al. 2006). Therefore, the value of $\alpha_s$ cannot be finally determined.

The sea surface wind friction velocity $u_*$ is obtained from

$$u_* = \sqrt{C_d U_{10}}$$

where $C_d$ is the drag coefficient. In a neutrally stable atmosphere condition, the drag coefficient is

$$C_d = 10^{-3}[(2.717/U_{10}) + 0.142 + 0.076U_{10}].$$

Based on field measurements, Cheng et al. (2006) proposed a statistical relationship among wind speed $U_{10}$, wave age factor $\bar{\sigma}_p$ and spectral width factor $\bar{\gamma}$

$$\begin{align*}
\bar{\sigma}_p &= 3.03[(\bar{\sigma}_p c_m)/U_{10} - 0.02]^{0.07} (\bar{\sigma}_p c_m)/U_{10} > 0.02 \\
\bar{\gamma} &= 2.0 (\bar{\sigma}_p c_m)/U_{10} \leq 0.02
\end{align*}$$

where $c_m = 0.23 \text{ ms}^{-1}$ is the minimum phase speed of gravity-capillary waves. With the statistical relationship (20) and equations given by Liu et al. (2003a,b), a new wind wave spectrum model for deep water is proposed. Compared with other existing wind wave spectrum models (Durden and Vesecky 1985, Apel 1994, Elfouhaily et al. 1997, Kudryatsev et al. 1999) in full wave number range, the new wind wave spectrum model is more suitable in describing the real wave stage (Cheng et al. 2006).

In the polar coordinates, the mean square slopes (MSS) of sea surface can be obtained by the following formulae

$$S_x^2 = \int_{k_p}^{k_d} \int_{-\pi}^{\pi} kS(k, \phi) k^2 \cos^2 \phi \, dk \, d\phi$$

$$S_y^2 = \int_{k_p}^{k_d} \int_{-\pi}^{\pi} kS(k, \phi) k^2 \sin^2 \phi \, dk \, d\phi$$

$$S^2 = S_x^2 + S_y^2$$

where $S_x^2$ and $S_y^2$ are the components of the MSS in the upwind and crosswind directions, respectively, and $S^2$ is the sum of the two components. $S(k, \phi)$ is the new directional wavenumber spectrum of wind waves and the gravity-capillary waves (see equations (1)–(20)). $k_p$ is spectral-peak wavenumber, and $k_d$ is called the cut-off wavenumber (Liu et al. 1997, 2000) because only the ocean waves with wavelengths longer than the radar wavelength contribute to the specular-point scatter of sea surface.

For the altimeter, the incidence angle is 0°, the NRCS ($\sigma_0$) due to specular reflection can be simplified as (Liu et al. 2000)

$$\sigma_0 = \frac{n}{n-1} \frac{|R(0)|^2}{2S_x S_y}$$

where $|R(0)|^2$ is the Fresnel reflectance coefficient for normal incidence (Xu and Liu 2004) and $n$ is the peakedness coefficient (Liu and Yan 1995, Liu et al. 1997, 2000).
Based on former investigations (Wu 1994, Liu et al. 2000), the NRCS calculated from MSS for smooth surface is

\[ \sigma_0(dB) = -4.2(dB) - 10\log_{10}(2S_xS_y) \] (25)

and for a rough surface is

\[ \sigma_0(dB) = -4.2(dB) + 10\log_{10}(n/n-1) - 10\log_{10}(2S_xS_y) \] (26)

3. The analytical algorithm with wave age factor

3.1 Mean square slopes of sea surface and normalized radar backscatter cross-sections

According to the specular reflection theory in oceanic remote sensing, the NRCS received by altimeter is related to wind speed through the MSS of sea surface (Apel 1994, Wu 1994, Liu et al. 2000, Zhao and Toba 2003). At small incidence angles the radar backscatter is mainly due to specular reflection (i.e. specular-point scatter) of sea surface. For a smooth sea surface, more signals will return to the altimeter, resulting in a large value of NRCS. For a rough sea surface, more signals will be reflected toward other various directions, resulting in a small value of NRCS. Thus, the altimeter NRCS is determined by the sea surface roughness. The rougher the sea surface, the lower the expected NRCS. The NRCS can therefore be considered as a function of the MSS of sea surface, which can be calculated from the wind wave spectrum and the gravity-capillary wave spectrum.

