

An evaluation of input/dissipation terms in WAVEWATCH III using *in situ* and satellite significant wave height data in the South China Sea

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Abstract

A WAVEWATCH III version 3.14 (WW3) wave model is used to evaluate input/dissipation source term packages WAM3, WAM4 and TC96 considering the effect of atmospheric instability. The comparisons of a significant wave height acquired from the model with different packages have been performed based on wave observation radar and HY-2 altimetry significant wave height data through five experiments in the South China Sea domain spanning latitudes of 0°–35°N and longitudes of 100°–135°E. The sensitivity of the wind speed correction parameter in the TC96 package also has been analyzed. From the results, the model is unable to dissipate the wave energy efficiently during a swell propagation with either source packages. It is found that TC96 formulation with the “effective wind speed” strategy performs better than WAM3 and WAM4 formulations. The wind speed correction parameter in the TC96 source package is very sensitive and needs to be calibrated and selected before the WW3 model can be applied to a specific region.

Key words: input/dissipation terms, atmospheric instability, WAVEWATCH III, South China Sea, wind speed correction parameter, significant wave height

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1 Introduction

Wave conditions in a given location at a certain time are fully described by the so-called two-dimensional spectrums. The sea surface is conceived as the superposition of a very large number of sinusoidal waves, each one is characterized by different values of frequency f , direction θ and energy F . The wave model solves the wave action balance equation:

$$\frac{dN(k, \theta; x, t)}{dt} = \frac{S(k, \theta; x, t)}{\sigma}, \quad (1)$$

where N is the action density spectrum, defined as $F(k, \theta)$ divided by the intrinsic frequency σ ; k and θ are the spectral wavenumber and direction; and x and t are space and time coordinates. Roughly, the net source term S consists of four terms, a wind input term S_{in} , a nonlinear wave-wave interactions term S_{nl} , a dissipation by whitecapping term S_{dis} and an additional term S_{bot} corresponding to wave-bottom interactions which is considered in shallow water. These define the net source terms as

$$S = S_{in} + S_{nl} + S_{dis} + S_{bot}. \quad (2)$$

The spectral dissipation is one of the least understood pro-

cesses implemented in contemporary wave models (The WISE Group, 2007). WAVEWATCH III version 3.14 (WW3) has several options for the parameterization of the input/dissipation term packages. The model's code is modular and operated by switches that allow the user to choose specific model options for each run. The WW3 model provides the following three options for input/dissipation source terms (Tolman, 2009):

(1) The input/dissipation source terms of WAM Cycles 1-3 (hereafter WAM3), which are based on Snyder et al. (1981) and Komen et al. (1984).

(2) The source term package of Tolman and Chalikov (1996, hereafter TC96), which consists of the input source term of Chalikov and Belevich (1993) and Chalikov (1995), and two dissipation constituents.

(3) The wind input source term of Janssen (1991), the dissipation source term of Bidlot et al. (2005) modified from WAM3 (hereafter WAM4).

In the process of wave modeling, the effect of an atmospheric stratification cannot be addressed by accounting for buoyancy effects in the surface stresses (Tolman, 2002). Generally, the atmospheric stratification is close to neutral for most of the oceans, so, it appears reasonable to tune a wave model for such conditions.

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But, Tolman (2002) suggests that the model should be tuned more closely to fetch-limited growth for unstable conditions through some tests. To enhance the wave model's accuracy, modeler should consider the effect of the atmospheric instability by the theoretical investigation of the source terms. However, it is a cumbersome and complicated process to retune the wave model with parameterization of the physics. Tolman (2002) presents a simple way to retune the model through defining an "effective" wind speed internal to the model. The elegant method keeps the present balance of source terms and includes explicit effects of stability, so it is adopted in the WAVEWATCH III version 1.15 and the following. The "effective wind speed" u_e is defined as

$$\frac{u_e}{u} = \left(\frac{c_0}{1 + C_1 + C_2} \right)^{-1/2}, \quad (3)$$

$$C_1 = c_1 \tanh \{ \max [0, f_1 (ST - ST_0)] \}, \quad (4)$$

$$C_2 = c_2 \tanh \{ \max [0, f_2 (ST - ST_0)] \}, \quad (5)$$

$$ST = \frac{hg}{u_h^2} \frac{T_a - T_s}{T_0}, \quad (6)$$

where u is the wind speed derived from the winds at 10 m height; ST is a bulk stability parameter, where g is gravity constant, u_h the wind speed at height h , and T_a , T_s and T_0 are the air, sea and reference temperatures, respectively (Tolman, 2009). The default settings of $c_0=1.38$, $c_1=-0.1$, $c_2=0.1$, $f_1=-150$, $ST_0=-0.01$ and $f_2=f_1c_1/c_2$ are used. c_0 is named as a wind speed correction parameter which is a very important factor for the source terms. The effect of the atmospheric instability on the friction velocity is parameterized using the effective wind speed u_e which depends on the surface air and sea temperature difference.

