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 Srpings, MD 21746
phone: (301) 763-8000 x 7253 fax: (301)763-8545 email: Hendrik.Tolman@NOAA.gov

Grant Number: N00014-101-0418
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 WAVEWATCHIII and SWAN. Calibration and performance of the source functions have to satisfy a set of physical constraints, and methodology is to be developed to enable testing the source functions separately before they are blended in the full model. Verification is to be 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.

For the dissipation, these are threshold behaviour of breaking/dissipation in terms of wave-steepness/spectral-density, cumulative effect 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 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. 2007a).

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. Recently, two new swell-dissipation terms were suggested, which imply different physics: interaction of swell with atmospheric boundary layer (Ardhuin et al. 2009) and with background turbulence (Babanin 2006, 2011a).

The project will use 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 momentum wind 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 to calibrate the input and dissipation one by one, before they incorporated in the model where their contributions are not possible to separate (Babanin et al. 2005, 2010, Tsagareli et al 2010, Rogers et al. 2011).

Other constraints were also formulated and calibration dependences for initial academic tests were selected (see Work Completed 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. 2011), Lake George (finite depth, no swell, Young and Verhagen 1996a,b, Young et al. 1996, Young and Babanin 2006b, 2009, Babanin and Makin 2008, Young 2010), 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. 2011a). Measurement data are available for all the chosen sites. Once the model is fully tested, global simulations for selected years will be performed and compared with the altimeter database (Zieger et al. 2009, Vinoth and Young 2011, Young et al. 2011) and with NOAA simulations based on the previous version of WAVEWATCH III.

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 will conduct 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 will 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 will implement the new input and dissipation terms into SWAN, apart from WW3, and will 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 second year of the project. In the first year, 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 (Rogers et al. 2011) 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 data base.

During the second year, the main aim of the project was implementation of the source functions into WW3. This is done, and academic testing and initial field validation of the model were concluded. 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.

The academic tests covered ability of the new version of the model to reproduce observational deep-water dependences for integral parameters, for spectral parameters and for directional parameters of wave fields (Babanin and Soloviev 1998a,b). New tests, intended on separate validation of the wind input function and the whitecapping dissipation term were developed. The field validation of the model was conducted by means of hindcasting for a selection of Lake Michigan storms (wind and wave data are available, no swell conditions).

Research on the other topics of the project continued. On wave breaking and dissipation, book was published (Babanin 2011a), breaking in directional wave fields (Babanin et al. 2011b, Toffoli et al. 2011a), breaking in spectral environments (Chalikov and Babanin 2011) and wind influence on the severity of the breaking (Galchenko et al. 2011) were investigated. The wind-input constraint, sea drag, and its dependence on the wave breaking (Babanin 2011a), on the directional spreading of waves (Ting et al. 2011) and on wind gustiness and air humidity (Le Roy 2011) were studied. New dynamic wave-bottom friction routine was suggested and tested in SWAN, which accounts for ripple formation and dissolution, grain size of the sediment (Smith, G. et al., 2011). Continued was research of the wave induced turbulence and its role in the swell dissipation (Babanin 2011a, Pleskachevski et al. 2011).

Particular attention was paid to preparing for future hurricane modelling and global simulations. Sensitivity tests for the source functions in extreme conditions, including bottom-limited breaking, diffraction, refraction and numerical schemes were conducted by means of simulating Typhoon Krosa (Babanin et al. 2011a). New technique for measuring spray concentrations in the course of the planned Australian tropical cyclone field experiment was developed (Toffoli et al. 2011b). Change of dynamical regime of air-sea interactions at hurricane-wind threshold is described (Babanin 2011b). The global altimeter database of Zieger et al. (2009) was used for investigating the global trends of waves and winds (Young et al. 2011) and for estimating their extremes (Vinoth and Young 2011), over the past 25 years.

RESULTS

The results already submitted, accepted for publication or published and their significance are outlined in sections Work Completed, Impact/Applications and Publications of this report. In this section, due to limited space, we will indicate on results achieved, but not published yet, and will highlight most relevant published results.

The academic evolution tests of new wind-input and breaking-dissipation functions were done by two means, with DIA parameterisation of the nonlinear interactions and with exact computations of these interactions by means of WRT code (Tracy and Resio 1982). The latter provides accurate estimates of energy fluxes within the wave system, in addition to those due to wind and breaking, but is not possible to employ operationally, and the former is approximate, but is routinely employed in the operational forecast. Results are summarised in captions to Figs. 1 and 2, and Fig. 3 demonstrates application of these functions to Lake Michigan and comparisons with buoy measurements.