Many efforts have been undertaken to investigate the MSS. The sun glitter photographs of Cox and Munk (1954) remain the most complete measurements of the slope probability density functions as a function of wind speed. Based on equations (21)–(23), the MSS calculated from the spectral models of wind waves and gravity-capillary waves proposed by Liu et al. (2000, 2003a,b) and further developed by Cheng et al. (2006), can match the measurements quite well (Cheng et al. 2006).

Figure 1 presents a comparison between the MSS calculated from the new wind wave spectrum models of Cheng et al. (2006) and those proposed by Wu (1994) and Apel (1994). In figure 1, the abscissa represents \( U_{10} \), the wind speed at height of 10 m in a neutrally stable atmosphere, and the ordinate represents the MSS of sea surface. The solid line denotes the MSS formula proposed by Apel (1994) based on the altimeter measurements at C, X, Ku and Ka bands. The dashed line denotes the MSS formula proposed by Wu (1994) based on altimeter measurements at X band. Pluses and circles denote the MSS calculated from the spectrum models of wind waves and gravity-capillary waves under different wave ages (see equations (1)–(20)), where \( \bar{\omega}_p = 1.0 \) denotes the fully-developed waves and \( \bar{\omega}_p = 1.2 \) or 2.0 denotes the developing waves (§3.2). The wave age factor \( \bar{\omega}_p \) will be explained in §3.2. The comparison shows that the MSS calculated from the spectrum models of fully developed wind wave and gravity-capillary waves waves keeps consistent with the formula of Wu (1994) when \( U_{10} < 7 \text{ m s}^{-1} \) and that of Apel (1994) when \( U_{10} > 10 \text{ m s}^{-1} \), respectively. It is shown in figure 1 that the younger the wind waves (i.e. larger value of \( \bar{\omega}_p \)), the larger the MSS. This is consistent with the conclusion of Zhao and Toba (2003).

Figure 2 shows the comparison between the NRCS calculated from the new analytical algorithm under different wave age conditions and that from W&C91
algorithm (Witter and Chelton 1991). Under the fully developed wind wave condition ($\bar{\sigma}_0 = 1.0$), the NRCS calculated from the analytical algorithm based on the new wind wave spectrum model can fit W&C91 algorithm quite well when $U_{10} > 10 \text{ m s}^{-1}$. When $U_{10} < 10 \text{ m s}^{-1}$, especially $U_{10} < 5 \text{ m s}^{-1}$, the stage of wave development becomes an increasingly important factor of the radar backscatter (Glazman and Pilorz 1990). Compared with the W&C91 algorithm, the wave age factor is considered in the new analytical algorithm. Therefore, there is a quite apparent difference in NRCS between W&C91 algorithm and the new analytical algorithm when $U_{10} < 10 \text{ m s}^{-1}$. It is approved in following sections that with considering the effects of wave age factor, the altimeter wind speed retrieved from the new analytical algorithm can fit buoy measurements better than that from W&C91 algorithm.

![Figure 1. Comparison between the MSS calculated from the wind wave spectrum models and those proposed by Wu (1994) and Apel (1994) under different wave age conditions.](image)

![Figure 2. Comparison between the NRCS calculated from the new analytical algorithm under different wave age conditions and that from the W&C91 algorithm.](image)
3.2 Determination of wave age factor

The roughness of sea surface is different under different stages of wave development, which influences NRCS through MSS. Therefore, the effects of wave age should be considered for altimeter wind speed retrieval. In this study, the wave age factor is determined from T/P altimeter measured wind speed and SWH. Once the wave age factor is given, the NRCS can be obtained from the new wind wave model with equations (1)–(26). Comparing the calculated NRCS with that measured from T/P Ku-band altimeter, the altimeter wind speed can be determined. Compared with former empirical algorithms, considering the effects of the wave age factor, the analytical algorithm based on the specular reflection theory of electromagnetic waves at rough sea surface and the spectral model of wind waves with the wave age factor has a stronger theoretical background for retrieving wind speed from altimeter data.

