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

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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 had 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, 2006, Babanin et al., 2010).

The new wind-input features are the non-linear behaviour of the input term (that is, the input rates depend on wave steepness (spectral density)) 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). At the start of the project, none of these features were incorporated in the input and dissipation functions used for operational wave forecasting.

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) conducted 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). While called 'swell dissipation', it is present in case of wind waves too. In presence of whitecapping it is small, but becomes a dominant energy sink as soon as the spectrum drops below the breaking threshold (for example, at the spectrum peak of fully developed waves, or following the wind drop). Young et al. (2013) conducted detailed satellite observations intended to verify and quantify such 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 the physical constraint 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. 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 separately, before they are incorporated in the model where their individual contributions cannot be distinguished (Babanin et al., 2005, 2010, Tsagareli et al., 2010, Rogers et al., 2012).

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, J.M., 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. Global simulations for 2004-2006 and 2013 have been performed and compared with the altimeter database (Zieger et al. (2009) and ongoing updates) and with NOAA simulations based on the previous version of WAVEWATCH-III (Chawla et al., 2012). 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 terms 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 Erick Rogers from NRL, Hendrik Tolman from NOAA and Jane Smith from CHL. 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 participate in the development of validation/calibration cases, and in particular those of extreme conditions observed in the Gulf of Mexico. The new input and dissipation terms are also implemented in SWAN, and therefore both SWAN and WW3 are now available with this consistent physics of the deep-water source functions across the two models.

WORK COMPLETED

This is a report for the fifth (last) year of the project. All the objectives of the project have now been achieved. New versions of the models are officially released and used for practical applications. The observation-based physics is a part of the new version 4.18 of WAVEWATCH-III released in March 2014 (Zieger, 2014). Version of SWAN with the same physics is also available.

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 (see APPROACH).

The negative input is due to interactions of waves with adverse wind, and effectively plays a role of extra dissipation (Donelan, 1999). This term is automatically 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 an adverse component of wind stress. This term is potentially essential for modelling waves in tropical cyclones (TC) where consistent overestimation of wave heights by models is observed at the weak side of the cyclones.

The swell-dissipation term is the dominant wave-energy sink on the water side once the waves stop breaking (Babanin, 2006, 2011, 2012, Young et al., 2013). Apart from the pure swell, these are also conditions at the spectral peak of mature seas, at the spectrum tail when the wind drops. In the fifth year, its dependence on the wave steepness was investigated (see RESULTS).

The new version of SWAN model, apart from the four deep-water input/dissipation terms same as in WW3, has a new term on coupled wave-bottom interactions included, tested and calibrated (Smith, G., et al., 2011). This term puts the bottom friction in dependence on the grain size of the bottom sediment, and is dynamically coupled with the bottom ripples, which can be created and subsequently erased by energetic waves, or diffused following a storm.

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 and air/sea coupling, including climate and hurricane applications. 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, the new model was scrutinised and further calibrated by means of extensive testing. These 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. 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., 2013) and validated through the three years of global hindcast (2004-2006).

In the fifth (present) year, further testing continued and comparisons with the new ST4 physics of the 4.18 version were performed. To achieve that, global hindcast of 2013 and comparison with the new CRYOSAT2 altimeter were conducted. As mentioned in the 2013 report, there appeared to be minor, but systematic bias in wave height between polar and tropical regions. This was expected to be due to steepness-dependent intensity for swell-turbulence interactions (Babanin, 2012), and such dependence is now obtained and included in WW3. It did allow us to reduce the polar-tropic bias.

Other research on source functions for spectral models continued. A new nonlinear interaction term was incorporated in a research version of WW3, as an alternative to the traditional Hasselmann term (Gramstad and Babanin, 2014). 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 least well-known physics of present wave-forecast models is that of wave-current interactions. Even in linear cases, currents give essential biases for the wave heights (e.g. Rapizo et al., 2014), and fully-nonlinear effects can lead to changes of the spectrum (e.g. Babanin et al., 2011) and are poorly understood. WW3 and SWAN hindcasts on currents with horizontal and vertical gradients, temporal oscillations, on large-scale Southern Ocean gyres, shows uncertain performance, and further research on this important topic is in progress.

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. A 1D version of the Chalikov and Rainchik (2011) WBL model, developed at Swinburne, is used for this purpose and the work 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.

RESULTS

The main output of Year 5 is that the new versions of WAVEWATCH-III and SWAN models are now complete, fully operational, and released to external users (Zieger, 2014). The 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. In 2014, the swell-dissipation term was advanced to include its wave-steepness dependence. New non-linear interaction term has also been developed and tested in WW3 (see WORK COMPLETED and below).

