Evaluating the sea state bias using wave model data

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Overview

The long term goal for this work is to improve the point-by-point estimation of the sea state bias range correction for any given satellite altimeter. The question we explore here is - Can surface wave estimates obtained from an operational wave model provide a path to this improvement? The issue driving this question is the need to acquire more information on the "instantaneous" sea state conditions during satellite passage over a given region.

The sea state's degree of wave steepness, or the effective level of nonlinearity, is what produces much of the range bias. It is understood that altimeter-derived surface estimates, the wave height and wind speed, do not fully parameterize this nonlinearity. Yet these data are coincident with the altimeter's range measurement. The spatial and temporal scale of large surface gravity wave field gradients extends from 1-200 km and 0.5-48 hrs. Operational wave models provide a full two-dimensional gravity wave spectral estimation at specified spatial and temporal scales falling well within this range. This work looks at both the WAM and WaveWatch III operational model output in tandem with TOPEX data to assess the feasibility of combining altimeter and wave model data to better understand and estimate sea state-dependent range biases. The methodology is applicable to any altimeter and may potentially benefit from the improved spatial surface sampling obtained in the tandem mission phase.

Steps that are addressed here include:

- Specific detail pertaining to wave model application to the sea state bias problem
- Use of the wave model data to statistically-affirm the connection between wave steepness and the sea state bias at a global scale
- Continued emphasis on the fact that the altimeter wind speed is not the true speed

Background

Previous work (Vandemark et al., 2002) shows that conditional ensemble averaging over the sea surface height anomaly provides a means to directly assess the range bias associated with sea state dynamics. This has been shown to work for any platform including Jason-1 and TOPEX. This approach is central to our evaluation of wave model applicability.

Operational wave model and wind model products have been collocated with all valid open ocean TOPEX measurements in the year 2000. The compilation holds more than 1.5 million altimeter estimates. For each estimate 32 variables related to the measurement, the surface wave spectrum, and the surface wind are stored. Both WAM and the WaveWatch III (Tolman, 2002) outputs have been processed and collocated in this manner. Wavewatch III data are being produced in-house while the WAM data were provided by Meteo-France.

What do we want from the wave model? Both theoretical and observational sea state bias work suggests that the first-order wave spectral parameters to focus upon are the acceleration and velocity variances. These parameters are derived from the nondirectional wave height spectrum, $S(\omega)$, as $m_4 = \int \omega^4 S(\omega)\, d\omega$ and $m_2 = \int \omega^2 S(\omega)\, d\omega$ where ω is the wave frequency. Three parameters enfolding these moments are:

- rms slope $= \sqrt{[(2\pi)^4 g^{-2} m_4]} = \sqrt{\text{slope variance}} = \sqrt{mss}$
- inverse wave age $= U/C_p = U\sqrt{(m_2/m_0)}$
- significant slope $= H_s k_p \approx H_s \langle k \rangle = (2\pi)^2 g^{-1} (m_2/m_0) \sqrt{m_0}$

where U is the wind speed at 10 m, C_p is the phase velocity of the dominant wave, k is the wavenumber, and k_p the wavenumber of the dominant wave. Each of these parameters are nondimensional candidates for examination within the sea state bias correction

$$\beta = \varepsilon \cdot H_s \quad \text{(units of m)} \qquad (1)$$

That is:

$$\varepsilon = F(\sqrt{m_4},\ U\sqrt{(m_2/m_0)},\ m_2/\sqrt{m_0}) \qquad (2)$$

This is a first-order development where the potential dependence upon wind and/or the altimeter radar cross section data is neglected.

Issues in wave model application

The even-order spectral moments, m_0, m_2, m_4 are identified for application to sea state bias study. A first step is to validate these wave model estimates. The operational centers focus on the wave height and the wave period in their wave model calibration, validation, and assimilations, i.e. m_0 and m_1. Typically, buoys and/or the satellite altimeters are used as the ground truth in these efforts. Our application involves higher order moments and suggests new means of quality assurance may be required.