In the new wind wave spectrum model, the wave age factor \( \bar{\omega}_p \) is used to describe the influence of wave age on spectral-peak frequency and total spectral energy level. The relationship between \( \bar{\omega}_p \) and ‘inverse wave age’ \( \Omega (\Omega = U_{10}/C_p, \text{where } C_p \text{ is phase speed of the dominant long wave}) \) defined by Donelan et al. (1985) is

\[
\bar{\omega}_p = 1.2\Omega = 1.2U_{10}/C_p. \tag{27}
\]

For fully developed wind waves, \( U_{10}/C_p = 0.84 \). Substituting this value into equation (27), we have \( \bar{\omega}_p = 1.0 \). The other variable that can be used to describe the wave state is dimensionless SWH, where \( \text{SWH} = gH_s/U_{10}^2 \), which correlates with wave age via

\[
\beta = C_p/U_{10} = A(gH_s/U_{10}^2)^B \tag{28}
\]

where \( \beta \) is called pseudo wave age (Anderson et al. 2000); \( H_s \) is SWH; \( gH_s/U_{10}^2 \) is non-dimensional SWH; and \( A \) and \( B \) are constants. Comparing equation (2) with equation (3), we get

\[
\bar{\omega}_p = 1.2/\beta. \tag{29}
\]

From Japan Meteorological Agency (JMA) buoys data, Zhao and Toba (2003) obtained \( A = 3.31 \) and \( B = 0.3 \). From National Data Buoy Center (NDBC) buoys data, Glazman and Greysukh (1993) obtained \( A = 3.24 \) and \( B = 0.31 \).

While retrieving the altimeter wind speed with the new analytical algorithm based on the new wind wave spectrum model of Liu et al. (2003a,b) and Cheng et al. (2006), the value of wave age factor \( \bar{\omega}_p \) is needed. With T/P-measured \( H_s \) and \( U_{10} \), the wave age factor can be obtained from equation (28) and equation (29). In equation (28), the wind speed \( U_{10} \) is retrieved using W&C91 algorithm (Witter and Chelton 1991), whose values are then only used to calculate wave age factor in the new analytical algorithm. There is no iteration process between \( U_{10} \) in equation (29) and the new wind speed retrieved from the new analytical algorithm. Values of \( H_s \) and \( U_{10} \) in equation (28) and equation (29) can be obtained simultaneously from the Ku-band altimeter measurements. Therefore, the analytical algorithm proposed based on the new wind wave spectrum model of Liu et al. (2003a,b) and Cheng et al. (2006) has a comprehensive applicability.
4. Validation and comparison

4.1 Altimeter and buoy data selection

The wind speed data measured by 18 buoys operated by the NDBC and three JMA buoys were collected for comparing with the T/P altimeter wind speed. The total 21 buoy locations are shown in figure 3. The buoy-measured wind speed at various heights above the sea surface are converted to wind speed at a height of 10 m using the method proposed by Wentz (1997).

To calculate and verify the altimeter wind speed retrieved from the analytical algorithm, isochronous altimeter and buoy data are collected. In general, the temporal lags and spatial distances between the altimeter and buoy observations are limited to less than 1.5 h and 150 km, respectively. To contrast with the temporal lags, lessening the spatial distances between altimeter and buoy observations can produce a smaller RMSE (Hwang et al. 1998). The temporal interval of the NDBC buoy observations is 1 h (see details at http://seaboard.ndbc.noaa.gov/index.shtml), while that of JMA buoy observations is 3 h (Zhao and Toba 2003). Thus, the temporal differences between NDBC buoys and altimeter observations are limited to be less than 1 h, and those between JMA buoys and altimeter observations are limited to be less than 3 h. To ensure the quantity and quality of the collected data, different spatial separation between the altimeter and different buoy observations is selected and shown in table 1. Within the time bin and spatial bin shown in table 1, the buoy and altimeter observations are considered to be isochronous. For a certain isochronous time, all the T/P data in the spatial bin are averaged. The averaged data of $U_{10}$ and $H_s$ are used to calculate the wave age factor through equations (28) and (29). The information for the selected 21 buoys is listed in table 1.

