Observation-Based Dissipation and Input Terms for Spectral Wave Models, with End-User Testing

Alexander V. Babanin
Swinburne University of Technology
PO Box 218
Hawthorn, Victoria 3140 Australia
phone: +61-3-9214-8033 fax: +61-3-9214-8264 email: ababanin@swin.edu.au

Ian R. Young
The Australian National University
Canberra, ACT 02000 Australia
phone: +61-2-6125-2510 fax: +61-2-6257-3292 email: IR.Young@anu.edu.au

W. Erick Rogers
Naval Research Laboratory, Code 7322
Stennis Space Center, MS 39529
phone: (228) 688-4727 fax: (228) 688-4759 email: rogers@nrlssc.navy.mil

Jane M. Smith
Coastal and Hydraulics Laboratory, CEERD-HF-CS
3909 Halls Ferry Road
Vicksburg, MS 39180
phone: (601) 634-2079 fax: (601) 634-4314 email: Jane.M.Smith@usace.army.mil

Hendrik L. Tolman
Marine Modeling and Analysis Branch, NOAA/ NCEP/ EMC
5200 Auth Road Room, 09
Camp Springs, MD 21746
phone: (301) 763-8000 x 7253 fax: (301)763-8545 email: Hendrik.Tolman@NOAA.gov

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http://ababanin.com/

LONG-TERM GOALS

The long-term goal is to implement input and dissipation source functions, based on advanced understanding of physics of air-sea interactions, wave breaking and swell attenuation, in wave-forecast models.

OBJECTIVES

The objectives are to use new observation-based source terms for the wind input, wave-breaking (whitecapping) dissipation and swell decay in the third-generation models WAVEWATCH-III and SWAN. Calibration and performance of the source functions have to satisfy a set of physical constraints, and the methodology is developed to enable testing the source functions separately before they are blended in the full model. Verification is conducted by means of academic tests and hindcasting real-life scenarios defined by the end users from the US Navy, Army and NOAA, to include deep and finite-depth conditions, closed seas (no swell) and open ocean, extreme weather events, and global simulations.

APPROACH

Physics of two primary source/sink terms employed by the operational models, namely wave-breaking energy dissipation and wind-to-wave energy input have not been updated for decades. In the meantime, the new physics is available. For the first time under field conditions, in the course of the ONR Lake George (Australia) project, estimates of the spectral distribution of the wave-breaking dissipation were obtained, and measurements of the wind-input spectral function were conducted at moderate-to-strong wind forcing (Young et al., 2005). Corresponding outcomes were parameterised as source functions suitable for spectral wave models, and both exhibit a number of physical features presently not accounted for in the models.

For the dissipation, these are threshold behaviour of breaking/dissipation in terms of wave-steepness/spectral-density, cumulative effects at scales smaller than the spectral peak, and direct coupling of the dissipation rates with input rates at very-strong/extreme wind forcing. Bi-modal directional distribution of the dissipation was also observed (Babanin et al., 2001, Babanin and Young, 2005, Young and Babanin, 2006a, Babanin et al., 2010). None of these features are present in the currently employed dissipation functions used for operational wave forecasting.

The new wind-input features are the non-linear behaviour of the input term (that is, the input rates depend on wave steepness) and full flow separation in extreme conditions (that is, relative slowing down of the wind-wave exchange in steep-waves/strong-winds circumstances) (Donelan et al., 2005, 2006, Tsagareli et al., 2010). Enhancement of the wind input due to wave breaking was also observed, quantified and parameterised (Babanin et al., 2007).

In the above-mentioned field measurements of the wind input, only the conditions of waves produced by the wind were observed. In real oceanic situations, there can occur conditions of the wind being adverse to the waves, either fully or in some parts of the wave directional spectrum. In such conditions, the waves have been measured to pass the energy and momentum back to the wind. In order to accommodate these physics, parameterisation of the negative input was incorporated, according to laboratory measurements of Donelan (1999) fulfilled in the same instrumental, theoretical, and parametric framework as Donelan et al. (2006).

While the wind input and dissipation are the main source/sink energy terms in the model, the latter has to be subdivided into separate terms: one term in case of breaking waves (for wind-generated waves), and another for non-breaking waves (swell). The first one (whitecapping dissipation) turns zero once the spectral density at a particular scale drops below the threshold as mentioned above, and a much weaker dissipation accompanies swell propagation across the ocean. While this dissipation is weak, it is not zero, and with swell present in some 80% of oceanic seas, it is most important to account for swell propagation and dissipation correctly and accurately.