Several conclusions have been drawn to date -

- The altimeter, through the use of C-band radar cross section data, can provide a useful service in the validation of wave model acceleration variance (m_4) estimates.
- Wave model outputs for all moments (m_0, m_2, m_4) are sensitive to the spatial and temporal resolution of the wind forcing products used and to the extent of assimilation (and implicitly on the spectral partitioning algorithm).
- High frequency wind forcing from the NCEP/QSCAT blended product leads to improved wave model estimation of the wave acceleration variance

Validation of wave model m_4 using a C-band satellite altimeter

It was recently shown (Gourrion et al., 2002a) that the C-band radar cross section data from an altimeter, σ_{oC}, can be used in tandem with the H_s estimate to derive the acceleration variance seen by a wave measurement buoy. The mss (i.e. m_4) data from a series of NDBC buoys in differing regions about the U.S. are shown if Fig. 1. These data are obtained by spectral integration up to a frequency cutoff of 0.4 Hz. As one can see the data can vary widely for a given level of wind and H_s. A neural network algorithm was developed using techniques similar to those in Gourrion et al. (2002b) and a large NDBC/TOPEX data compilation to estimate mss_{NDBC} using altimeter data as:

$$mss_{NDBC} = [(2\pi)^4 g^{-2}]\, m_{4\_NDBC} \approx mss_{\_T/P} = f(\sigma_{oC}, H_s) \qquad (3)$$

The 0.4 Hz buoy cutoff for mss_{NDBC} is the same used in deriving moments from the wave models. Therefore, we use the collocated $mss_{\_T/P}$ estimates in our year-long data set to evaluate wave model mss estimates in Figs. 2 and 3.

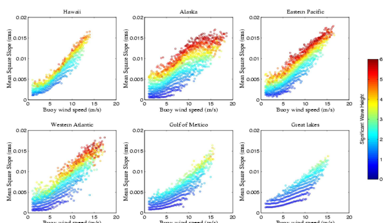

Fig. 1 – Long wave slope climatology for NDBC buoys. Eight year average of buoy-derived mean square slope (mss_{NDBC}) for the noted regions. A TOPEX algorithm to reproduce these observations was developed using the W. Atlantic and E. Pacific observations taken at TOPEX overpass times. Note the dependence of the wave slopes on both H_s and U and the regional differences.

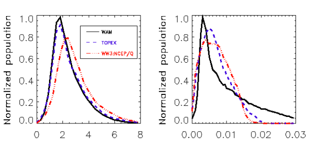

Fig. 2 – Wave model validation. Global WAM, WaveWatch 3 and TOPEX estimates of wave height and slope variance. Data are from our fusion of wave model and TOPEX data. The outliers are the wave height pdf from WaveWatch 3 and mss from WAM. Explanation for the first is the use of a high frequency wind product in the WaveWatch run. The WAM anomaly may be partially due to error in deriving this product from the WAM spectra.

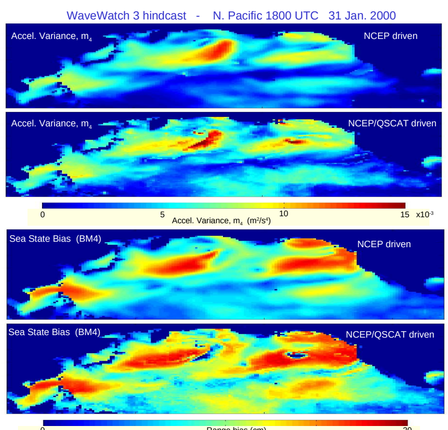

Fig. 4 – Wave model differences due to wind field choice. Global WaveWatch 3 output generated using NCEP and NCEP/QSCAT blended wind fields. The upper panels show m_4 while the lower panels show the the sea state bias estimated using the TOPEX MGDR SSB algorithm (BM4) with H_s and wind coming from the model fields.

The changes in spatial dynamics are clear and indicate that the scatterometer-impacted blended wind product leads to wave model information with higher spatial resolution.

Wave model sensitivity to the wind forcing

Wave model statistics from WAM and WaveWatch III are derived on a global scale at 0.5 and 1.0 deg. grids respectively. Both are forced by 6 hourly wind fields. For WAM the ECMWF winds were used. For WaveWatch we use the NCEP/QSCAT blended wind product (Milliff et al. 1999). This latter wind product provides much higher spatial resolution and the real-world surface wind observations from the scatterometer. Rogers and Whittman (2002) discuss the sensitivity of these wave models to the choice of wind forcing products as it pertains to the lowest order moments (i.e. m_0). They suggest that the wind, and not wave model physics, is the critical factor describing observed model differences. We also find that this is the case (see Fig. 2), and that the differences are also apparent in the higher order moment m_4 (see Figs. 2 and 3). To confirm this we've also run WaveWatch III with NCEP alone. The global maps at left show the wave model output for NCEP and for the NCEP/QSCAT blend. For sea state bias work where contemporaneous high frequency content (in the spatial domain) is required, the blended wind product is highly desirable and likely to be the preferred choice.