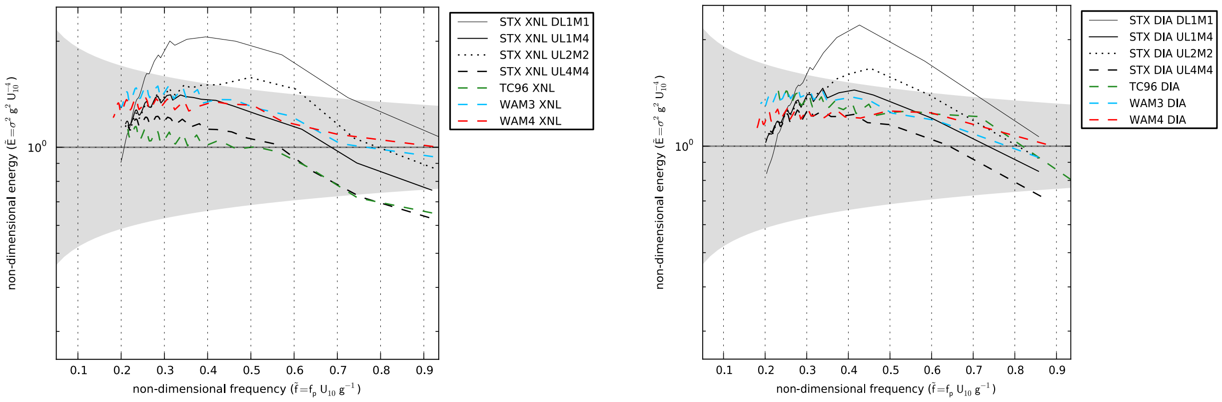

Fig.1. Total wave energy (dimensionless) versus dimensionless peak frequency, for different source functions as indicated in the legends. The dependences are normalised by the observational parameterisation of Babanin and Soloviev (1998a), which therefore equals unity in Figure, with shaded areas showing 95% confidence limits. Green lines indicate Tolman and Chalikov (1996) source functions, blue lines WAM3 and red lines WAM4 physics, respectively. Suit of black lines correspond to Donelan et al. (2006) wind input in the Tsagareli et al. (2010) version and to the four versions of Babanin and Young (2005) dissipation, following Rogers et al. (2011). UL4M4 is the preferred version for the subsequent modelling. (Left) Exact nonlinear term is used. (Right) DIA nonlinear-interaction term is used

The integral growth curves are usually subject to main scrutiny and tuning and all the source functions perform reasonably well with respect to the experimental dependence. Since the tuning is typically done with the use of DIA in evolution simulations, it is noticeable in Fig. 1 that performance of some source terms actually deteriorates once the exact nonlinear term is employed.

In Fig. 2, evolution results are shown with the use of WRT nonlinear term only. For the level of the spectrum tail (left), the new dissipation functions lead to overestimating this level by comparison with measurements and to corresponding bias of high moments in the hindcast of Lake Michigan storms in Fig. 3. In Fig. 2 right, Donelan et al. (2006) input (top) and *UL4M4* dissipation (bottom) are compared with the same set of source functions as before. The differences are essential, from overestimating to underestimating by a factor of 2 or more.