Recently, two new swell-dissipation terms were suggested, which imply different physics: interaction of swell with background oceanic turbulence (Babanin, 2006, 2011, 2012) and with the atmospheric boundary layer (Ardhuin et al., 2009). Young et al. (2013a) conducted detailed satellite observations intended to verify and quantify the swell dissipation term.

The project employs both the new source terms and a new approach to their validation. The main feature of the approach is stringent physical constraints on the momentum/energy fluxes in and out the wave system: that is, the integrated wind momentum input must not exceed independently known total stress, and the integrated dissipation must constitute the experimentally known proportion with respect to the total input. For the total dissipation, independent parameterisations based on profile measurements of volumetric dissipation rates are also available. Such constraints, first of all, are necessary to make the source functions physically consistent, and most importantly, they allow calibration of the input and dissipation one by one, before they are incorporated in the model where their contributions cannot be separated (Babanin et al., 2005, 2010, Tsagareli et al., 2010, Rogers et al., 2012).

Work on the physical constraints is continuing. For the total stress, a number of new dependences on the properties of waves and the atmospheric boundary layer have been identified (see Work Completed below). In the case of oblique winds, some parts of the wave spectrum can be subject to a negative component of the wind stress vector. This component is not restricted by the total-stress constraint, and as such may play an essential role in air-sea coupling in the tropical cyclones (see Transitions below).

For practical testing and hindcasting, a set of field sites and datasets were chosen which include Lake Michigan (deep water, no swell, Rogers et al., 2012), Lake George (finite depth, no swell, Young and Verhagen, 1996, Young et al., 2005), Gulf of Mexico (open sea, deep-to-finite depths, swell, hurricanes, IPET, 2006, Smith, 2006), and a selection of tropical cyclones from the Australian region (Young, 2006, Babanin et al., 2011). Measurement data are available for all the chosen sites. Now that the model is fully tested, global simulations for 2004-2006 have been performed and compared with the altimeter database (Zieger et al., 2009) and with NOAA simulations based on the previous version of WAVEWATCH-III (Chawla et al., 2011). These data are also used for validation of the tropical-cyclone modelling results.

The research group includes academics from Swinburne University of Technology (SUT), US Naval Research Laboratory (NRL), US Army Corps of Engineers (CHL), and US Weather Service (NOAA). SUT group consists of Alex Babanin and Ian Young who had developed the new dissipation term and participated in development and testing of the new wind-input term in the course of the earlier ONR project, and Stefan Zieger, Research Fellow employed on the current project. This group conducts the bulk of the academic research and implementation of the new source terms into WW3, the latter in collaboration with Hendrik Tolman from NOAA and Erick Rogers from NRL. Erick Rogers and Jane Smith from CHL contribute to the project goals in the development and verification of the new physical formulations, to replace the formulations currently used in Navy and Army operational models. A specific goal of NRL and CHL is to create models that are physically consistent with what we know about the real ocean, while at the same time ensuring that the new models are optimal for Navy and Army applications. NRL and CHL have also implemented the new input and dissipation terms into SWAN, apart from WW3, and participate in the development of validation/calibration cases, and in particular those of extreme conditions observed in the Gulf of Mexico.

WORK COMPLETED

This is a report for the fourth year of the project. Main objectives of the project have been achieved. New versions of the models are released and used for practical applications. The SWAN model with observation-based physics is employed extensively by PIs and their external collaborators, and WAVEWATCH-III is prepared as an α-version at NOAA.

In addition to the originally planned wind-input and whitecapping-dissipation functions, based on observations at Lake George (Australia), two other observation-based functions have been included in the final version of WW3. These are negative input and swell dissipation.

The negative input is due to interactions of waves with adverse wind (Donelan, 1999). This term is activated if there is a negative component of wind stress in any part of the directional spectrum. Apart from situations of the counter wind, it has proved useful and necessary in any conditions of oblique winds where waves at some directions can be subject to adverse wind stress. This term is potentially essential for modelling waves in tropical cyclones where, apart from wind impact on the waves, it may be responsible for waves influencing the radial component of the wind vector.

