Use of a global wave model to correct altimeter sea level estimates

H. Feng[1], D. Vandemark[2], B. Chapron[3] and B. Beckley[4]
1:Center for Atmospheric Sciences, Hampton University, Hampton,VA, USA.
2:NASA/GSFC, Wallops Island, VA 23337, USA.
3:IFREMER/Center de Breast, Plouzane, France.
4:Raytheon/ITSS, VA, USA

Abstract— **The study reports an assessment of global ocean wave model (Wavewatch III) outputs using altimeter algorithms wave statistics at global and regional scales. The focus is upon the sensitivity if the modeled wave moments to two distinct types of wind forcing fields, one from the NCEP atmospheric model analysis and the other from a blended product combining NCEP with scatterometer winds (QuickSCAT).**

I. INTRODUCTION

Ocean surface waves induce a bias in the satellite altimeter range measurement, the sea state bias (SSB). This SSB correction is critical for accurate altimetry measurement of sea level. To date, both theory and observations in [1]-[2] have indicated that long wave orbital velocity and short-scale wave slope variances, which are related to the second and fourth-order moments of a given wave spectrum, directly drive the SSB and its variability. The current operational SSB correction [3] relies only on the altimeter-derived wind speed U-alt and significant wave height Hs-alt. Though effective, this two-parameter SSB correction model is not entirely accurate because 1) the altimeter-derived wind is not uniquely mapped to the in situ wind, dependent on the overall sea state [4]; 2) the use of wind speed and wave height, even if accurate, does not fully parameterize the bias. One means to deal with these issues is to obtain more reliable wind measurements such as by scatterometry. Second, is to obtain measurements of higher-order ocean wave statistics to capture more subtle and physical SSB signatures. The other defining need is that such data must be contemporaneous and of high enough quality to provide information related to sea surface at the location of the fairly high resolution 6 km satellite footprint.

One potential means to gain information is through a wave model. Global ocean wave modeling has now entered an operational stage, capable of providing a full two-dimensional gravity wave spectrum that may be useful in sea state bias work. Thus, we have implemented an open source surface wind-wave model WaveWatch III, WW3 [5]. Our approach is to merge wave model, altimeter, and scatterometer data, with an overall goal being to evaluate the feasibility of combining this information to develop an improved point-by-point sea state bias range correction. As one step towards this goal, this study looks at the global and regional characteristics of wave model spectral parameters and their sensitivity to changes in the wind forcing fields.

II. METHODS

A. WW3 and wind forcing fields

WW3, a fully third-generation ocean wind wave model, has been developed at NOAA/NCEP/NWS and operationally run by the U.S. Navy and numerous operational and research sites. It solves the spectral action density balance equation for wavenumber-direction spectra with nonlinear physics for forecasting the evolution of directional wave energy spectra used to estimate mean wave parameters. The source and sink terms in WW3 (v1.18) were tuned and validated using ERS-2 altimeter wave height data [5]. In our application, WW3 is run for the entire year 2000 on a global 1^o by 1^o grid over the integration domain from 70S to 70N in latitude and at a 6 hourly time step. The spectral resolution (i.e. wave-number grid) is determined by 24 directions and 25 frequencies which are logarithmically spaced from 0.042 Hz to 0.405 Hz with intervals of $\Delta f/f = 0.1$.

The quality of the wind fields used to force a global wave model is a first-order control upon the wave field output. Two different types of wind fields were used to force the wave model and hindcast the mean wave parameters. One is the standard NCEP/NCAR reanalysis atmospheric model having winds similar to those by which WW3 (v1.18) was forced. The other is a blended wind product derived through the spatial blending of high-resolution scatterometer (QuickSCAT) wind data with the NCEP global model analyses [6]-[7]. This product provides a potential means to drive the ocean waves with a higher resolution wind. We wish to ascertain the value of a highly-resolved and more precise wind field from the NCEP/QSCAT blended product. Is it critical for generating more accurate estimation of high-order wave model moments for SSB correction studies? Both NCEP model and the blended NCEP/QSCAT wind fields are discussed and resultant model outputs are assessed to identify the value of using the scatterometer winds in this context of the altimeter sea level correction.

B. Data compilation

WW3 model-estimated wave parameters, NCEP and blended NCEP/QSCAT winds, and altimeter (TOPEX side B)-derived data were all collocated by spatial and temporal interpolation onto the standard NASA/GSFC altimeter pathfinder locations [8]. That is, all data are collocated along the TOPEX ground

0-7803-8743-0/04/$20.00 (C) 2004 IEEE

tracks for the entire year. There are over 1.5 million data records for the year 2000. The collocated parameter subset used here is summarized in Table I.