The effects of various input/dissipation source term packages with enable stability correction are evaluated and compared in this study. Also, the sensitivity of the model performance to the wind speed correction parameter is analyzed in order to obtain the optimal wind speed correction parameter value before the wave model is applied to a special region. The results have certain reference meaning for the wave modeling, using of the WW3 model, studying of the air-sea interaction and so on.

The outline of this work is as follows: A brief statement of wave model WW3 is provided in Section 2, including the descriptions of the South China Sea; Section 3 depicts the HY-2 altimeter and wave observation radar (WOR) significant wave height (SWH) data which are used to verify the model results under different input/dissipation terms; in Section 4, some comparing results about the five tests are listed and the sensitivity of the wind speed correction parameter is analyzed; discussion and conclusions are described in the last section.

2 Model setup

The WW3 is an operational global wave model to produce a wave hindcast, nowcast and short-term forecast. It was developed at US National Centers for Environmental Prediction (NCEP). With additional diffusion terms, the WW3 solves a wave propagation using a third-order finite difference scheme. Constantly optimized computer code and utilizing of the massively parallel processing make the model calculation more efficient. Full details of the WW3 can be found in User Manual and References Therein (Tolman, 2009).

In this work, the wave model is setup in the domain spanning

latitudes of 0° – 35° N and longitudes of 100° – 135° E. A regularly grid with spacing $(1/2)^\circ$ and $(1/6)^\circ$ is utilized for the two nested grids, the high resolution grid spans the South China Sea in an area of 4° – 25° N, 105° – 122° E (Fig. 1). This area is chosen because the South China Sea, being the deepest and biggest sea around China with an average water depth of 1 212 m and the deepest place of 5 567 m, is the third biggest epicontinental sea in the world after the Coral Sea and the Arabian Sea. Also, the South China Sea is a semi-enclosed tropical sea in complex topography between the Asian land mass to the north and the west, the Philippine Islands to the east, Borneo to the southeast, and Indonesia to the south (Chu and Cheng, 2008).

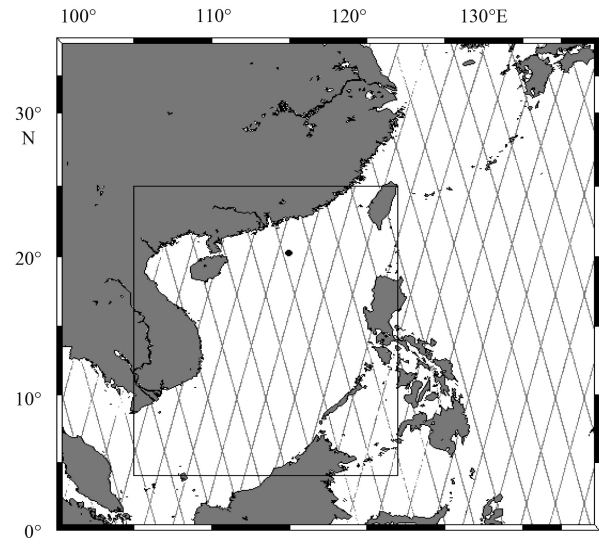


Fig. 1. Set of the nest grids of the study area. The gray lines correspond to the HY-2 altimeter track in January 2012. Black solid circle means the location of oil platform PY30-1.