4.2 Comparison between retrieved altimeter wind speeds and buoy observations

The RMSE and bias between T/P altimeter wind speeds and buoys observations are calculated and shown in figure 4. Here T/P altimeter wind speeds are calculated from the new analytical algorithm based on the model of wind wave spectrum listed in §2.

Figure 3. Locations of the 21 buoys: the buoy number corresponds to that in table 1 (buoy nos 1, 5, 7 and 12 denote B22001, B41002, B42001 and B46002, respectively).
and W&C91 empirical algorithm, respectively. The abscissa in figure 4 represents the buoy number corresponding to buoy ID listed in table 1, and the ordinate denotes errors between retrieved wind speed and buoy measurements. In figure 4, ‘NEW’ denotes T/P wind speed retrieved using the analytical algorithm, where the wave age factor is calculated from T/P measured wind speed $U_{10}$ (W&C91 algorithm) and SWH, $H_s$ (see equations (28) and (29)). ‘W&C91’ denotes T/P wind speed retrieved using W&C91 empirical algorithm.

Figure 4 shows clearly that when considering the effects of wave age factor, compared with the W&C91 algorithm, the altimeter wind speed retrieved using the new analytical algorithm based on the wind wave spectrum model can fit the buoy measurements better and there are significant decreases in both RMSE and bias. At B42003 (buoy ID 42003, no. 9 in figure 3), the RMSE between altimeter wind speeds retrieved from the new analytical algorithm and buoy observations is 21% lower compared with the W&C91 algorithm. At B41002 (no. 5 in figure 3), the bias between altimeter wind speeds retrieved from the new analytical algorithm and buoy observations is 79% lower compared with the W&C91 algorithm. Figure 4 also indicates that there is a significant improvement in altimeter wind speed retrieval accuracy at Gulf of Mexico (nos 7–9 in figure 3) with considering the effects of wave age factor.

At B22001, B51001 and B51003 (nos 1, 18 and 20 in figure 3), the RMSE between buoy observations and altimeter wind speeds retrieved from the analytical algorithm is lower compared with the W&C91 algorithm. However, the bias becomes larger due to the errors from wave age factor estimation. For example, the wind speed at B22001 is recalculated under different wave age factors, and more accurate wind speed can be retrieved with $\bar{\sigma}_p=1.2$ (§5).

<table>
<thead>
<tr>
<th>No.</th>
<th>Buoy Station ID</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Spatial bin (°)</th>
<th>Temporal bin (h)</th>
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<td>135.00</td>
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<td>97</td>
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<tr>
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<td>228.98</td>
<td>0.5</td>
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<td>23.43</td>
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<td>121</td>
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<tr>
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<td>0.4</td>
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<td>19.16</td>
<td>199.26</td>
<td>0.2</td>
<td>1</td>
<td>63</td>
</tr>
<tr>
<td>21</td>
<td>51 004</td>
<td>17.52</td>
<td>207.52</td>
<td>0.5</td>
<td>1</td>
<td>142</td>
</tr>
</tbody>
</table>
Based on the results in figure 4, the improvement for altimeter wind speed retrieval with the new analytical algorithm can be shown by the $R_{\text{Imp}}$ and $B_{\text{Imp}}$, which are defined as

$$R_{\text{Imp}} = \frac{1}{N} \sum_{i=1}^{N} \frac{(R_{\text{W&C91}}^i - R_{\text{NEW}}^i)}{R_{\text{W&C91}}^i}$$

(30)

$$B_{\text{Imp}} = \frac{1}{N} \sum_{i=1}^{N} \frac{(B_{\text{W&C91}}^i - B_{\text{NEW}}^i)}{B_{\text{W&C91}}^i}$$

