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

Michael L. Banner
School of Mathematics and Statistics
The University of New South Wales
Sydney 2052, Australia
Tel : (+61-2) 9385-7071 fax: (+61-2) 9385-7123 email: m.banner@unsw.edu.au

Russel P. Morison
School of Mathematics and Statistics
The University of New South Wales
Sydney 2052, Australia
Tel : (+61-2) 9385-7064 fax: (+61-2) 9385-7123 email: r.morison@unsw.edu.au

Award Number: N00014-1010390

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

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. The performance of this updated source term was 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.

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. During the next 12 months we expect to use other implementations of S_{nl} as they become available.

WORK COMPLETED

During FY13 we have further refined our source terms due to availability of new data. As part of our modeling effort, we investigated the performance of our refined dissipation and input source terms during increasing and decreasing wind events up to 100 m/s. We validated this against a number of field experiments for wind speeds up to O(25 m/s). The source terms have been implemented in the WaveWatch III environment, and we are now examining their performance against a number of criteria, including significant wave height, wave periods, wave train evolution, breaking wave probabilities, spectral 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 subsets of NCEP’s Climate Forecast System Reanalysis (http://cfs.ncep.noaa.gov/cfsr/). A detailed publication describing the refinements to our source terms and their performance is in preparation.

RESULTS

The areas of model refinements made and their outcomes are summarized below:

(i) Refined breaking probability formulation.
We obtained access to two new field measurement datasets for very young wind sea conditions, from locations in the Strait of Juan De Fuca and in the Adriatic Sea. These datasets have allowed us to refine our model breaking probability formulation, based on the normalized wave saturation (see Banner and Morison (2010 for details), for higher winds and younger sea states. We have modified our

code accordingly and our revised breaking formulation reduces the levels of forecast breaking probabilities to agree more closely with the new observations for very young seas, as well as for higher winds and older seas from previously available field data. In addition to improving the accuracy of breaking probability forecasts, refining the formulation for breaking probability has modified both the dissipation rate and wind input source terms, as well as the wave model outputs, including the forecast drag coefficient.

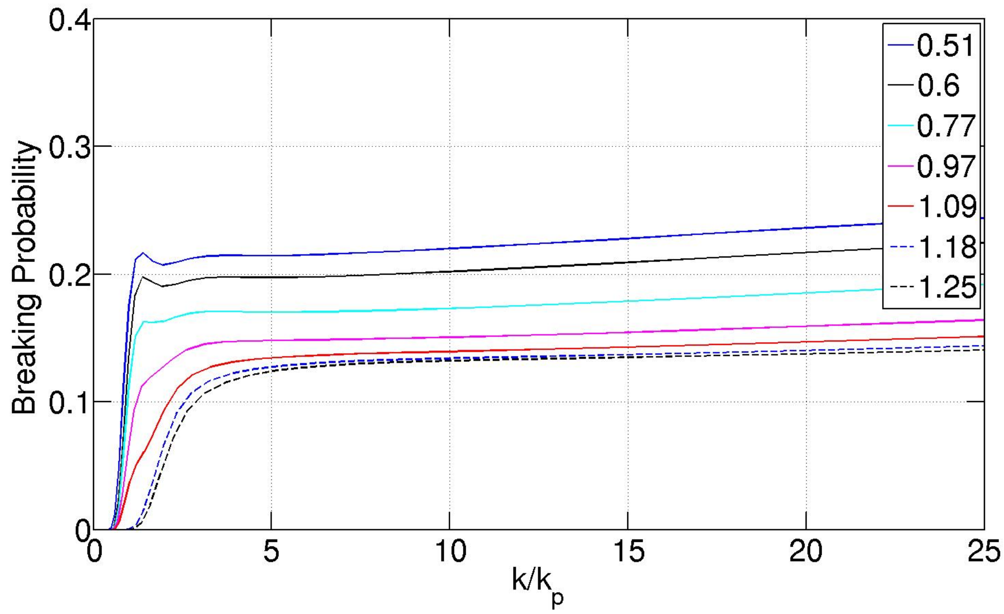

Figure 1. Modeled breaking probability for U_{10} =18 m/s, shown for the different wave age (c_p/U_{10}) conditions shown in the legend. The breaking probabilities are based on the computed normalized spectral saturations, modified from Banner and Morison (2010).

ii) Sea state and drag coefficients

We have systematically investigated the performance of our refined dissipation and input source terms during observed increasing and decreasing wind events up to 100 m/s., and all the standard parameters, such as wave height and wave evolution, source term levels, spectral energy levels etc. all match the standard curves well.