TABLE I. LIST OF THE COLLOCATED PARAMETERS

TOPEX-derived variables	
ssha	sea surface height anomaly
Hs-alt	significant wave height
U-alt	sea surface 10 m wind speed
σ_{ku} and σ_c	Ku- and C-band radar cross sections
Winds and WW3 model parameters	
(u, v)_N	(E/W, N/S) wind components (NCEP)
(u, v)_Q	(E/W, N/S) wind components (NCEP/QSCAT)
(m0,m1,m2,m4)_N	$1^{st}.2^{nd},3^{rd},4^{th}$ order moments (WW3/NCEPWinds)
(m0,m1,m2,m4)_Q	$1^{st}.2^{nd},3^{rd},4^{th}$ order moments (WW3:NCEP/QscatWinds)
Calculated wave parameters	
Hs_N,Hs_Q	(WW3 modeled significant wave heights by NCEP and NCEP/Qscat winds)
Tm_N,Tm_Q	WW3 modeled mean wave periods by NCEP and NCEP/Qscat winds
mss_N, mss_Q	WW3 modeled mean square slope by NCEP and NCEP/Qscat winds

Wave parameters calculated from the wave model moments are based on the following definitions:

Significant wave height Hs = $4\sqrt{m_0}$

Mean wave period Tm = $\sqrt{m_0 / m_2}$

Mean square slope mss= $(2\pi)^4 g^{-4} m_4$

C. Evaluation of wave model output using global altimeter data

Assessment of wave model-estimated parameters needs special consideration, particularly for the higher-order moments relevant to SSB corrections. These are m2 and m4, the velocity and acceleration variances. The operational wave forecasting centers usually focus on model validation using the significant wave height [9]. The calibration and validation of WW3 in NCEP/NWS was also focused on Hs. Our needs are somewhat different and we turn to recent altimeter studies to propose additional checks upon the wave model output. Several studies have evaluated coincident satellite altimeter and NDBC wave buoy measurement data sets to develop algorithms for deriving wave field statistics beyond the well accepted altimeter-derived significant wave height.

Gourrion et al. in Ref. [10] have shown that C-band radar cross section σ_c from satellite altimeter can be used along with the altimeter-derived wave height Hs to estimate the mean square slope that would be obtained by a typical 3 m NDBC discus buoy. In the development of that altimeter mss algorithm, they first calculate the buoy-based mss by spectral integration up to a frequency cutoff of 0.4 Hz, similar to that used in WW3. Using a large dataset of collocated NDBC and TOPEX observations, a neural network was then trained to estimate the buoy mean square slope (mss) using C-band radar cross section σ_c and altimeter-derived ("true") wave height Hs:

$$\text{Mss\_alt} = \text{FNN1}(\sigma_c, \text{Hs}) \qquad (1)$$

With a similar reasoning and approach, an algorithm was recently developed [11] to infer the mean surface wave period by using altimeter Ku-band radar cross section σ_{ku} and the altimeter-derived wave height Hs:

$$\text{Tm\_alt} = \text{FNN2}(\sigma_{Ku}, \text{Hs}) \qquad (2)$$

Finally, Gourrion et al. in Ref. [5] reports a neural network algorithm for altimeter-derive wind speed in terms of Ku-band radar cross section σ_{ku} and altimeter wave height Hs. This routine provides the operational satellite wind speed product for the Jason-1 altimeter. These altimeter algorithms are used below for the wave model evaluations. We select the three parameters Mss_alt, Tm_alt, U_alt plus altimeter-derived Hs_alt along with the counterparts from WW3 model driven by NCEP and blended NCEP/QSCAT winds for intercomparison. It should be noted that the effort here should not be considered a validation of Tm and Mss but more of an assessment. Eqs. 1 and 2 above are routines developed to crudely estimate the given wave statistics from the altimeter wave height and cross section data. The assessment is thus one of general distribution characteristics (e.g. the mode and shape) and of the relative changes seen between model wind forcing.

III. RESULTS

In order to evaluate deviations from the global view, some regions representative of different wind-wave climates have been selected. Table II gives their geographical coverage.