(31)

where $R_{\text{Imp}}$ and $B_{\text{Imp}}$ denote the improvements in RMSE and bias between buoy measurements and altimeter wind speeds retrieved by the new analytical algorithm ($R_{\text{NEW}}$ and $B_{\text{NEW}}$) with respect to those retrieved by W&C91 algorithm ($R_{\text{W&C91}}$ and $B_{\text{W&C91}}$), respectively; and $N$ denotes buoy numbers. On average, the RMSE and bias between buoy measurements and altimeter wind speeds retrieved by the
new analytical algorithm are 11% and 21% lower compared with the W&C91 algorithm (B22001 is not included for the reason mentioned above), respectively. Thus the new analytical algorithm with the new wind wave spectrum model and wind age factor can produce more accurate wind speed than the operational empirical algorithm.

5. The effects of the wave age factor on altimeter wind speed retrieval

Previous studies have shown that the wave age factor has a significant influence on altimeter wind speed retrieval (Glazman and Pilorz 1990, Zhao and Toba 2003). To describe the effects of wave age factor on altimeter wind speed retrieval quantitatively, a series of experiments was carried out based on the observations at B22001, B46002, B42001 and B41002. The selected buoys denote four disparate wind wave conditions in different geographical areas. Figure 5 presents the scatter plots of the wind speed $U_{10}$ versus SWH, $H_s$ for the data in each area, together with the relationship between $U_{10}$ and $H_s$ for the fully developed sea derived from the Pierson and Moskowitz spectrum (Anderson et al. 2000)

$$H_s = 0.0235 \frac{9.8}{g} U_{10}^2$$

(32)

where $g$ is acceleration of gravity ($g=9.8 \text{ m s}^{-2}$) in P–M spectrum (Pierson and Moskowitz 1964).

In figure 5, pluses denote observations from the four buoy datasets, and the solid line denotes the relationship given in equation (32) for the fully developed sea. Data points lying above the fully developed curve are classified as case of developing waves, while those on or below the fully developed curve are classified as case of

![Figure 5](image_url)

Figure 5. Buoy $H_s$ versus buoy $U_{10}$ in the four geographical areas, together with the $H_s$ and $U_{10}$ relationship given in equation (32) for the fully developed sea: (a) B22001, East China Sea; (b) B46002, Eastern Pacific Ocean; (c) B42001, Gulf of Mexico; (d) B41002, Western Atlantic Ocean.
fully- or over-developed waves. It can be clearly seen that in the open ocean (B46002), almost all the data correspond to case of fully- or over-developed waves. In the Gulf of Mexico (B42001) and East China Sea (B22001), due to the various fetch in different seasons, many data points correspond to under-developed conditions, and the wave age factor will have significant effects on altimeter wind speed retrieval in these areas.

In retrieving altimeter wind speed in the four areas using the analytical algorithm, the effects of wave age factor on altimeter wind speed retrieval can be clearly shown by selecting different wave ages. Table 2 lists the RMSE and bias between T/P wind speeds retrieved from the analytical algorithm and buoy observations under different wave age conditions. In table 2, ‘W&C91’ denotes the RMSE and bias between T/P wind speeds calculated from W&C91 empirical algorithm and buoy observations. The wave age $\widehat{\phi}_p = 1.0$ and $\widehat{\phi}_p > 1.0$ denote fully developed and underdeveloped sea conditions, respectively.

From table 2 we can see that for B22001 (in the East China Sea) and B42001 (in the Gulf of Mexico), the T/P wind speeds retrieved from the analytical algorithm fit buoy observations better than those retrieved from W&C91 algorithm. In particular, they match the observations best when the wave age factor $\widehat{\phi}_p = 1.2$, which means that the wave age has a significant influence on altimeter wind speed retrieval in these areas. Based on equations (30) and (31), for B22001, the RMSE and bias between altimeter wind speeds retrieved from the analytical algorithm with $\widehat{\phi}_p = 1.2$ and buoy observations are 22% and 50% lower, respectively, compared with the W&C91 algorithm. For B42001, they are 16% and 79% lower, respectively. For B46002 (in the Eastern Pacific Ocean), the wind speeds retrieved from the analytical algorithm with $\widehat{\phi}_p = 1.0$ can match buoy measurements best, which means the wind waves are always fully developed at this location. For B41002 (in the Western Atlantic Ocean), the RMSE and bias between altimeter wind speeds retrieved from the analytical algorithm with $\widehat{\phi}_p = 1.05$ and buoy observations are 14% and 93% lower, respectively, compared with the W&C91 algorithm. Table 2 indicates that it is appropriate to retrieve altimeter wind speed using the analytical algorithm with new wind wave spectrum model and wind age factor.