Given the page limit, only two new results of the further source-term development are highlighted. In Figure 1, comparisons of the global 2013 hindcast with the CRYOSAT2 altimeter measurements is shown, without (left) and with (right) wave-steepness dependence for the swell dissipation. Polar/tropical bias is reduced.

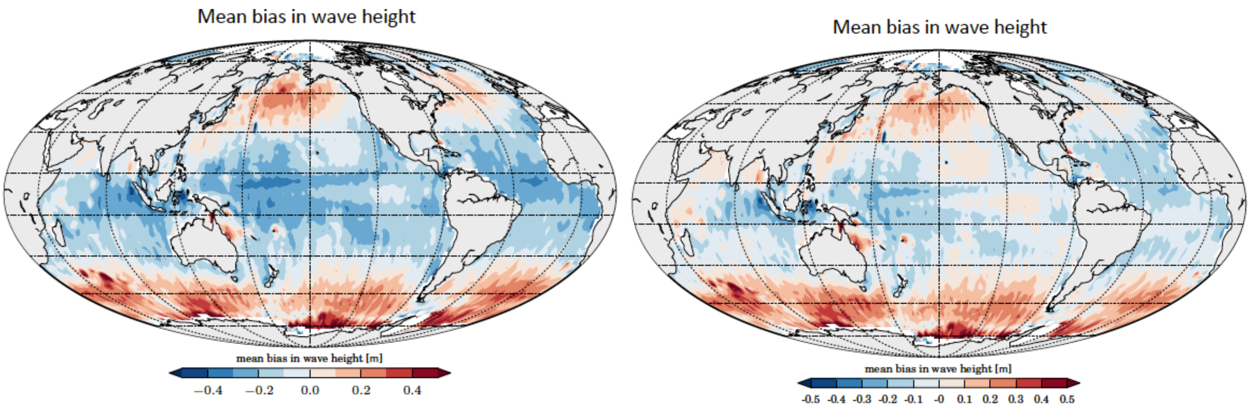

Figure 1. Bias of the global 2013 WAVEWATCH-III hindcast with respect to CRYOSAT2 observations. Scale is in units of meters at the bottom. (left) constant decay coefficient; (right) steepness depended decay coefficient for swell.

Figure 2 demonstrates differences between the new nonlinear term (GKE, Gramstad and Babanin, 2014), WRT version of the Hasselmann resonant term (Tracy and Resio, 1982) and DIA approximation routinely used in the operational forecast (Hasselmann et al., 1985). A spectrum narrow both in the frequency and directional domains is used, as these conditions are expected to endure most of the differences between GKE and WRT terms.

IMPACT/APPLICATIONS

The new version of WAVEWATCH-III (4.18) is released by NOAA in March 2014, which includes the observation-based physics (ST6) of the reported project (Zieger, 2014). A new version of SWAN, which fully incorporates the ST6 physics combined with the new coupled wave-bottom interaction term, was prepared and tested (see TRANSITIONS). Illustration of performance of the new swell dissipation routine in SWAN is given in Figure 3.

Various applications related to the dynamics of ocean waves and wave-coupled physics have been pursued. Studies of the fully nonlinear wave dynamics included simulations of one-dimensional (Babanin et al., 2014, Chalikov and Babanin, 2014, Iafrati et al., 2014) and three-dimensional

(Chalikov et al., 2014, Sanina et al., 2014) wave evolution. Babanin et al. (2014) demonstrated a new type of instability at very close wavenumbers; Chalikov and Babanin (2014) showed that 1D evolution (i.e. evolution without resonant nonlinear interactions) can follow the JONSWAP scenario; Iafrati et al (2014) investigated atmospheric part of wave energy dissipation due to breaking; Chalikov et al. (2014), Sanina et al. (2014) published a new fully nonlinear dynamic model of 3D waves and used it for research of various nonlinear phenomena. Babanin and Rogers (2014) suggested a review of physical mechanisms which can drive the wave breaking and dynamics of rogue waves. Continued were observations and modelling of global, seasonal and regional wind/wave trends (Young and Vinoth, 2013, Zieger et al., 2014), of wind-wave climate in the Arctic (Babanin et al., 2014, Khon et al., 2014a,b, see also TRANSITIONS); of wave-current interactions (Rapizo et al., 2014). Investigations of the waves in finite-depth environments included modulational instability in such conditions (Babanin and Ewans, 2014), wave reflection due to Bragg scattering (Hsu et al., 2014). Research of the wave-coupled effects both on the water side of the interface (Ghantous and Babanin, 2014) and on the air side (Bakhoday Pasyabia et al., 2014) also continued.