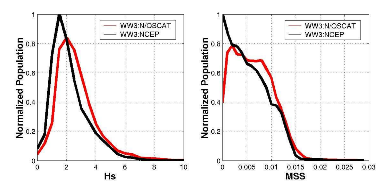

Fig. 3 – Wave model differences due to wind field. Global WaveWatch 3 output generated using NCEP and NCEP/QSCAT blended wind fields. The scatterometer-influenced wind product produces wave heights with a systematic positive bias. The pdfs for **mss** (or m_4) in Fig. 2 and Fig. 3 suggest that the NCEP-driven hindcast produces an underestimate of this higher order moment. This is consistent with the global m_4 maps in Fig. 4.

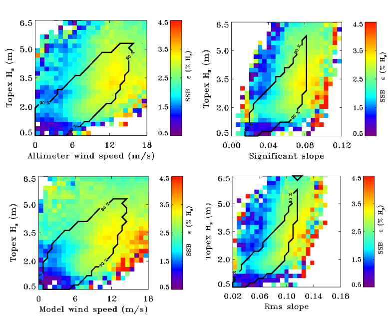

Fig. 5 – Two parameter statistical mappings of the global sea state bias. Data come from the year-long fusion of wind (NCEP/QSCAT) model, wave (WW 3) model, and TOPEX side B. Roughly 1.5 million samples are assessed to generate the ensemble averaged sea level bias estimates given here. Points to note –

- All results inside the 90 % contour are quite similar
- Model wind results show some diff. with altimeter wind. This has been anticipated and should be examined further.
- All mappings show very low SSB at the low wave height – method signal-to-noise ?
- More dynamic range seen in the sig. slope and rms slope mappings than for the altimeter wind
- Rms slope and significant slope share similarities – clear range bias increase with wave steepness for the higher wave heights.

Sea state bias versus wind/wave model parameters

Shown at left are ensemble-averaged estimates of the TOPEX sea state bias (as % H_s) versus both wave height and the given variable. These represent candidates for ε mentioned above in Eq. 3. The global renderings represent an average over a year-long period. The figures represent only two-dimensional results yet they already yield some interesting results as discussed under Fig. 5. The upper left panel is the 'standard' on-orbit 2 parameter mapping. One can see that it bears much similarity to the other panels, but there are also some obvious differences. These data provide a new means to globally depict the first-order physics of the sea state bias – it is clear that the range bias increases with long wave steepness, either the significant slope or the rms slope. As a further illustration, and anticipating a pragmatic path to 3-parameter SSB models, Fig. 6 provides the residual from the usual [Hs, U] mapping at one particular state versus the noted model-derived long wave parameters.

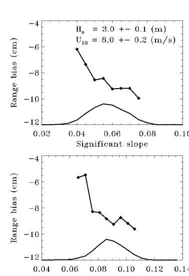

Fig. 6 – Sea state bias for fixed altimeter wave height and wind speed as indicated. The averaged range bias magnitude increases with increasing wave steepness (either sig. slope or rms slope). A 3-4 cm range in this residual is seen for both parameters. The curves at bottom are the sample population. There are a total of 2500 samples within this data subset.

Future work

Results in this ongoing study continue to suggest that combination of altimeter, wind model, and wave model estimates may yield an improved sea state bias estimator. The interim goal to validate the physics involved in the process also looks obtainable. TOPEX data are used here, but the approach developed is easily transferred to Jason-1. In fact, the tandem phase TOPEX/Jason-1 mission is an ideal opportunity to examine strong spatial gradients in the sea state bias as well as the wave model spatial resolution issues such as that observed in Fig. 4.

Several key issues to nail down are the generation and validation of adequate wave model information (e.g. does the scatterometer-driven 'blended' wind provide substantially improved results in sea state bias evaluations?), the optimal multi-variate fusion of model and altimeter estimates for operational range bias correction, and the development of metrics to demonstrate the skill for any new proposed algorithm.

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