Figure 6 shows the comparison between retrieved T/P wind speeds and buoy observations. Figure 6(a) and (b) show T/P wind speeds retrieved from the W&C91

Table 2. Difference between T/P wind speeds and buoy observations under different wave age conditions (m s$^{-1}$).

<table>
<thead>
<tr>
<th>Buoy ID</th>
<th>$\widehat{\phi}_p$</th>
<th>RMSE</th>
<th>Bias</th>
<th>Buoy ID</th>
<th>$\widehat{\phi}_p$</th>
<th>RMSE</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>B22001</td>
<td>1.0</td>
<td>1.17</td>
<td>-0.39</td>
<td>B46002</td>
<td>1.0</td>
<td>1.33</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>1.11</td>
<td>-0.19</td>
<td></td>
<td>1.1</td>
<td>1.36</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td><strong>1.2</strong></td>
<td><strong>1.08</strong></td>
<td><strong>-0.03</strong></td>
<td></td>
<td>1.2</td>
<td>1.38</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>1.07</td>
<td>0.06</td>
<td></td>
<td>1.3</td>
<td>1.39</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>1.09</td>
<td>0.19</td>
<td></td>
<td>1.4</td>
<td>1.42</td>
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</tr>
<tr>
<td>W&amp;C91</td>
<td>1.39</td>
<td>0.06</td>
<td>W&amp;C91</td>
<td>1.47</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B42001</td>
<td>1.0</td>
<td>1.03</td>
<td>-0.36</td>
<td>B41002</td>
<td>1.0</td>
<td>1.11</td>
<td>-0.11</td>
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<tr>
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<td>-0.10</td>
<td></td>
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<td><strong>0.01</strong></td>
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<tr>
<td></td>
<td><strong>1.2</strong></td>
<td><strong>0.92</strong></td>
<td><strong>0.05</strong></td>
<td></td>
<td>1.1</td>
<td>1.11</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>0.94</td>
<td>0.18</td>
<td></td>
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<td>1.13</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
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<td>1.3</td>
<td>1.13</td>
<td>0.46</td>
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<tr>
<td>W&amp;C91</td>
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<td>-0.14</td>
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</table>
algorithm and the analytical algorithm with the new wind wave spectrum model and wind age factor, respectively. In the new wind wave model, the wave age factors are 1.2, 1.0, 1.2 and 1.05 (table 2) for B22001, B46002, B42001 and B41002, respectively. It is clearly shown that when considering the effects of wave age factor, the T/P wind speeds from the analytical algorithm fit the buoy observations better than those from W&C91 algorithm.

6. Altimeter wind speed retrieval – in the Gulf of Mexico

It has been noted in §4.2 that there is a significant improvement in altimeter wind speed retrieval accuracy in the Gulf of Mexico when considering the effects of the wave age factor. In this section, the three buoys located in the Gulf of Mexico (see figure 3 and table 1) are used to describe the effects of the wave age factor on altimeter wind speed retrieval. Figure 7 gives buoy-measured $H_s$ and $U_{10}$ at the locations of B42001, B42002 and B42003. The curve denotes the relationship given in equation (32) between $H_s$ and $U_{10}$ for fully developed waves in deep water.

