Refined Source Terms in WAVEWATCH III
with Wave Breaking and Sea Spray Forecasts

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LONG-TERM GOALS

Several U.S. Federal Agencies operate wind wave prediction models for a variety of mission specific purposes. Much of the basic science contained in the physics core of these models is over a decade old, and incorporating recent research advances over the last decade will significantly upgrade the model physics. A major goal is to produce a refined set of source and sink terms for the wind input, dissipation and breaking, nonlinear wave-wave interaction, bottom friction, wave-mud interaction, wave-current interaction as well as sea spray flux. These should perform demonstrably better across a range of environments and conditions than existing packages and include a seamless transition from deep to shallow water outside the surf zone. After careful testing within a comprehensive suite of test bed cases, these refined source terms will be incorporated into the prediction systems operated by these agencies and by the broader wave modelling community.

OBJECTIVES

Our aim to improve the accuracy of ocean wave forecasts over a wide dynamic range of wind speeds out to hurricane conditions, contributing a dissipation source function that adds explicit wave breaking statistics for the wind sea to the forecast products. Allied aims are to effectively decouple swell systems from the wind sea and to provide a framework that allows full coupling to the associated atmospheric and ocean circulation models. As part of this project we aim to refine the parameterization of air-sea and upper ocean fluxes, including wind input and sea spray as well as dissipation, and hence improve marine weather forecasts, particularly in severe conditions.

APPROACH AND WORK PLAN

We have continued using our refined version of the threshold-based spectral dissipation rate source term S_{ds} introduced by Alves and Banner (2003), as described in detail by Banner and Morison (2010). This replaces the original Komen-Hasselmann integral formulation for S_{ds} presently used in most operational models. Our refined S_{ds} parameterization provides a spectral localization of the dissipation according to the scales of the waves that are breaking. The performance of this updated source term is being investigated in conjunction with a modified Janssen (1991) wind input source term and the ‘exact’ form of the nonlinear source term S_{nl} (Tracy and Resio, 1982) over a very wide range of wind speeds using a broad computational bandwidth for the wave spectrum. This avoided the known spurious effects arising in faster approximate versions for this source term. PIs Banner and Morison worked closely on refining the source terms and validating the results, with Morison leading the computational effort.

A significant issue is the additional wind stress component due to the separated air flow over breaking waves. Our methodology produces breaking wave stress parameterizations linked to computed breaking wave properties, and indicates that this additional wind stress component can be an appreciable fraction of the total wind stress depending on the wind speed and wave age conditions, consistent with observations of Banner (1990). In hurricanes, our calculations suggest it can approach around one third of the non-breaking wave stress.

Detailed comparisons have already been made with growing wind sea results from the ONR FAIRS open ocean data set (e.g. Edson et al., 2004) gathered from FLIP in 2000. Here, breaking wave observations that were made along with measurements of wind stress, wave height and water-side dissipation rate. Our model results closely reproduced these observations, including the breaking wave properties. We have also tested our model framework over the wind speed range of 3-100 m/s and found the model behaved stably and has produced plausible results for both wave and sea surface drag coefficient behaviour.

Our model framework has been transitioned into the WaveWatch III environment, using the Exact NL and DIA options for the nonlinear source term S_{nl} in our model refinement. Our approach can use other implementations of S_{nl} as they become available. We are validating our WaveWatch III implementation and will continue with this key aspect of our effort.

WORK COMPLETED

During FY14 we continued our study on the impact of our source terms, as refined in our FY13 annual report, as a result of new data becoming available. We were especially interested in investigating what controls the modeled directional spreading width in the spectral tail, and how to increase the accuracy of forecast breaking wave properties.

A key focus of our effort was investigating the performance of our refined dissipation (S_{ds}) and wind input (S_{in}) source terms against a comprehensive data set for the very young wind sea evolution reported by Schwendeman et al. (2014). This was based on their high wind, short fetch observations, including detailed properties of the breaking waves, in the Strait of Juan de Fuca, north of Sequim, Washington. This verification was carried out with our research fetch/duration limited model that utilizes the ‘Exact NL’ formulation for the nonlinear spectral transfer term S_{nl}. We also formulated and tested a sea-state dependent, spectral sea-spray models to refine existing windspeed-only sea spray models presently used in severe sea state applications.

In parallel, our source terms have been implemented in WaveWatch III . We have been assessing their performance against a number of criteria, including significant wave height, wave periods, wave train evolution, breaking wave probabilities, spectral breaking crest length per unit area distributions, and others. One of the key validation properties we are also examining is the drag coefficient, and how it behaves as a function of U_{10}, sea state and other conditions in both the model and the available data. For the latter, we are using NCEP's Climate Forecast System Reanalysis Version 2 (http://cfs.ncep.noaa.gov/cfsv2.info/CFSv2_paper.pdf/). A detailed publication describing refinements to our source terms and their performance is in preparation.