In order to compute efficiently, the WW3 adopts four time steps. The maximum global time step used here is 1 500 s, the maximum CFL time step is 700 and 800 s for x - y and k - θ , respectively, and minimum source term time step is 30 s. Simulation time range is from January 1 to 31, 2012. The period is selected because, in the South China Sea, the winter northeast monsoon is most prevalent in January. The northeast wave plays a dominant role and the wind sea and swell characteristics are obvious, relatively. A wave spectrum is discrete in 24 equidistant directions and in 25 frequencies ranging from 0.041 2 to 0.405 6 Hz. At the open boundaries, JONSWAP-type spectral parameterizations are used. Expect for the input/dissipation terms, details of the model setup are similar to the default settings (Tolman, 2009). There are six optional switches for the input/dissipation terms in the WW3 model (Table 1). For convenience, the tests for the latter five switches are named WAM3_ST1, TC96_ST2, TC96_STAB 2, WAM4_ST3 and WAM4_STAB 3, respectively. The "STAB 2" switch is corresponding to the "effective wind speed" strategy mentioned in Section 1. Abdalla and Bidlot (2002) take into account a stronger gustiness in unstable atmospheric conditions. This effect is included in the present parameterization and is activated with the "STAB 3" switch in the WW3 wave model.

The bathymetry of the domain was extracted from ETOPO5 which is provided by the National Geophysical Data Center of the NOAA. ERA-interim wind field was downloaded during the peri-

Table 1. The switch to the input/dissipation terms in the WW3 model

Switch	Description	Name list of tests
ST0	no input and dissipation used	–
ST1	WAM3 source term package	WAM3_ST1
ST2	TC96 source term package	TC96_ST2
STAB 2	TC96 source term package with enabled stability correction	TC96_STAB 2
ST3	WAM4 and variants source term package	WAM4_ST3
STAB 3	WAM4 source term package with enabled stability correction	WAM4_STAB 3

od of simulation from January 1 to 31, 2012. The wind fields contain high-resolution analyses at 00:00, 06:00, 12:00 and 18:00 every day with grid spacing of $(1/4)^\circ$. The WW3 model is driven by the ERA-interim wind fields every 6 h.

3 Data

3.1 HY-2 altimeter

In order to monitor ocean and study of marine, human has launched several satellites carrying altimeters since May 1973 when the “SkyLab” loading the first altimeter was launched. HY-2 was launched by China on August 16, 2011. It flies at an altitude of 971 km and orbital inclination angle of 99.34° , this angle allows for measurement closer to the poles. Its remote sensing loads include microwave scatterometer, radar altimeter, scanning microwave radiometer and so on. The radar altimeter is used to detect the height of the sea surface, SWH, the wind speed and marine basic parameters. In this work, the SWH data of HY-2 altimeter are Level 2 product data distributed by National Satellite Ocean Application Service (NSOAS), the State Oceanic Administration of China. The data are generated after the Level 1 data inversion and with ocean and land identification as well as quality controlling. Level 2 product data mainly include the SWH, the wind speed, the sea surface height and relevant corrections used to calculate the sea surface height. One month (from January 1 to 31, 2012) of Level 2 product data, 26 673 points located in the study area, are used here (Fig. 1). Altimeter passes took less than a minute to traverse a 50 km along the orbit, with each pass typically resulting in 15–18 individual observations that can be assumed to be simultaneous (Durrant et al., 2009). After removing abnormal data, these data were averaged for one value which yielded 652 data points. The collections were used to check the wave model under the different input/dissipation terms. The HY-2 SWH fields compared well with Jason-2 satellite and NDBC buoy observed SWH fields (Wang et al., 2013) and the comparison results are satisfactory.

3.2 Wave observation radar

In the South China Sea, the direct-measurements are very scarce. Fortunately, we have obtained the SWH data of C-band WOR which fixed on oil platform PY30-1. The oil platform PY30-1 is located in the northern South China Sea at 20.245°N , 114.941°E (Fig. 1) where the annual mean wave period is 6–7 s. The annual mean wave period of the northern South China Sea is the biggest in the maritime area of China. In January, northeast wind sea and swell play a dominant role, big wave with height over 2 m occurs

frequently. The wave characteristic is typical in the northern South China Sea.

The WOR is made by the company MIROS of Norway. It is a kind of direct sensor which calculates the height of waves by measuring a water particle velocity. The WOR is based on the range gated pulsed Doppler radar technology. This radar operates in the low grazing angle mode. By using several antennas, it may be used as a directional wave sensor. The working frequency of the WOR is 5.8 GHz and a SWH measurement accuracy can reach 0.2 m. The WOR data were used to verify the wave model under the different input/dissipation terms.