In figure 7, about 43% of the total data corresponds to underdeveloped wind waves. Figure 8 presents the comparison of wind speeds retrieved from two different algorithms with buoy observations for underdeveloped wind waves. In figure 8(a) and (b), the wind speeds are retrieved from the W&C91 algorithm and the new analytical algorithm, respectively. It can be seen from figure 8 that when considering the effects of wind wave age factor, the accuracy of wind speed retrieved from altimeter is improved. Table 3 lists the RMSE and bias between the retrieved wind speeds from the two algorithms and buoy observations for underdeveloped wind waves. Here ‘NEW’ denotes T/P wind speeds calculated from the analytical algorithm, and ‘W&C91’ denotes those from the W&C91 empirical algorithm. The
results indicate that wave age factor has a significant influence on altimeter wind speed retrieval. When considering the effects of wave age, the accuracy of the altimeter wind speed retrieved from the new analytical algorithm is greatly improved.

7. Summary

The wind wave spectrum model for deep water proposed by Liu et al. (2003a,b) includes three parameters, i.e. the wind speed, wave age factor and spectral width factor. Based on field measurements and the wind wave spectrum model of Liu et al. (2003a,b), Cheng et al. (2006) proposed a statistical relationship among the three parameters and developed a new wind wave spectrum model for deep water. The surface roughness associated with microwave altimeter radar backscatter can be described by MSS of sea surface, which are controlled by both sea surface wind speed and wind wave age. The MSS are calculated from the new wind wave spectrum model with wind wave age factor (Cheng et al. 2006).

Since the altimeter can measure the SWH and sea surface wind with higher resolution simultaneously, much effort has been devoted to improving altimeter wind measurements and dozens of algorithms have been developed to enhance the accuracy of altimeter wind speed. However, progress has been seen to be rather slow (Chen et al. 2002). None of the empirical algorithms cover the effects of wave age.

Table 3. The RMSE and bias between the retrieved wind speeds from the two algorithms and buoy observations for underdeveloped wind waves (m s\(^{-1}\)). ‘NEW’ denotes T/P wind speeds calculated from the analytical algorithm, and ‘W&C91’ denotes those from the W&C91 empirical algorithm.

<table>
<thead>
<tr>
<th>Buoy ID</th>
<th>Algorithm</th>
<th>RMSE</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>B42001</td>
<td>W&amp;C91</td>
<td>1.13</td>
<td>−0.72</td>
</tr>
<tr>
<td></td>
<td>NEW</td>
<td>0.86</td>
<td>0.14</td>
</tr>
<tr>
<td>B42002</td>
<td>W&amp;C91</td>
<td>1.32</td>
<td>−0.69</td>
</tr>
<tr>
<td></td>
<td>NEW</td>
<td>0.98</td>
<td>0.11</td>
</tr>
<tr>
<td>B42003</td>
<td>W&amp;C91</td>
<td>1.26</td>
<td>−1.03</td>
</tr>
<tr>
<td></td>
<td>NEW</td>
<td>0.75</td>
<td>−0.15</td>
</tr>
</tbody>
</table>

Figure 8. Comparison of wind speeds retrieved from two different algorithms with buoy observations for underdeveloped wind waves: (a) W&C91 algorithm, (b) the new analytical algorithm proposed in this study.
Compared with the operational empirical algorithms for altimeter wind speed retrieval, the proposed analytical algorithm with the new wind wave spectrum model and wave age factor is better at retrieving the sea surface wind speed. The RMSE and bias between altimeter wind speeds retrieved from the new analytical algorithm and buoy observations are 11% and 21% lower than those obtained using the W&C91 algorithm, respectively. A series of experiments confirms that the wave age factor has a significant influence on altimeter wind retrieval. The wave age factor can be calculated from altimeter-measured $H_s$ and $U_{10}$ obtained using the W&C91 algorithm. In the sea areas with fetch limitation, such as the Gulf of Mexico, the new analytical algorithm with wind wave factor, proposed in this study, is better than the W&C91 algorithm at retrieving sea surface wind speed.

Acknowledgements
The authors express their thanks to Professor Zhao Dongliang for providing JMA buoy data. This study was supported by the National Basic Research Program of China under Grant No. 973-2007CB411807, National High Technology Development Project under Grant No. 863-2006AA09Z140, China Postdoctoral Science Foundation funded project under Grant No. 2008041345 and the Scientific Research Starting Foundation for Post-doctoral of Institute of Meteorology, PLA University of Science and Technology.

References