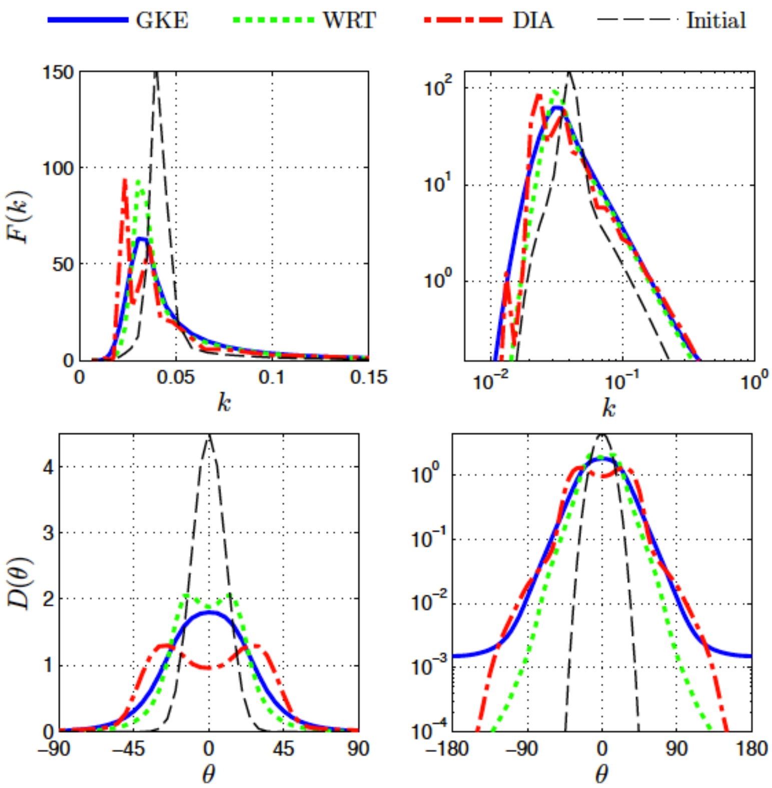

Figure 2. Evolution of JONSWAP-like spectrum with $\cos^n$ *directional distribution (n=32, JONSWAP's* $\alpha = 3.7 \cdot 10^{-3}$ *and γ=20). Dashed line is the initial spectrum, other spectra are shown after 1000 period of nonlinear evolution due to GKE (solid blue), WRT (dotted green), DIA (dash-dotted red). Top panels are for the wavenumber spectrum and bottom for the directional spread; left panels are linear and right panels logarithmic*

TRANSITIONS

The version of WAVEWATCH-III with the new physics of deep-water source terms has been released for external users as the 3.18-version at NOAA. Users from academic institutions, forecasting agencies and industry had expressed interests in trying and applying the model, and started using it, following the release.