4 Results

4.1 On the basis of the WOR

Five experiments have been executed in order to give insight to the effect of the different input/dissipation terms and the influence of the atmospheric instability. Figure 2 and Table 2 show that the TC96_STAB 2 is statistically closer to the WOR SWH data than others are. The WAM4_STAB 3 takes the second place. The TC96 input/dissipation terms were evolved in a similar way as

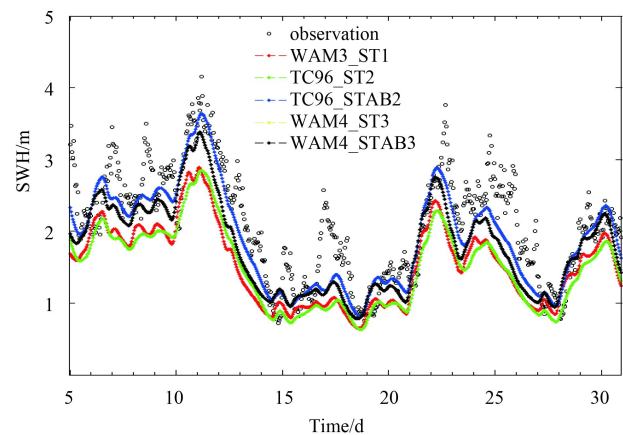


Fig. 2. Comparison of SWH between the model simulation and observed from the WOR at point 20.245°N , 114.941°E during January 5 to 31, 2012. Black circles indicate WOR measurement and dash dot lines mean model simulation results with input/dissipation term WAM3 (red), TC96 (green), TC96 considering the effect of the atmospheric instability (blue), WAM4 (yellow) and WAM4 considering the effect of the atmospheric instability (black).

Table 2. Statistical indicators for wave model SWH of the different tests comparing with the WOR data during January 5–31

Statistical indicator	WAM3_ST1	TC96_ST2	TC96_STAB 2	WAM4_STAB 3
Bias/m	0.56	0.60	0.19	0.32
RMS/m	0.71	0.71	0.41	0.52
Max bias/m	1.81	1.66	1.40	1.54

WAM3, only the TC96 dissipation function comprises two constituents: one for each of the low and high frequency parts of the spectrum (Kalantzi et al., 2009). So, the red dash dot line is almost the same with the green dash dot line in the Fig. 2 and the RMS for the WOR SWH is just the same, coincidentally. The difference of the green and blue dash dot lines (Fig. 2) show that the effect of the atmospheric instability in the TC96 source terms is remarkable and the strategy of the “effective wind speed” is significant.

In input/dissipation terms WAM4, the unstable atmospheric conditions’ effect is included in the present parameterization and is activated with the “STAB 3” switch. In this work, the results show that there is no obvious difference between the model outputs SWH with the input/dissipation terms WAM4_ST3 and the WAM4_STAB 3. In other words, the effect of the atmospheric instability in the WAM4 could not be displayed by the wave model WW3. Similarly, Bidlot et al. (2005) used the parameterization into the ECWAM model, they found that the stress lookup tables were verified to be identical, some minor differences remain which are under investigation (Tolman, 2009). So, the yellow dash dot line did not bring out owing to the overlap of the black dash dot line.

It is clear that, in the five experiments, all results with different source terms seem to be consistently underestimated with respect to the WOR SWH. Now, we utilize the “good” results of the TC96_STAB 2 to analyze the possible reason. In Fig. 3, the blue dash circle line means the SWH H_{sw} for fully developed seas as estimated from The WAMDI Group (1988) relation of wind and wave:

$$H_{sw} = \begin{cases} 1.614 \times 10^{-2} U_{10}^2, & 0 \leq U_{10} \leq 7.5 \text{ m/s}, \\ 10^{-2} U_{10}^2 + 8.134 \times 10^{-4} U_{10}^3, & 7.5 \text{ m/s} < U_{10} \leq 50 \text{ m/s}, \end{cases} \quad (7)$$

where U_{10} means the 10 m height wind speed which is WW3 model’s output parameter. Figure 3 shows that the tendency of the simulated SWH (red) during the study period is in accord with the SWH obtained from the empirical formula (blue), roughly. At the points which are enclosed by the big circles, the value of the SWH is relatively large with the low wind speed oppositely. The SWH may seem as the SWH affected by the swells. Obviously, the input/dissipation terms mentioned above are un-