TABLE II. SELECTED REGIONS WITH THEIR GEOGRAPHICAL EXTENTS

Regions	Longitude range	Latitude range
Global	0-360	-66S – 66N
Northern Ocean	0-360	47N – 66N
Southern Ocean	0-360	66S – 47S
Equatorial Pacific	173-246	20S – 20N
Eastern Eq. Pacific	250-268	0– 20N

A global view of validation and comparison is shown in Fig. 1. First, the blended NCEP/QSCAT wind field may be considered closer to the surface truth. Globally, the NCEP model winds have a negative bias in comparison with the blended NCEP/Qscat winds. Interestingly, the WW3 model Hs-Qscat generated by NCEP/Qscat winds has a systematic positive bias that is consistent with what Rogers and Wittman reported in a recent study [12]. They discussed the sensitivity of wave field energy to different model physics and to different wind forcing fields, and indicated that it was the wind forcing, rather than wave model physics, that drove model differences in Hs. Furthermore, altimeter-derived wave height Hs-alt accords with Hs-NCEP very well. It is most likely because WW3 model was tuned and validated in terms of a global run driven by wind fields similar to our NCEP winds.

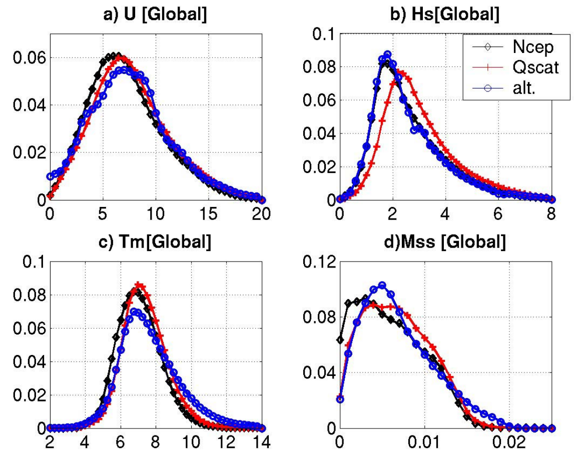

Figure 1. Validation and comparison of the distributions of the four parameters (**Global**); the WW3 products generated using NCEP and NCEP/QSCAT blended wind fields and altimeter estimates are all shown . (a) Windspeed U; (b) wave height Hs; (c) mean wave period Tm and (d) mean square slope Mss.

Mean wave periods for the three products accord fairly well with each other, showing a consistent distribution mode. The discrepancy between WW3 mean wave periods (Tm- Ncep and Tm-Qscat) and altimeter period Tm-alt (Eq. 2) can be identified by a critical period (~= 8.2 second). Beyond and below it, WW3 model periods are under- and over- estimated, respectively. Finally, the distributions of mean square slope (Mss) shown in Fig. 1 exhibit more complicated and distinctive pdf patterns. But the general expectation that this highest-order statistic follows the wind distribution appears to be true. In general, the distribution pattern of Mss-Qscat is more consistent with that of Mss-alt from Eq.1. One particular distinction between Mss-Qscat from Mss-NCEP is that Mss-Qscat accords with Mss-alt very well in the lower Mss while the NCEP driven product seems biased to low values. Mss-Qscat seems overestimated in the higher Mss in comparison with Mss-alt.

To further investigate the details of these distribution features beyond the global view, we offer two typical regional views in Figs. 2 and 3. Fig. 2 displays intercomparison of the four parameters for the region of the Northern Ocean defined in TABLE II. Note that results for the Southern Ocean region (not shown) are similar to Fig. 2. Some distinct features are observed. Three wind fields match one another very well, and so do the wave height fields. For the other two parameters Tm and Mss, both WW3 model products are highly consistent with each other, particularly for the high sea states. Subtle difference is seen at the lowest seas states (Hs < 1.5m). Model agreement may suggest that in the regions with strong winds WW3 model performs consistently when using either wind field as forcing, even for these higher-order moment estimates. In other words, the wave response to winds by WW3 model is driven mainly by wind strength rather than spatio/temporal forcing field differences, at least in the high latitude regions. On the other aspect, if compared with the altimeter-derived Tm-alt and Mss-alt, a similar model vs. altimeter discrepancy

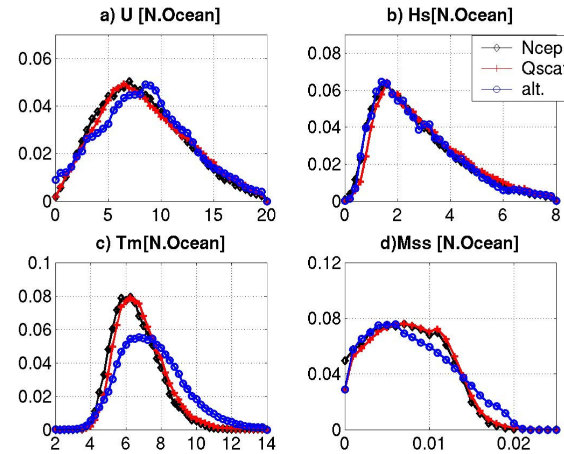

Figure 2. Validation and comparison of the distributions of the four parameters (Northern Ocean). Note that all other explanations are the same as in Figure 1.