RESULTS

Details of the model refinements made during FY14 and their outcomes are summarized below:

(i) a*ngular spreading dependence in the wind input: implications for directional spreading*

The standard Janssen (1991) wind input source term has the input dependent on $(u_* \cos\theta)^2$. However, the directionally-resolved wind stress has a $u_*^2 \cos\theta$ dependence. With this in mind, we modified the directional dependence of the wind input source term S_{in} from $\cos^2\theta$ to $\cos\theta$. This produced an increase of about 10 degrees in the total directional spreading width of the spectral tail. This brings the modeled directional spreading width into closer agreement with the limited available observations. We note that WaveWatch III uses the DIA form in S_{nl}, which has an intrinsically broader spreading width than Exact NL. This produces broader direction spreading in the spectral tail in closer agreement with observations.

(ii) *new formulation for breaking probability against normalized saturation.*

We obtained access to two new field measurement datasets for young wind sea conditions, from locations in the Strait of Juan de Fuca and in the Adriatic Sea. By combining these new data with our existing breaking observations, we refined the dependence of the breaking probability on the directionally-normalized wave saturation introduced by Banner et al. (2002). We replaced the linear dependence with a square-root dependence, as indicated in Fig. 1. This provides forecast

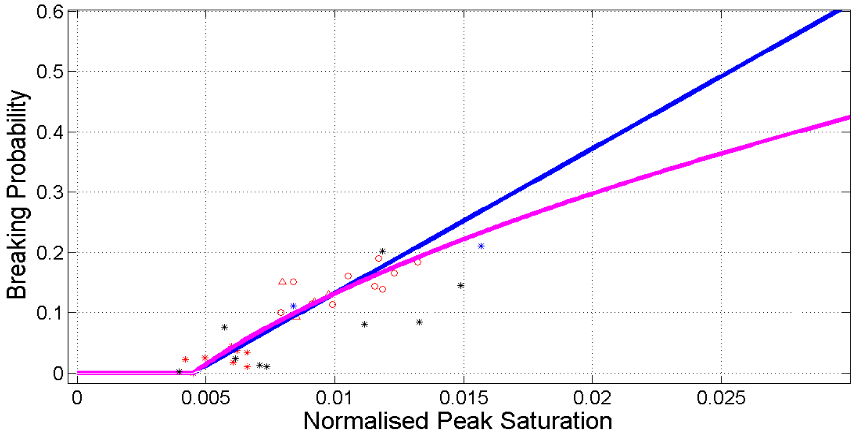

Fig.1 Measured and parameterized breaking probability for the spectral peak waves as a function of the directionally-normalized spectral peak saturation, as defined in Banner et al. (2002).The symbols show available spectral peak breaking probability data. The blue line is the linear fit used in Banner and Morison (2010). The magenta line is the square-root dependence now being tested in our model.

breaking probability estimates that agree more closely with the new observations for very young seas, as well as for higher wind sea states and older seas available from previous` field data. We also modified the source terms in our wave model code accordingly. In addition to improving the accuracy of breaking probability forecasts, refining the breaking probability formulation modifies the dissipation rate and wind input source terms, which influences the wave model outputs. Results with our modified source terms are described below.

iii) *source term validation*

We investigated the performance of our refined source terms for wave dissipation and wind input integrated over the spectrum against the observed terms during the young wind sea growth episode in the Strait of Juan de Fuca reported by Schwendeman et al. (2014). The results in Fig. 2 compare the fetch evolution of our modeled integrated S_{in} and S_{ds} source terms with those observed (left panel) and the computed versus observed significant wave height H_s (right panel). The close correspondence of the results is very reassuring.