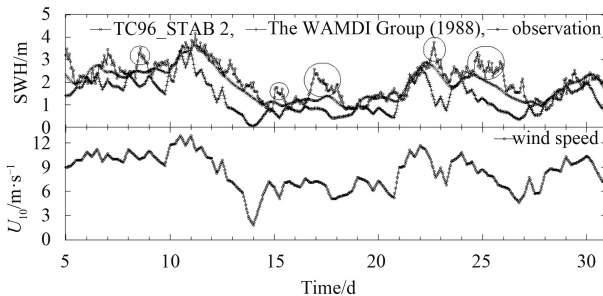


Fig. 3. Comparison of SWH between model simulation and observed from the WOR during January 5 to 31, 2012. In the top panel, black circle solid line indicate WOR measurement SWH, black product solid line means model simulation SWH with input/dissipation term TC96 considering the effect of the atmospheric instability and black solid plus line express the SWH for fully developed seas as estimated from the WAMDI Group (1988) relation of wind and wave. The wind speed is shown in the bottom panel.

able to perform adequately during a period when the area can be mostly affected by the swell which has been investigated by Kalantzi et al. (2009).

4.2 On the basis of the HY-2 altimeter

Further, here we attempt to analyze the performance of the four input/dissipation terms included in the WW3 model with respect to collocated HY-2 altimeter data. In order to verify the altimeter data against the model data better, in this work, the SWH of altimeter and model outputs data those large than 5 m or small than 0.5 m are discarded. Figure 4 lists the scatter plot of collocated SWH observations for HY-2 altimeter and model outputs with the four different input/dissipation terms. As can be seen, the WW3 with different input/dissipation terms tends to underestimate slightly the SWH through the whole study period. This can be, at least partly, attributed to the fact that the observation HY-2 SWH data set is obtained by a procedure that includes some smoothness of the final results due to interpolation. Because the wave height is usually assumed to scale with the square of the wind speed, this in principle implies that the wave model doubles the relative error of the driving wind field. On the other hand, the well-known difficulties of the WW3 on successfully simulating the swell decay contribute also to this problem.

On the whole, the comparison results are consistent with the comparison results between model and WOR SWH data. The RMS errors of the results of the WAM_ST1 (Fig. 4a), the TC96_ST2 (Fig. 4b), the TC96_STAB 2 (Fig. 4c) and the WAM4_STAB 3 (Fig. 4d) are 0.60, 0.62, 0.46 and 0.48 m, and the biases of these are 0.49, 0.53, 0.23 and 0.32 m, respectively. The result of the TC96_STAB 2 shows excellent and is statistically closer to the HY-2 altimeter SWH data than others are. The result of the WAM4_STAB 3 also takes the second place. The effects of the atmospheric stability have a potentially significant impact on a wave growth. The most logical way to model this is by adding a physical parameterization of the effects of the stability on the wave growth. But, unfortunately, such physical parameterizations have not yet been suggested.

4.3 Sensitivity analysis of the wind speed correction parameter

In all the input/dissipation terms provided by the model WW3, the TC96 parameterization with the “effective wind speed” strategy, that is, TC96_STAB 2, was proved better than others through comparing with the WOR and HY-2 SWH data during the January 5 to 31, 2012 in the study area. The parameters in the “effective wind speed” strategy need to be calibrated before a model can be applied to a specific region. The sensitivity analysis of the parameters can deal with uncertainties in model parameters. On the basis of the wave model WW3, Lee et al. (2009) selected the eight most important parameters and justified the significance priority of each parameter. They indicated that the wind speed correction parameter c_0 defined in Eq. (3) is the most sensitive and important parameter. In this work, we tuned the parameter c_0 to test its sensitivity and to give the optimal value in our study area.

There are many optimization methods to search for the optimal parameters. Considering the simplification and efficient in calculations, the same as the method used in Lee et al. (2009), we adopt an adaptive random search (ARS) (Törn and Žilinskas, 1989) method to obtain regional optimal values. Some experiments have been performed with the parameter c_0 as $1.38 \times (1 \pm i \times 10\%)$, where 1.38 is the default value and i is 1, 2, 3, and so on. The results with $i = \pm 1$ are listed in Fig. 5 comparing with the WOR SWH data, that is to say, $c_0 = 1.518$ and 1.242. The