The magnitude of the swell-dissipation term is small by comparison with the whitecapping dissipation, but once the wave steepness drops below a certain threshold and wave breaking stops it becomes the only energy sink in the system (Babanin, 2006, 2011, 2012, Young et al., 2013a). With swells present in some 80% of seas, this source term is very important for global models like WW3, and a significant part of the fourth-year effort was dedicated to its calibration and validation. Apart from conditions of pure swell, this term is also dominant at the spectral peak of mature or fully developed seas. Their steepness can be below the breaking threshold, and such conditions appear to be regular occurrence in the Southern Ocean.

In the first year of the project, the formulations for the observation-based source terms, were validated, individually calibrated, and tested together in a two-dimensional wave research model with exact computations of the non-linear interaction term (Tsagareli et al. 2010, Babanin et al. 2010). The new source terms and the physical-constraint approach were implemented in SWAN and tested by means of the Lake Michigan and a selection of the Gulf of Mexico cases. Field data sets for further model-testing were selected and prepared: Lake George, Black Sea, global altimeter database. During the second year, the main aim of the project was implementation of the source functions into WW3. This was done, and academic testing and initial field validation of the model were concluded (Zieger et al., 2011). In addition, the model performs an automatic self-correction routine by comparing the input total stress with the integral of the wind input over the computed spectrum at each time step. Research on other topics of the project also continued. These included breaking and dissipation, sea drag, wave-bottom friction, and wave-turbulence and its role in the swell dissipation. Particular attention was paid to preparing for future hurricane modelling and global simulations. The global altimeter database, developed earlier, was used for investigating the global trends of waves and winds over the past 25 years. In the third year, the broad and intensive testing of the new version of the model was started, by means of hindcasting. In order to apply the model to the ocean, it required adding auxiliary source terms, for swell dissipation (Babanin, 2011, 2012) and for negative wind input (interaction with adverse components of the wind, following Donelan (1999)). This full model was then applied to Lake Michigan (i.e., no-swell conditions) and Tropical Cyclone Yasi (full physics test).

In the fourth year (current), the new model was scrutinised and further calibrated by means of extensive testing. The tests included integral, spectral and directional academic tests, 2004-2006 global hindcast validated by means of the altimeter database, and selection of hurricanes in the Gulf of Mexico and tropical cyclones in Australia. These are also prepared as testbeds for other NOPP groups and applications.

Substantial effort was dedicated to calibrating the swell-dissipation routine. Its detailed quantitative calibration was done by means of altimeter observations of swell in the Great Australian Bight (Young et al., 2013a) and validated through the three years of global hindcast (2004-2006). While overall bias, scatter and rms errors are small and show improvements compared with the default versions of WW3, there appears to be minor, but systematic bias in wave height between polar and tropical regions. This is likely to be due to steepness-dependent intensity for swell-turbulence interactions (Babanin, 2012), and work on further rectification of the swell routine is continuing.

Other research on source functions for spectral models is continuing. The work is in progress on a new nonlinear interaction term. While computationally expensive, it is planned to be included as a research option in WW3 and SWAN as an alternative to the traditional Hasselmann term. In addition to the exact resonance interactions, it is able to calculate quasi-resonant interactions (and therefore describe modulational instability of wave trains and one-dimensional wave fields), it is applicable to non-homogeneous wave fields, it accounts for Stokes corrections to dispersion relationships and for unlocking the wave phases due to wave breaking (Gramstad and Stiassnie, 2013).

The next logical step in advancing the wave models would be to employ a model of the wave boundary layer (WBL) instead of parameterisations of the wind input. This would be a transition to the fourth generation of wave models, which would use basic equations rather than parameterisations for the wind input. Such a model would take the mean wind speeds as an input and convert them into pressure working on the ocean surface, without relying on the sea drag or other substitutes for the physics of WBL. A 1D version of the Chalikov and Rainchik (2011) WBL model is now available at Swinburne, and it is fast enough to be implemented operationally. Work on implementing this WBL in WAVEWATCH-III instead of wind-input parameterisations is in progress.

An important element that was identified for future work is directional distributions for source functions. Academic tests showed that wave directional distributions are the least well performing feature of the wave model. This is possible to tune, but not possible to consistently improve without knowledge of directional behavior of the source functions for input and dissipation. Some observations of such behavior are available, e.g. Ting et al. (2012) for the input, Young and Babanin (2006) and Babanin et al. (2010) for the dissipation, but this is a major problem for the spectral models that requires attention.

Research on the other topics of the project also continued. Impact/Applications below outline research completed.