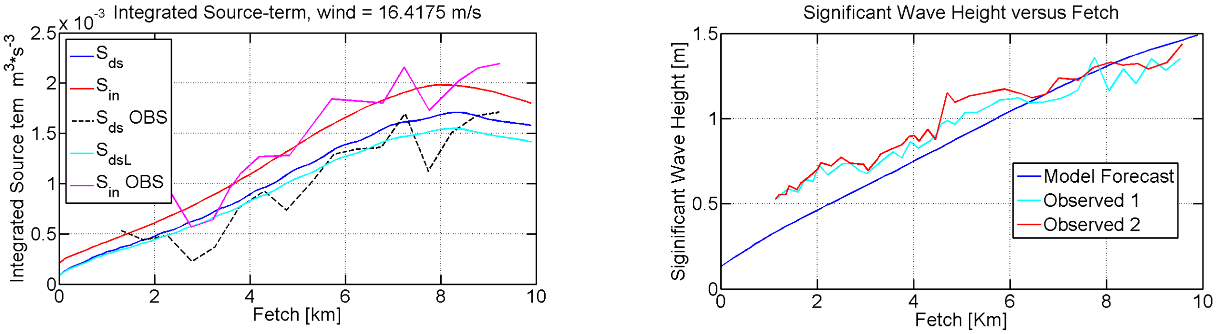

Fig. 2. Comparisons of modeled and observed fetch evolution of the source terms for the Strait of Juan de Fuca experiment. Left panel shows the spectrally-integrated computed wind input S_{in} (red), observed total input (magenta), computed total dissipation rate S_{ds} (blue), which is dominated by the wave breaking component S_{dsL} (cyan), and the observed dissipation rate (black dashed line). The right panel shows the modeled significant wave height H_s (blue) versus the two available observations (cyan, red).

iv) *refinements of modeled wave breaking properties*

From our modeled refined source terms, we post-processed the breaker dissipation source term S_{ds} results to recover the Phillips (1985) spectral breaking measures: breaker crest length per unit area Λ(k) and breaking strength b(k). Present breaking wave measurements, including those made in the Strait of Juan de Fuca field experiment, provide Λ(c) and the spectrally-integrated breaking strength b_{eff}, which is defined (Gemmrich et al., 2013) by

$$\int S_{ds}(c)\,dc = b_{eff}\int c^5\,\Lambda(c)/g\,dc$$

Fig. 3 shows the modeled behavior of b_{eff} with wave age for a wide range of wind speeds, which embrace those during the Strait of Juan de Fuca field experiment. The model predicts a modest decrease in b_{eff} as the seas age, with a consistent trend for a wide range of wind speesds. The modeled results shows levels similar to those observed by Schwendeman et al. (2014, figs. 10 and 11) which show $b_{\mathrm{eff}} \sim O(10^{-3})$.

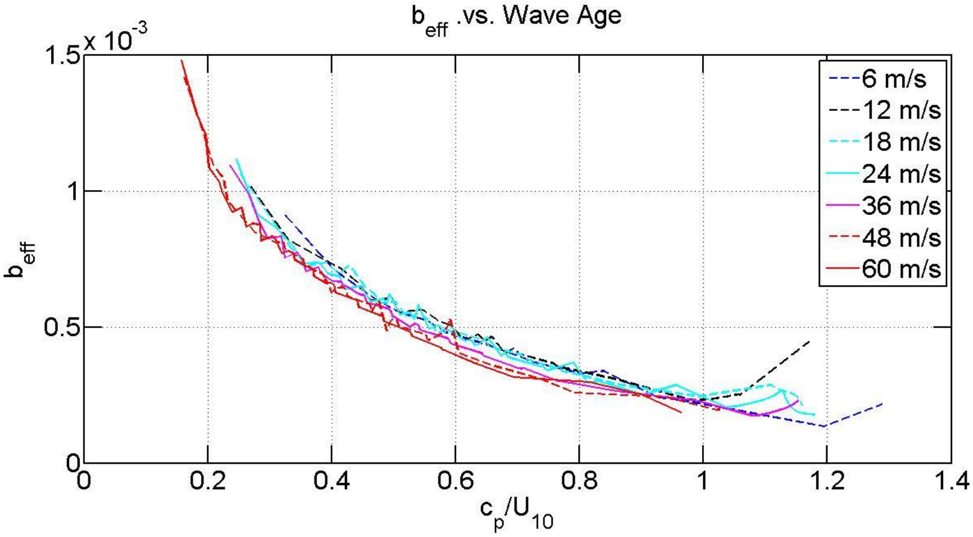

Fig. 3 Modeled behavior of spectrally-averaged breaking strength b_{eff} against wave age c_p/U_{10} for a wide range of wind speeds. These model results indicate that b_{eff} is relatively insensitive to the absolute wind speed and decreases only modestly with wave age.

v) *wave crest slowdown* – key to relating modeled to observed Λ and b spectral distributions.`

In Banner et al. (2014), we reported on a generic wave crest slowdown mechanism that is intrinsic to unsteady dispersive wave packets, applicable to waves of any steepness, including breaking waves. As a result, observed initial breaker speeds are aliased to slower speeds by about 20%. This needs to be taken into account when relating whitecap imagery in c-space to model results obtained in k-space. This important finding is being used in our ongoing reconciliation of modeled and observed breaker distributions.