Recently published drag coefficient data from Edson et al. (2013) shows a drag coefficient dependence on U_{10}, friction velocity u_* and wave age that is significantly different from the results of Powell et al. (2003) (see figure 2) obtained within hurricanes. The drag coefficient in the model is the summation of the different components of the total stress (the viscous stress, the wave from drag, and the breaking enhanced wave from drag) normalized by U_{10}^2. The previously mentioned changes to the breaking probabilities, as well as changes to both the input and dissipation source terms, all affect the drag coefficient. As shown in Table 1, our fetch/duration-limited calculations closely reproduce the wind speed and wave age results reported by Edson et al. (2013). The Edson et al. (2013) data also show a relationship between U_{10} and wave age for the coastal regions where data was obtained. To validate our source terms for more complex sea state conditions, such as those experienced in the results of Powell et al. (2003), we are presently investigating a set of hurricane cases using our source term implementation in WaveWatch III.

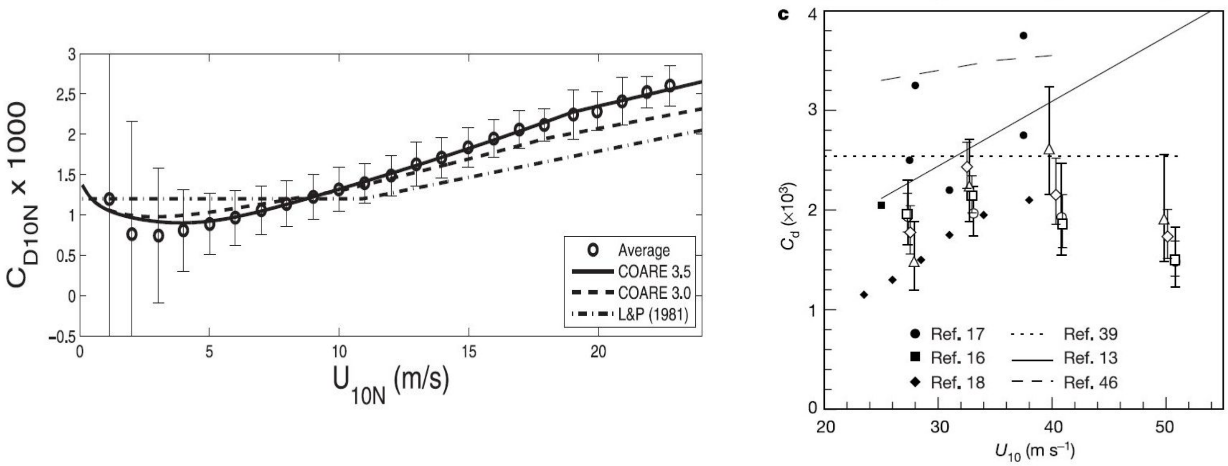

Figure 2. The observed U_{10} dependence of the drag coefficient C_d by Edson et al. (2013) (left panel) and Powell et al. (2003) (right panel). The Edson et al. (2013) results are from buoy and tower measurements in open seas, while the Powell et al. (2003) results are from aircraft-deployed dropsonde data in hurricane conditions.

Table 1. Comparison showing that our fetch/duration-limited calculations closely reproduce the wind speed and inverse wave age results reported by Edson et al. (2013). Also shown are the corresponding CFSR re-analysis results (see our FY12 Annual report) and the results from Powell et al. (2003) for hurricane conditions. *Note: the Edson et al. (2013) results for above 24 m/s are extrapolated, and are shown for comparison only. Also the Powell data does not contain any wave age information, and are mean values from collected data.

U_{10} [m/s]	u_*/c_p	Edson C_d *10^3	Our C_d *10^3	CFSR C_d*10^3	Powell C_d *10^3
6	0.02	1.0	1.1	1.1	-
12	0.04	1.5	1.5	1.5	-
18	0.06	2.1	2.0	1.9	-
24	0.08	2.6	2.3	2.2	1.8
36	0.09	Above 3.0*	2.7	3.0	2.4
48	0.10	Above 3.0*	3.1	-	2.0

iii) friction velocity u_*

The standard formulation of u_* in both WaveWatch III and WAM wave forecast models leads to a value for u_* that is strongly dependent on U_{10}, but independent of wave age c_p/U_{10}, or spectral peak wave speed c_p. This lack of wave age sensitivity is associated with a lack of sensitivity of both the form drag, and the breaking-enhanced form drag to wave age. In our model, both the wave induced form drag and the breaking enhanced form drag have a significant dependence on wave age. This leads to a moderate dependence of the u_* formulation on the wave age. An example of the variation of the components of the drag against wave age, and the u_* dependence on wave age is shown in Figure 3 below.