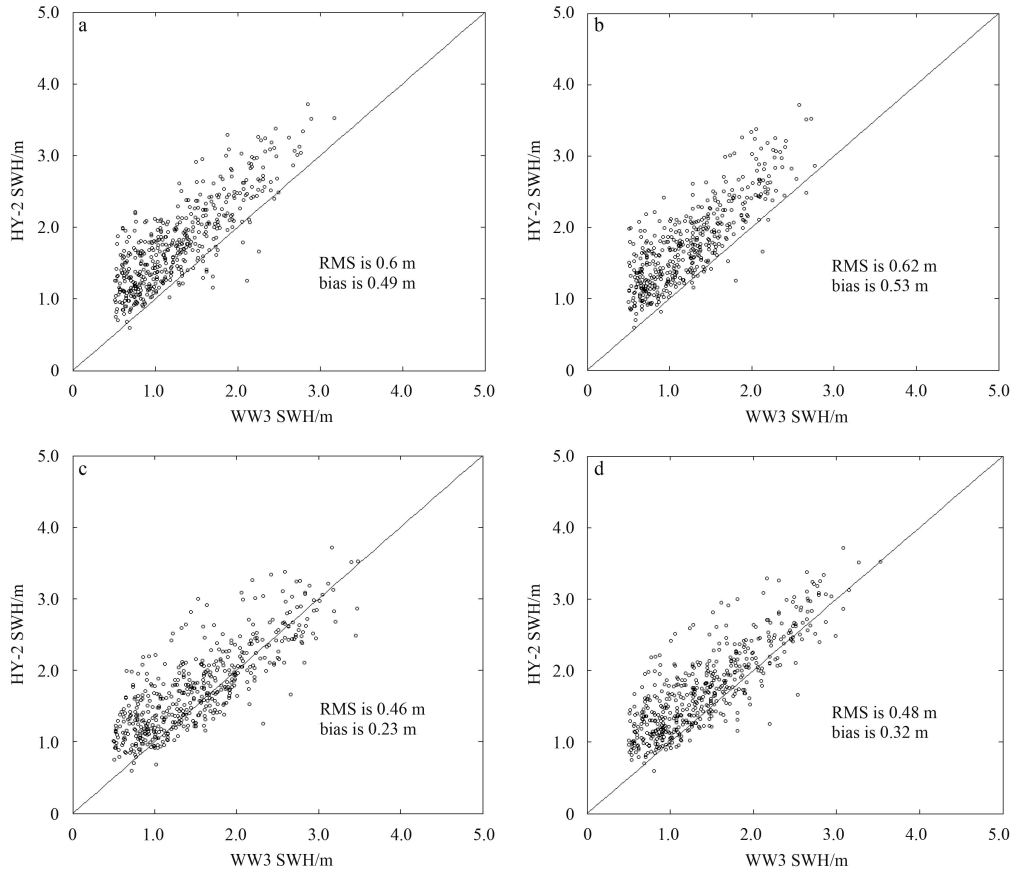


Fig. 4. Scatter plot of collocated SWH observations for HY-2 altimeter and model outputs with the four different input/dissipation terms WAM_ST1 (a), TC96_ST2 (b), TC96_STAB 2 (c) and WAM4_STAB 3 (d).

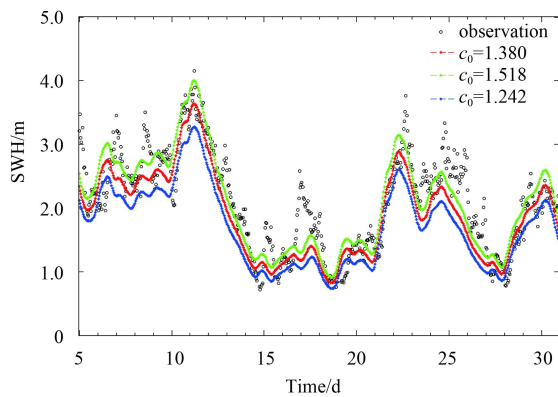


Fig. 5. Comparison of SWH between model simulation and observed from the WOR during January 5 to 31, 2012. Black circles indicate WOR measurement SWH, red dash circle dot line means model simulation SWH with input/dissipation term TC96_STAB 2 with default parameter $c_0=1.380$, blue dash dot line and green dash dot line express the same with red line only with the parameter $c_0=1.242$ and 1.518 .

results comparing with the HY-2 altimeter SWH are displayed in Fig. 6 of the parameter c_0 with the above values.