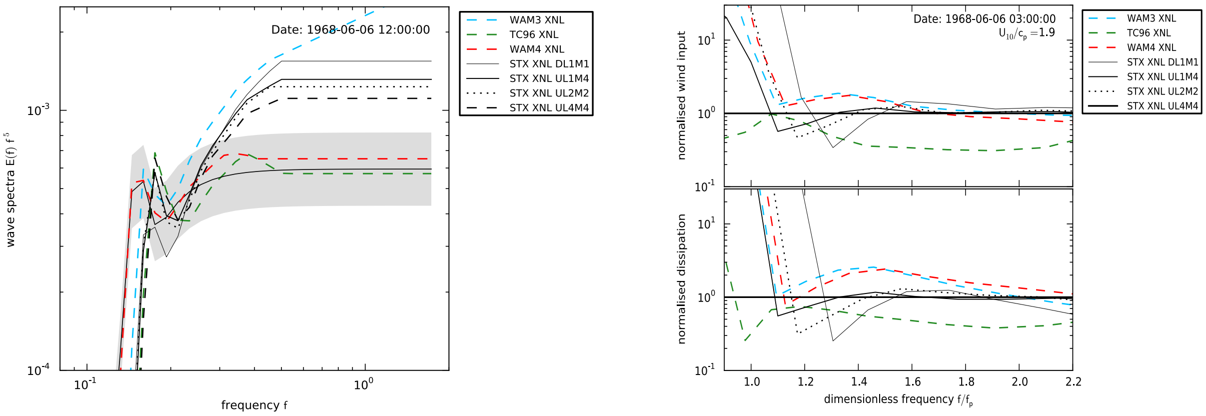

Fig.2. Evolution tests with WRT nonlinear term and the same selection of other source functions as in Fig.1. (left) Spectrum tail level versus dimensionless frequency. The dependences are normalised by observational parameterisation of Babanin and Soloviev (1998a), which therefore equals unity in Figure, with shaded areas showing 95% confidence limits. (right) Comparison of wind input (top) and dissipation (bottom) functions, normalised by Donelan et al. (2006) input function and UL4M4 dissipation function, respectively. $U_{10} / c_p = 1.9$*, bottom scale is relative frequency* f / f_p.

In Fig. 3, the new source functions are used for a Lake Michigan hindcast. Since the integral dependences are reproduced well in academic tests (Fig. 1), so are the integral wave properties in Fig. 3 (wave height, peak period, mean direction). Since the tail is overestimated in academic tests in Fig. 2, the weighted periods are expectedly biased in Fig. 3. It is now known experimentally that at strong forcing at a particular scale the extra wind energy flux cannot be effectively transferred by nonlinear interactions and a part of it is dissipated locally (Babanin and Young 2005, Babanin et al 2007b). This effect should reduce the tail level and is now parameterised in order to optimise the tail and high-moment behaviour (not shown).

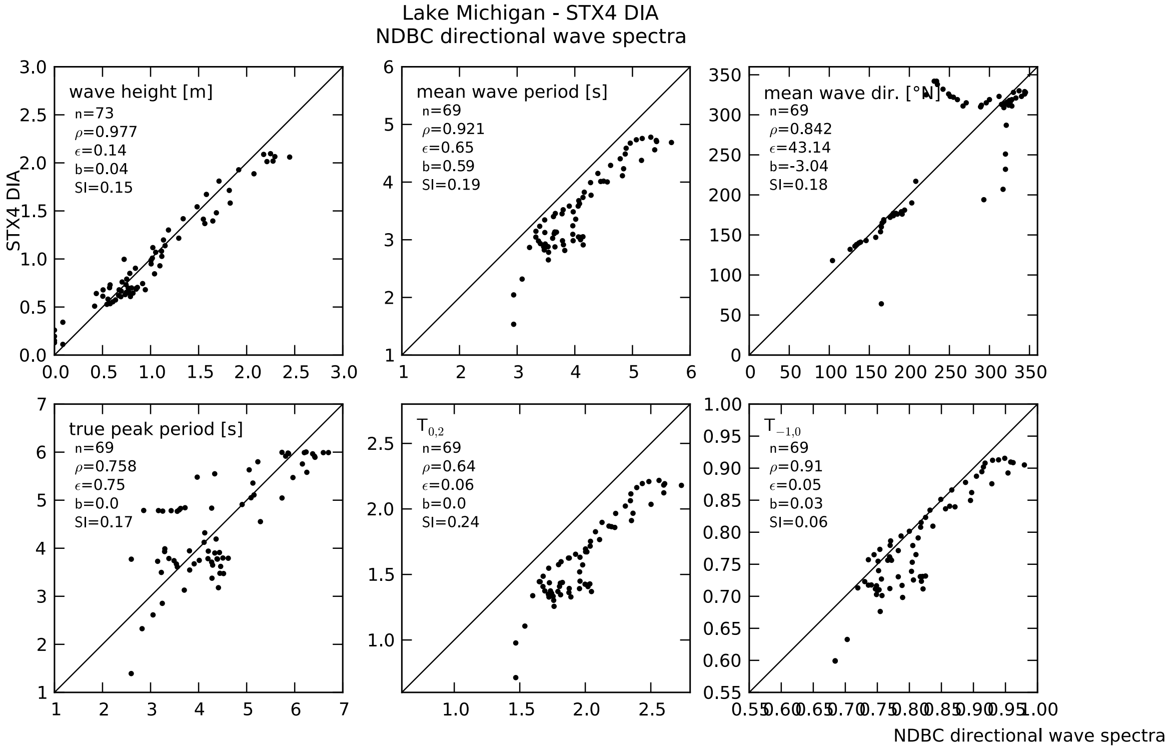

Fig.3. Comparison between the model (Donelan et al. (2006) input and UL4M4 dissipation of Rogers et al. (2011)) and NODC buoy 45007 from a 3 day hindcast (12-15 October 2002). DIA nonlinear term is used. Legends in the panels show parameters compared and statistics of the

comparisons. (Top row, left to right) Wave height, Mean wave period, Mean wave direction, respectively. (Bottom row, left to right) Peak period, $T_{0,2}$ *period,* $T_{-1,0}$ *period, respectively*