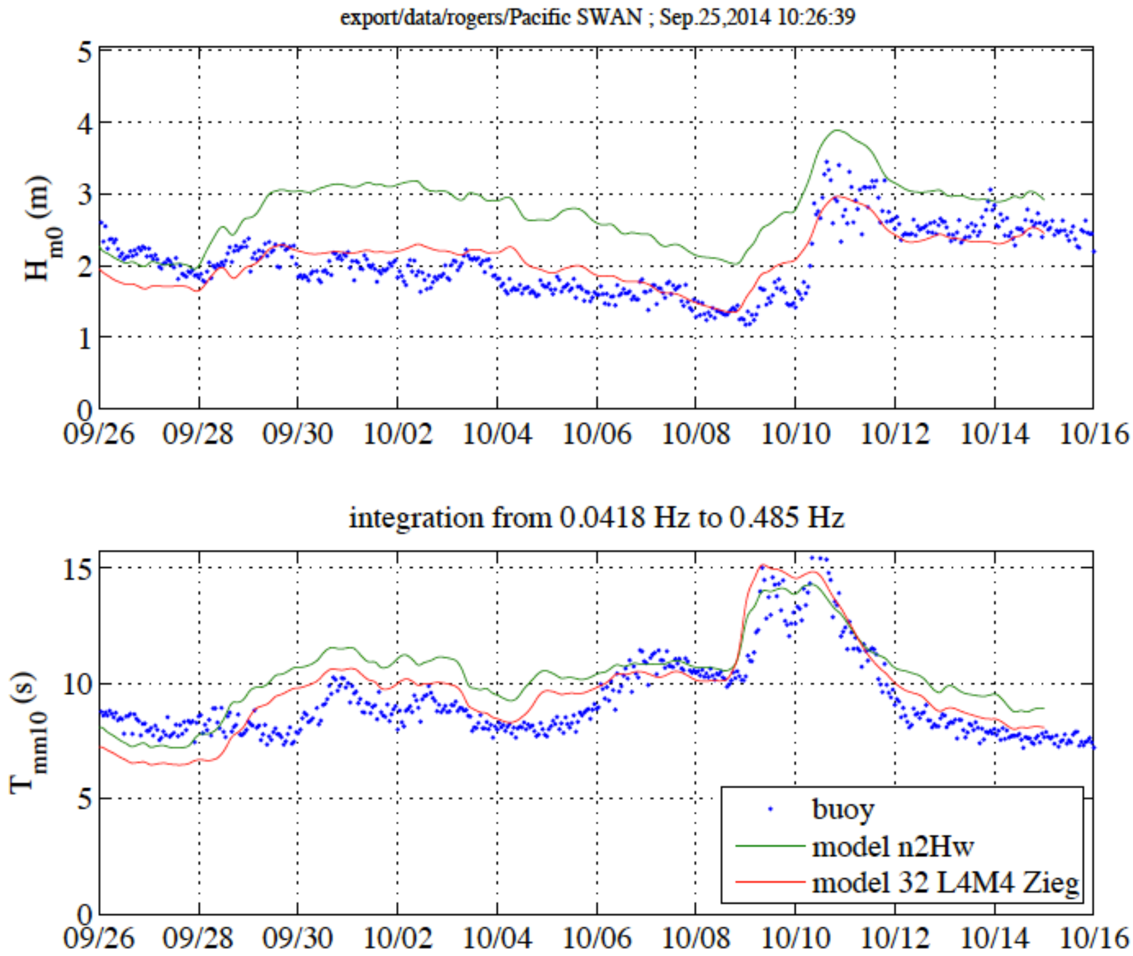

Figure 3. Pacific swell, measurements (buoy 51002) and modelling (SWAN). Dots – measurements, green – default, red – the new physics. Top panel – mean wave height, bottom panel – mean wave period

The same physics is also implemented in SWAN. Initially, Rogers et al. (2012) incorporated the input and whitecapping functions, and now a version with the full observations-based physics as in WW3 is available and submitted to the code holder (TU Delft) for distribution. It also includes a new coupled wave-bottom interaction routine (Smith, G. et al., 2011). This version 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, among others.

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 carried out 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 the RELATED PROJECTS listing).

There are also important synergies and transitions, in terms of wave modelling by means of WAVEWATCH-III and SWAN models, between this project and projects from the ONR Sea State DRI (see RELATED PROJECTS).

RELATED PROJECTS

Allard, R.A., Smith, T.A., Jensen, T.G., Chu, P.Y., Rogers, W.E., Campbell, T.J. "Coupled Air-Ocean-Wave Prediction System Verification and Validation". SPAWAR 6.4. Joint publications (Allard et al., 2012, Smith, T. et al., 2013)

Anguelova, M., Dowgiallo, D., Smith, Geoffrey, Hwang, P., Means, S., Rogers, E. “"Oceanic Whitecaps as a Surface Expression of Under- and Above-Water Processes: Toward an Integral Remote Sensing of the Air-Sea Interface". NRL Core 6.1

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)

Babanin, A.V., Young. I.R., Zieger, S. “Wave climate in the marginal ice zones of Arctic Seas, observations and modelling”. ONR Sea State DRU project. Studies wave climate in the Arctic by remote sensing and modelling means (Babanin et al., 2014, Zieger et al., 2014)

Babanin, A.V., Walsh, K., Young, I.R., Sandery, P.A., Hemer, M.A., Qiao, F., Ginis, I. “Coupling tropical cyclone and climate physics with ocean waves”, Australian Research Council (ARC) Discovery grant. Coupled wind/wave/ocean physics in large-scale air-sea applications (Iafratti et al., 2013, Ghantous and Babanin, 2014)

Ginis, I. “Advancing NOAA's HWRF Prediction System through New and Enhanced Physics of the Air-Sea-Wave Coupling”. Funding agency: NOAA, Hurricane Forecast Improvement Project (HFIP).

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Young, I.R., Babanin, A.V., Stiassnie, M.A., Greenslade, D.J. “Numerical modelling of extreme waves generated by tropical cyclones”, ARC Discovery. Modelling tropical cyclones, investigation of the nonlinear source term for spectral models (Chalikov and Babanin, 2012, 2013)

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