The model performance is sensitive to the wind speed correction parameter c_0 . The SWH from the experimental simulation with $c_0=1.518$ is more accurate than that of the default run, but the simulation with $c_0=1.242$ is worse than that of the default sim-

ulation with $c_0=1.380$. Comparing with the observed WOR SWH data, the RMS errors of the three experiments with $c_0=1.518$, 1.242 and 1.380 are 0.45 , 0.52 , 0.46 m, and biases are 0.10 , 0.37 and 0.23 m, respectively. As a result of the ARS method, the optimal parameter value is 1.501 with the RMS error of 0.46 m and bias of 0.09 m. In view of the different conditions, the optimal value of the wind speed correction parameter may be different which is related to the wind field, bathymetry and so on. In this work, the wind speed correction parameter of the value 1.5 , greater than the default value, may be a good choice. The procedure adopting optimal wind speed correction parameter in wave simulations did improve the accuracy of the WW3 model in comparison with default runs based on the altimeter and radar data.

5 Discussion and conclusions

In this work, comparisons of SWH acquired from the five input/dissipation source term packages in the WW3 model have been performed based on the WOR and HY-2 altimetry SWH data. The sensitivity of the wind speed correction parameter in the TC96 package also has been analyzed. The WW3 with different input/dissipation terms tends to underestimate the SWH in the South China Sea. The model is unable to dissipate the wave energy efficiently during the swell propagation with either source packages. It was found that the TC96 formulation with the stability correction Eqs (3)–(6), that is to say, the TC96_STAB 2, performed better than the WAM3 and WAM4 formulations. The effects of atmospheric stability have a potentially significant impact on the wave growth. The model performance is very sensitive to the wind speed correction parameter in the TC96 source

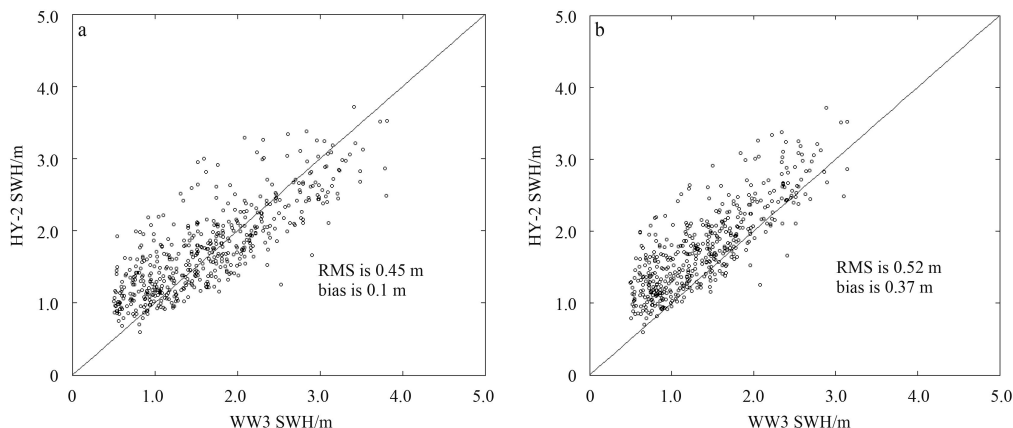


Fig. 6. Scatter plot of collocated SWH observations for HY-2 altimeter and model outputs using the input/dissipation terms TC96_STAB 2 with the parameter $c_0=1.518$ (a) and $c_0=1.242$ (b).

package. The optimal value of the speed correction parameter can be obtained through the ARS method, mathematically. The speed correction parameter needs to be calibrated and selected before the WW3 model can be applied to a specific region in order to obtain the model outputs of high quality.

The results have certain reference value for the wave modeling, using of the WW3 model, studying of air-sea interaction and so on. On the basis of point spectra, the further investigation is needed. Although the examination of the SWH gave a valuable insight into the performance of the model in different input/dissipation source terms, other integral spectral wave parameters and the wave spectrum is necessary to be examined. The effects of the atmospheric instability on the wave growth should be modeled by adding a “physical” parameterization in the future. There are two newly switches for the input/dissipation terms in the latest Version 4.18 of the wave model WAVEWATCH III named ST4 and ST6 (Tolman and the WAVEWATCH III Development Group, 2014). The further work also should include the evaluation and verification of the two input/dissipation terms.

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