One of major developments over the year was use of the Swinburne University altimeter database (Zieger et al. 2009) for investigating changes of mean and extreme values of winds and waves since 1985, which will then be employed in global testing of the new version of the model. Fig. 4, reproduced from *Science* paper by Young et al. (2011) shows growth of their values globally.

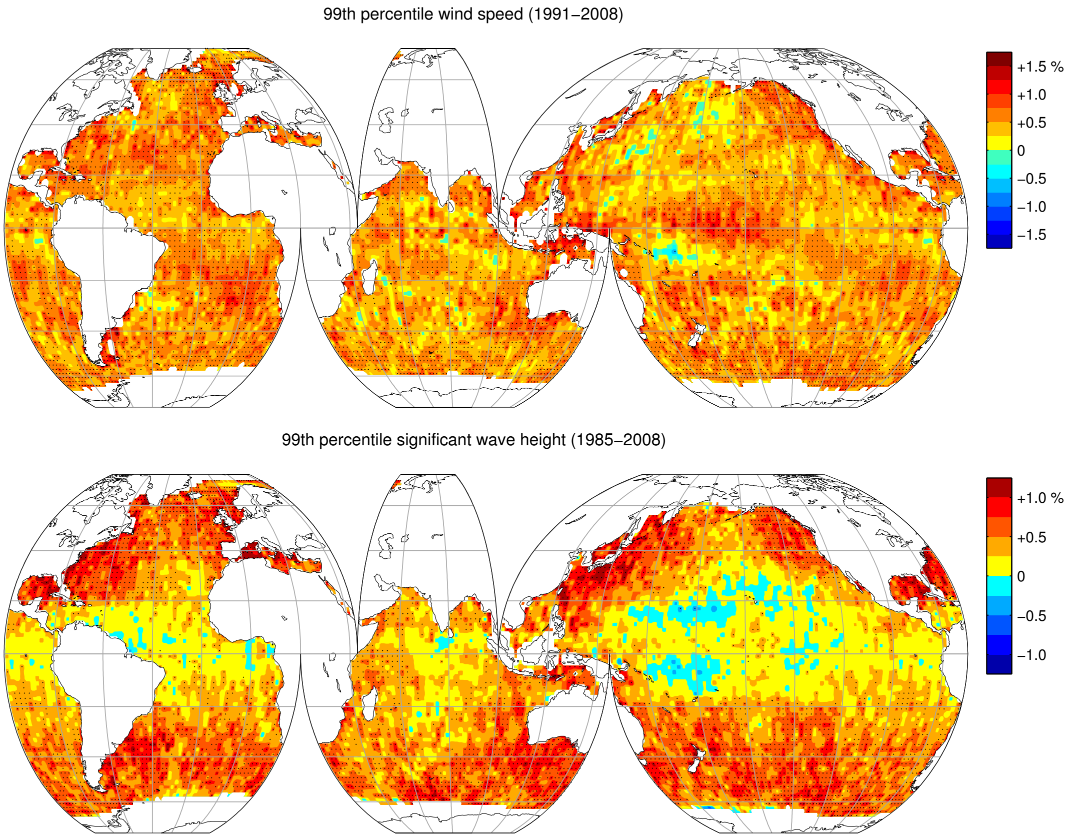

Fig.4. Colour contour plots of the 99^{th}*-percentile trend (per cent per year, 1985-2008 period, colour scale is shown on the right). Points that are statistically significant according to Seasonal Kendall test are shown with dots. (top) Wind speed. (bottom) Wave height*

IMPACT/APPLICATIONS

Economic Development and Quality of Life

The impacts of the outcomes, outlined below, pertain to applications relating to improving the wave forecast, and will result in Economic Developments, such as increased efficiency of coastal and offshore industries, marine waterways, and Quality of Life, such as safety in coastal and open-sea areas, recreational activities at sea, management of coastline.