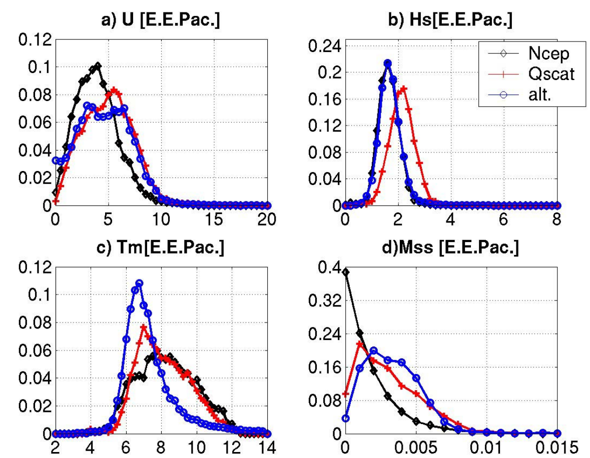

Figure 3. Validation and comparison of the distributions of the four parameters (**Eastern Equatorial Pacific**). Note that all other explanations are the same as in Figure 1, but the scale in (d) has been changed, different from in Figures 1 and 2)

can be seen more obviously than for the global view of Fig. 1. Specifically, there is a critical period (~7.8 seconds shorter than what is documented in the global view) beyond and below which the WW3 model Tm gets under- and over-estimated, respectively, using Tm-alt as a reference. Generally consistent with what is seen in Fig. 1, WW3 modeled Mss matches Mss-alt well in the lower Mss region, but there is a critical Mss that divides WW3 model Mss into two, showing beyond and below it WW3 model Mss is over- and under-estimated, respectively.

Fig. 3 displays the four parameters for the Eastern Equatorial Pacific (TABLE II). The blended NCEP/Qscat winds match U-alt well and are much higher than NCEP winds. The WW3 Hs-Qscat has a high positive bias. Interestingly, the discrepancy of the WW3 model Tm and Mss with respect to altimeter-derived ones is opposite to that seen in Fig. 2 (for the high latitude cases). For WW3 model mean slope variance, Mss-NCEP is significantly lower than Mss_Qscat while the latter accords with the altimeter Mss-alt.

A further check into Mss-alt, Mss-NCEP and Mss-Qscat by means of wind-dependent sea surface roughness is shown in Fig. 4. In the high latitude regions (i.e. the Northern and Southern Oceans), the wind-dependent Mss patterns of the two WW3 model products agree, generally consistent with the global pattern. However, the deviations between the two model Mss products are most apparent in the Eastern Equatorial Pacific region where both winds and wave heights are low. For instance, the most likely speed occurs around 3-5 m/s (see Fig. 3) where the most significant difference between the two models is seen in Fig. 4. Mss-NCEP is substantially lower. It should be pointed out that the altimeter sea state range bias in this region is fairly significant.

IV. SUMMARY

This study reports an altimeter-based evaluation of wave model (Wavewatch III) parameters, including Hs, Tm and Mss from low to high order moments at both a global scale and regional scales. One focus is on the sensitivity of the high-order moments to two distinct types of wind forcing fields, NCEP model winds and the blended winds products using scatterometer (QuickSCAT) and NCEP model wind analyses. On a global scale, we have found WW3 model wave parameters accords with altimeter derived ones. In different regions with different wind-wave environments, the model wave parameters compare with altimeter parameters differently. For high sea state cases (high latitude regions), the model parameters calculated by WW3 runs driven by NCEP and NCEP/QSCAT winds match very well, and also accord greatly with altimeter-derived parameters. Their sensitivity to wind forcing seems. In the cases of low sea states, the difference between the two model products from NCEP and NCEP/QSCAT winds is significant, particularly for Hs and Mss, but is very small for Tm, suggesting that Hs and Mss is quite sensitive to winds, but much less sensitive for Tm. It is important to note that modeled Mss-NCEP appears unreasonably low for this case. The sea state bias in this region is fairly significant. Special attention may be required in this context.