RESULTS

The main output of Year 4 is that the new models are now complete, fully operational, and released for external users. The new version of WW3 with new observation-based physics of all deep-water source terms (apart from nonlinear interactions) includes wind input, whitecapping dissipation, interaction of waves with adverse wind (negative input) and swell (non-breaking) dissipation.

Validations/calibrations performed in the first three years have been repeated and extended, to accommodate new features of the source functions, new data and observations, and outputs of the new three-year hindcast, and to test the model extensively before its public release. These have been described in the previous reports, and these will be made available to the other participants of NOPP. In Figures below, some new results on the new features of the relevant source functions are highlighted.

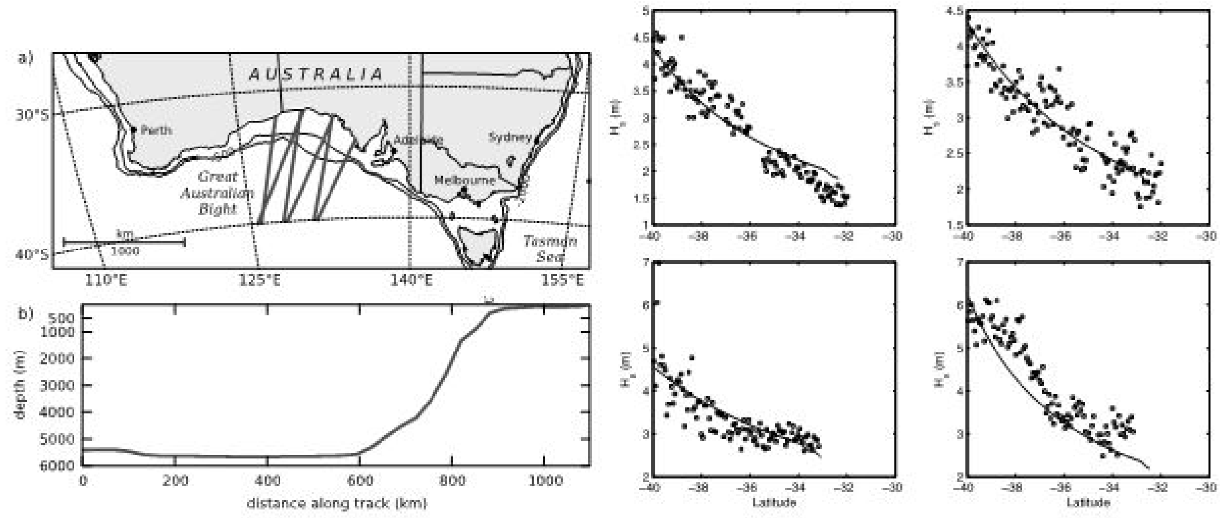

Figure 1. Remote sensing study, used to calibrate the swell-dissipation term (Young et al., 2013a). (left) The study area in the Great Australian Bight region of the Southern Ocean with typical altimeter ground tracks (top); variation of water depth along a typical altimeter great circle path (bottom). (right) Four typical cases of the measured (altimeter) decay of the swell along the transects (squares). The predicted decay from the model is shown by the solid line.

IMPACT/APPLICATIONS

The new version of WAVEWATCH-III is prepared for release an α-version at NOAA.

The new swell-decay function was further tested, validated and calibrated by means of satellite observations (Young et al., 2013a). Iafratti et al. (2013) investigated dissipation of wave energy through generation of turbulence in the air, numerically, and Babanin and McConochie (2013) investigated wave-induced profiles and wind momentum fluxes very near the water interface, experimentally. Both studies are important for the physical constraints introduced in WAVEWATCH-III within this project, and the second paper has significant implications for hurricane modelling. Rogers and van Vledder (2013) investigated limitations of the traditional DRI approximation for the nonlinear interactions in third-generation wave models, and Chalikov and Babanin (2013) developed a fully nonlinear three-dimensional wave model that can be used for investigations of nonlinear interactions in realistic wave fields by solving dynamic rather than phase-average equations. Babanin (2013) suggested a new approach to the research of extreme and rogue waves, and Ribal et al. (2013) investigated the extreme and rogue wave issue by means of the Alber equation. Young et al. (2013b) quantified trends for 100-year return winds and waves, and Zieger et al. (2013) studied regional trends for surface winds in particular months.