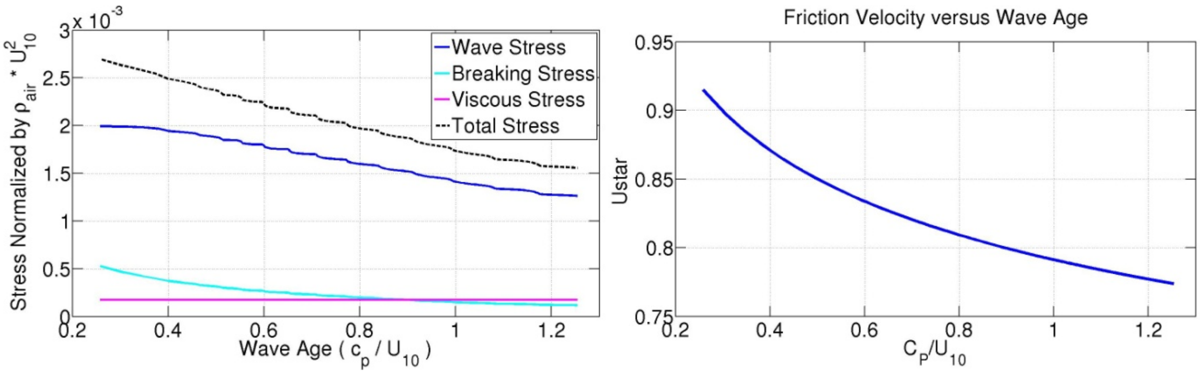

Figure 3. The left panel shows the individual dependence of the stress components on wave age c_p/U_{10}. The right panel shows the u_* dependence on wave age for a typical 18 m/s duration-limited model run.

iv) 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 wav 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).

IMPACTS and APPLICATIONS

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 various Federal agencies for incorporation 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.

REFERENCES

Alves, J.H and M.L. Banner (2003). Performance of a saturation-based dissipation source term for wind wave spectral modeling. J. Phys. Oceanogr. 33, 1274-1298.

Ardhuin, F., B. Chapron, and F. Collard, (2009). Observation of swell dissipation across oceans. *Geophys. Res. Lett.* 36 (6), L06607.

Ardhuin, F., et al., (2010). Semi-empirical dissipation source functions for wind-wave models:

Part 1, Definition, calibration and validation. J. Phys. Oceanogr., 40 (9), 1917-1941.

Banner, M. L., (1990) The influence of wave breaking on the surface pressure distribution in wind-wave interaction. J. Fluid Mech., 211, 463–495.

Banner, M.L. and R.P. Morison (2010) Refined source terms in wind wave models with explicit wave breaking prediction. Part I: Model framework and validation against field data. Ocean Modell., doi:10.1016/j.ocemod.2010.01.002.

Collard, F., F. Ardhuin and B. Chapron (2009). Monitoring and analysis of ocean swell fields from space: New methods for routine observations, *J. Geophys. Res.* 114, C07023, doi: 10.1029/2008JC005215.

Edson, J.B., C.J. Zappa, J.A. Ware, W.R. McGillis and J.E. Hare (2002) Scalar flux profile relationships over the open ocean, J. Geophys., 109, C08S09, doi:10.1029/2003JC001960.

Edson, J.B. et al. (2013) On the exchange of momentum over the open ocean. J. Phys. Oceanogr., 43, 1589-1609.

Janssen, P.A.E.M., (1991) Quasi-linear theory of wind-wave generation applied to wave forecasting. J. Phys. Oceanogr., 21, 1631–1642.

Powell, M.D., P.J. Vickery and T.A. Reinhold (2003). Reduced drag coefficient for high wind speeds in tropical cyclones. Nature, 422, 279-283.

Tracy, B.A. and D.T. Resio (1982) Theory and calculation of the nonlinear energy transfer between sea waves in deep water, WIS Rept 11, US Army Engineers Waterway Experiment Station.

Young, I., A. Babanin, and S. Zieger, (2013) The decay rate of ocean swell observed by altimeter. J. Phys. Oceanogr. doi:10.1175/JPO-D-13-083.1, in press.