Logically, the altimeter comparison approach in this work is, at minimum, independent since WW3 model wave parameters (Hs, Tm and Mss) are determined without access to any altimeter assimilations. The altimeter wave parameters are retrieved using routines tuned to NDBC buoy data (ground truth, but certainly not global). Still, from a global view, the model-estimated Tm is consistent with altimeter-derived values. Once viewed separately in high-latitude and equatorial regions, the distinguishing features of the pdf patterns of WW3-derived Tm (and Mss) with respect to altimeter-estimated ones are noticed in the two regions where wind wave climates are different. A further investigation into these distinguishing features is needed to understand if there is geophysical meaning behind the feature differences in different regions. Initial looks suggest that excessive swell generated at higher latitudes using the NCEP/Quikscat winds is responsible for much of the WW3 model disparities at the lower latitudes.

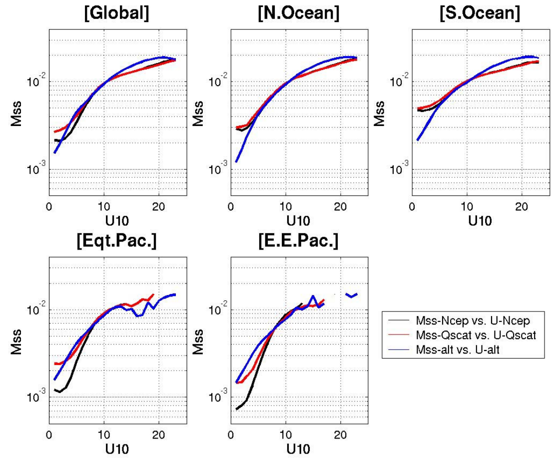

Figure 4. Wind dependence of the mean square slope variance (Mss) of the WW3 model Mss-Ncep and Mss-Qscat and altimeter-derived Mss-alt. Note that the corresponding wind fields were used in this analysis.

REFERENCES

[1] B. Chapron, D. Vandemark, T. Elfouhaily, D.R. Thompson, P. Gaspar and S.LaBroue, "Altimeter sea state bias, A new look at global range error estimates," J. Geophys. Res., vol. 28, pp. 20,3947-3950, 2001.

[2] F. Millet, D.V. Arnold, K. F. Warnick, and J. Smith , "Electromagnetic bias estimation using in situ and satellite data: 1. RMS wave slope," J. Geophys. Res., vol. 108, no. C2, pp. 3040, 2003.

[3] P. Gaspar P., S. Labroue, F. Ogor, and G. Lafitte, L. Marchal, and M. Rafanel, "Improving nonparametric estimates of the sea state bias in radar altimeter measurements of sea level," J. Atmos. Oceanic Technol., 2001.

[4] J.Gourrion, D.Vandemark, S. A. Bailey, B. Chapron, C. Gommenginger, P. Challenor and M. A. Srokosz, "A two parameter wind speed algorithm for Ku-band altimeters," J. Atmos. and Oceanic Technol., vol .19, no.12, pp . 2030-2048, 2002.

[5] H.L. Tolman, "Validation of WAVEWATCH III version 1.15 for a global domain. NOAA / NWS / NCEP / OMB Technical Note," 2002.

[6] T.M. Chin, R.F. Milliff, and W.G.Large, "Basin-scale, high-wavenumber sea surface wind fields from a multiresolution analysis of scatterometer data," J. Atmos. and Oceanic Technol. , vol. 15, pp. 741-763, 1998.

[7] R.F. Milliff., W.G. Large, J. Morzel, G. Danabasoglu, and T.M. Chin, " Ocean general circulation model sensitivity to forcing from scatterometer winds," J. Geophys. Res.,*Oceans*, vol. 104, no.C5, pp.11337-11358, 1999.

[8] C.J. Koblinsky, B.D. Beckley, R.D. Ray,Y.-M. Wang, and A. Brenner, "NASA Ocean Altimeter Pathfinder Project Report No. 1: Data Processing Handbook, Goddard Technical Memorandum," 1998.

[9] J.R. Bidlot, D.J. Holmes, A.P. Wittmann, R. Lalbeharry, and H.S. Chen, "Intercomparison of the performance of operational ocean wave forecasting systems with buoy data. Weather and Forecasting," vol. 17, pp. 287-310, 2002.

[10] J.Gourrion, D. Vandemark, S. A. Bailey and B. Chapron, "Investigation of C-band altimeter cross section dependence on wind speed and sea state," Can. J. Rem. Sens., vol. 28, no. 3, pp. 484-489, 2002.

[11] Y. Quilfen, B.Chapron, F. Collard, and M. Serre, "Calibration/validation of an altimeter wave period model and application of Topex/Poseidon and Janso-1 altimeters", (personal communication)

[12] Rogers, W.E. and P.A. Wittmann, Quantifying the role of wind field accuracy in the U.S. Navy's global ocean wave nowcast/forecast system, NRL Memorandum Report, 2002.