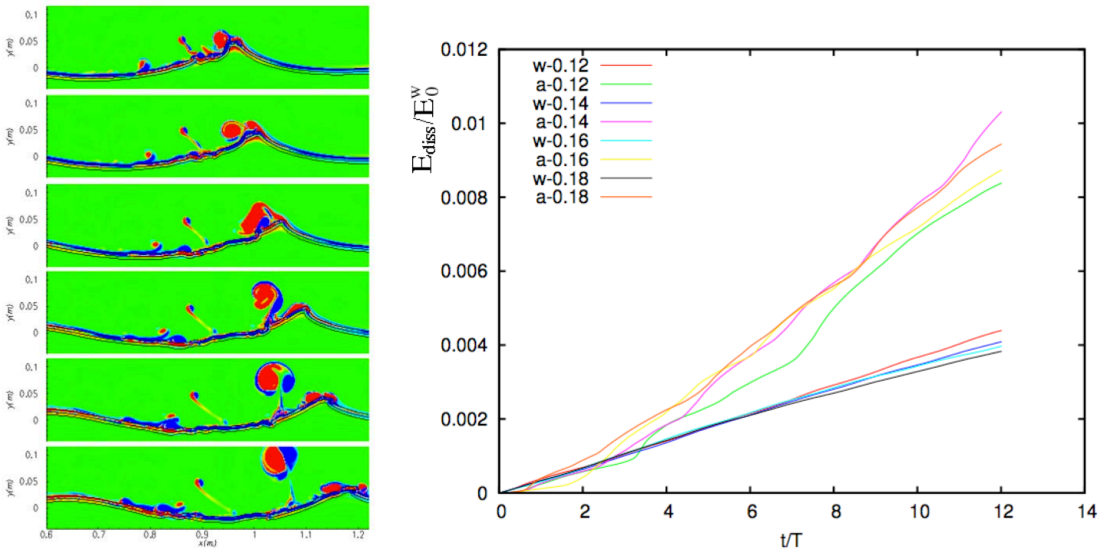

Figure 2. Numerical study of wave-breaking dissipation. While usually constraints for such dissipation are imposed by measurements in the water, this study showed that a substantial part of the energy lost by the waves is passed to the air turbulence and dissipated in the air (Iafrati et al., 2013). (left) Sequence of formation of a dipole in the air as a consequence of the wave breaking. Time delay between subsequent images is 0.05 sec. (right) Time-integrated dissipation, for different values of the wave steepness as indicated by colours, in water (w) and air (a).

TRANSITIONS

The version of WAVEWATCH-III with new physics of all deep-water source terms has been prepared for release for external users as an α-version at NOAA. A number of such users from academic institutions and industry have already expressed interests in trying and applying the model. The new physics is also implemented in SWAN (Rogers et al., 2012). It is now applied routinely in coupled modelling at NRL-Stennis and is part of the transition to NAVOCEANO. This SWAN version or its modules are also used for research and hindcast at the University of Adelaide, South Australia, the University of Darmstadt, Germany, and the National Cheng Kung University, Taiwan.

Both Australian and American PIs are applying knowledge gained in this project to other projects (see below). PIs Babanin and Young, in collaboration with the Australian Bureau of Meteorology, use the new versions of WAVEWATCH-III and SWAN in the projects funded by the Australian Research Council intended for advance modelling of tropical cyclones, for studies of the wave climate and for coupling large-scale air-sea interaction models for weather and climate with wave influences. Joint research, by coupling the new wave models with hurricane models, is commenced with the hurricane NOPP group of the University of Rhode Island. PI Rogers showed that recent analysis and improvement of the accuracy of the total input and dissipation predicted by these models has proven useful in two regards. First, these quantities are of primary importance in the context of momentum exchanges between models, and so this plays a key role in planning the next generation of coupled modelling systems (Earth System Prediction Capability, ESPC). Second, improved confidence in predictions of total dissipation is a prerequisite to applying associated model output quantities in the interpretation of data from the NRL WINDSAT radiometer (see Anguelova et al. in Related Projects listing).

RELATED PROJECTS

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Ardhuin et al. “Ocean Wave Dissipation and Energy Balance toward Reliable Spectra and First Breaking Statistics”. NOPP project. Implements new dissipation function based on similar physical principles. Joint publications (Ardhuin et al., 2010, Filipot et al., 2010)

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AWARDS

In 2012 research quality evaluation by the Australian government (Excellence in Research for Australia), the Centre for Ocean Engineering, Science and Technology, which conducts this project, was awarded the top rating in Maritime Engineering research (ERA-5)