Paper by Rogers et al. (2011) is implementation of the new wind-input and whitecapping-dissipation functions in SWAN model. These are functions based on observations and advanced understanding of respective physics, which have a potential to become operational for wave-forecast models. The paper also suggests and employs new approach to verifying the source functions individually at each computation step, which approach has a potential to replace the existing tradition of testing the models based on bulk performance of the energy sources together.

New swell-decay function developed by Babanin (2011a) is based on measurements and modelling of wave-turbulence interactions, a phenomenon not accounted for before. It provides estimates of swell dissipation consistent with field observations of Ardhuin et al. (2009) and is a critical new term for the models with threshold behaviour of whitecapping dissipation where such dissipation ceases once the wave spectrum is below the threshold. Dissipation due the wave-induced turbulence is most important in the context the upper-ocean mixing and sediment suspension, and this topic is further investigated by Pleskachevsky et al. (2011).

New bottom-friction routine was developed and introduced in SWAN which accounts for sediment size and provides dynamic coupling of the ripple-caused friction with the waves (Smith, G. et al. 2011). Simulations of Typhoon Krosa by means of SWAN and WWMII revealed bottom-limited-breaking terms as most problematic in finite depths (Babanin et al. 2011a). These results have essential implications for finite-depth modelling.

Topic of extreme wind-wave interactions is most important for the project in general, as major hindcast testing cases will be those for hurricanes in North America and tropical cyclones in Australia. Babanin (2011b) analysed this topic in general and found transition to a new dynamics in all three relevant media: in the atmospheric boundary layer, on the ocean surface, and below the surface, at the hurricane-threshold winds of 30-35m/s. Toffoli et al. (2011b) developed a new method of measuring spray in field experiments in hurricanes, which spray is a critical feature for hurricane dynamics according to many theoretical models.

Book of Babanin (2011a) published by Cambridge University Press is the first book on the wave breaking and dissipation. It also analyses features and phenomena in the atmospheric boundary layer and below the ocean surface related to the breaking, including those phenomena and transitions which occur in extreme weather conditions.

Publications of Babanin et al. (2011b,c), Chalikov and Babanin (2011), Galchenko et al. (2011), Toffoli et al (2011b) further develop the topic of wave breaking. Quantitative criteria for wave breaking in directional fields and for wave trains with continuous spectrum are analysed, influences of the wind forcing on wave breaking severity are studied. Potential impact of this research is significant across variety of related topics, including modelling the wave dissipation.

The sea-drag was shown to be affected by wave breaking (Babanin, 2011a) and to depend strongly on the directional spreading (Ting et al. 2011), on the gustiness and humidity (Le Roy 2011). In the context of the present project, the drag is used as a wind-input constraint, but impact of potentially improved sea-drag parameterisations is much broader in the air-sea interaction modelling of all scales.

Essential outcomes came from analysis of altimeter satellite database of Zieger et al. (2009). Young et al. (2011) revealed global positive trends for both mean and extreme values of surface winds and wave heights, and Vinoth and Young (2011) provided estimates of global extremes for such winds and waves. These results will be used for global testing of the model with new source functions at the final stage of the project.

Finally, but not the least important, is impact of the project on research training. 4 PhD and 1 Master theses have been defended or submitted on the topics of wave breaking, sea drag, altimeter data, wave-bottom interaction, whose results were influenced and were used in the present project.

TRANSITIONS

Economic Development and Quality of Life

As with Impact/Applications above, the transitions pertain to applications relating to improving the wave forecast, and will result in Economic Developments, such as increased efficiency of coastal and offshore industries, marine waterways, and Quality of Life, such as safety in coastal and open-sea areas, recreational activities at sea, management of coastline.

The input function (Tsagareli et al. 2010) and dissipation (Babanin et al. 2010) are used in research wave models at the University of Darmstatd, Germany and the National Cheng Kung University, Taiwan

RELATED PROJECTS

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., Phillips, W.R.C., Ganopolski, A. “Wave-induced upper-ocean mixing”, Australian Research Council (ARC) Discovery grant. Investigation of the wave-induced turbulence and non-breaking dissipation (Babanin 2011, Pleskachevsky et al. 2011)

Babanin, A.V., Young, I.R., Phillips, W.R.C., Donelan, A.M., Makin, V., Ardhuin, F. “Oceanic Conditions within Extreme Tropical Cyclones”, ARC Linkage grant. Field investigation of wind input and dissipation in extreme conditions (Toffoli et al. 2011b)

Young, I.R., Babanin, A.V. “A Global Satellite Altimeter Database for Ocean Engineering Applications”, ARC Linkage. Creation of the global altimeter wind and wave database over the period 1985-2008 and investigation global and regional trends (Vinoth and Young 2011, Young et al. 2011)