(vi) *wave-breaking dependent sea-spray parameterization*

A sea-spray droplet distribution forecast model that depends on the spectral wave breaking dissipation distribution has been developed. This overcomes the limitations of sea spray parameterizations that are based solely on wind speed, whose spray forecasts are independent of the sea state. In collaboration with Dr. C. Fairall (NOAA ESRL, Boulder, Co), we formulated and implemented a spectral version of the sea spray droplet distribution reported in Fairall et al. (2009). This formulation uses the spectral dissipation rate due to wave breaking computed in our spectral wave forecast model. In Fig. 4, the integrated spray mass flux from this sea state dependent model is compared with the bulk level from a standard windspeed-only sea spray formulation The results show a strong wave age contrast between very young wind seas (right side of figure), where the dominant waves are breaking with high probability, to mature seas (left side of figure) where the spectral peak waves have a low breaking probability.

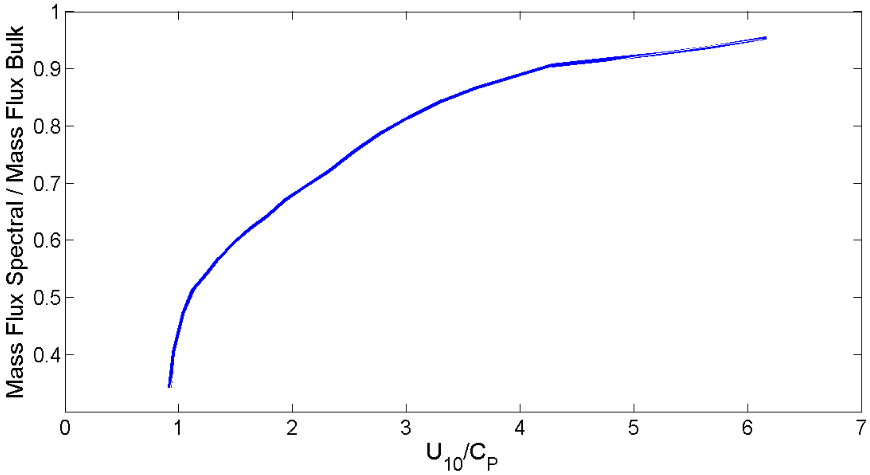

Fig. 4 Ratio of the sea spray mass flux from our sea state dependent model to that from a standard windspeed-only model plotted against the inverse wave age (U_{10}/c_p). Note how the ratio of the mass flux changes as the inverse wave age increases from old seas (left side) where breaking at the spectral peak is minimal, towards very young seas (right side) where there is frequent breaking of the spectral peak waves. The results shown are for U_{10}=24 m/s.

vii) *swell dissipation*

Collard et al. (2009) and Ardhuin et al. (2009) measured the dissipation of swell across the Pacific Ocean in a number of storms, and Ardhuin et al. (2010) formulated a swell dissipation source term that is a nonlinear function of wave steepness. We modified our swell dissipation source term parameterization to more closely match the observed dissipation from the results of Collard et al. (2009) and Ardhuin et al., (2009). Collard et al. (2009) report a swell significant wave height decrease of 30 to 40% over 1000 km, and our new model results match this with a corresponding significant wave height decrease of 35 to 40%. These results also closely match those of Young et al. (2013).

We also looked at the dependence of the swell dissipation on the steepness of the peak waves, and on the interaction between swell waves and wind seas. This is being further investigated in our global scale WaveWatch III implementation, and will be reported in due course.

IMPACTS AND APPLICATIONS

Our results in this NOPP project contribute to National Security, Economic Development and Quality of Life, as described below. The written research papers we will produce will contribute to the scientific record. This effort will contribute significantly to the major NOPP goal of upgrading the model physics for wind-generated ocean waves, the near-surface winds and upper ocean circulation in the WaveWatch III model environment. The upgraded WaveWatch III model code will be distributed to the US Navy for improving the accuracy of their ocean global forecasting capability. The US Army Corps of Engineers and NOAA - US Weather Service will benefit from this work in their mission-specific systems. The major impact will be more accurate and comprehensive sea state and marine meteorological forecasts from the next generation of operational sea state models.

TRANSITIONS

In 2014, the Marine Modelling and analysis branch of the National Centers for Environmental Prediction transitioned their operational WAVEWATCH III to some of the new source terms developed by this NOPP. These will include the contribution to the model physics developed by our team, and implemented in combination with ideas developed by other teams within this NOPP program.

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