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 (Babanin et al., 2011a)

REFERENCES

References to the 2011 publications by PIs are in Publications below

Ardhuin, F., B. Chapron, and F. Collard, 2009: Observation of swell dissipation across the ocean. *Geophys. Res. Lett.*, 36, L06607, 4p

Ardhuin, F., E. Rogers, A. Babanin, J.-F. Filipot, R. Magne, A. Roland, A. van der Westhuysen, P. Queffeulou, J.-M. Lefevre, L. Aouf, and F. Collard, 2010: Semi-empirical dissipation source functions for ocean waves: Part I, definitions, calibration and validations. *J. Phys. Oceanogr.,* 40, 1917-1941

Babanin, A.V., and Yu.P. Soloviev, 1998a: Field investigation of transformation of the wind wave frequency spectrum with fetch and the stage of development. *J. Phys. Oceanogr.*, 28, 563-576

Babanin, A.V., and Yu.P. Soloviev, 1998b: Variability of directional spectra of wind-generated waves, studied by means of wave staff arrays. *Marine & Freshwater Res.*, 49, 89-101

Babanin, A.V., I.R. Young, and M.L. Banner, 2001: Breaking probabilities for dominant surface waves on water of finite constant depth. *J. Geophys. Res.,* 106(C6), 11659-11676

Babanin, A.V., and I.R. Young, 2005: Two-phase behaviour of the spectral dissipation of wind waves. *Proc. Ocean Waves Measurement and Analysis, Fifth Int. Symp. WAVES2005, 3-7 July, 2005, Madrid, Spain*, Eds. B. Edge and J.C. Santas, Sponsors CEDEX (Spain) and CORPI of ASCI (USA), paper no.51, 11p

Babanin, A.V., I.R. Young, and H. Mirfenderesk, 2005: Field and laboratory measurements of wave-bottom interaction. *Proc. 17th Australasian Coastal and Ocean Eng. Conf. and 10th Australasian Port and Harbour Conf., 20-23 September 2005, Adelaide, South Australia*, Eds. M.Townsend and D.Walker, The Institution of Engineers, Canberra, Australia, 293-298

Babanin, A.V., 2006: On a wave-induced turbulence and a wave-mixed upper ocean layer. *Geophys. Res. Lett.,* 33, L20605, 6p

Babanin, A.V., M.L. Banner, I.R. Young, and M.A. Donelan, 2007a: Wave follower measurements of the wind input spectral function. Part 3. Parameterization of the wind input enhancement due to wave breaking. *J. Phys. Oceanogr.*, 37, 2764–2775

Babanin, A.V., I.R. Young, R. Manasseh and E. Schultz, 2007b: Spectral dissipation term for wave forecast models, experimental study. *Proc. 10th Int. Workshop on Wave Hindcasting and Forecasting and Coastal Hazards, Oahu, Hawaii, November, 11-16, 2007,* 19p

Babanin, A.V., and V.K. Makin, 2008: Effects of wind trend and gustiness on the sea drag: Lake George study, *J. Geophys. Res.,* 113, C02015, 18p

Babanin, A.V., K.N. Tsagareli, I.R Young, and D.J. Walker, 2010: Numerical investigation of spectral evolution of wind waves. Part 2. Dissipation function and evolution tests. *J. Phys. Oceanogr.,* 40, 667-683

Donelan, M.A., A.V. Babanin, I.R. Young, and M.L. Banner, 2006: Wave follower measurements of the wind input spectral function. Part 2. Parameterization of the wind input. *J. Phys. Oceanogr*, 36, 1672-1688

Filipot, J.-F., F. Ardhuin, and A.V. Babanin, 2010: A unified deep-to-shallow-water spectral wave-breaking dissipation formulation. *J. Geophys. Res.,* 115, C04022, 15p

Interagency Performance Evaluation Task Force (IPET), 2006: Performance evaluation of the New Orleans and southeast Louisiana Hurricane Protection System. *Volume IV – The Storm* (main text and technical appendices). US Army Corps of Engineers, 1197p, https://ipet.wes.army.mil/

Smith, J. M. 2006. "Modeling Nearshore Waves for Hurricane Katrina," *Proc. 9th International Workshop on Wave Hindcasting and Forecasting,* http://www.oceanweather.com/9thwave/

Tolman, H.L., and D. Chalikov, 1996: Source terms in a third-generation wind wave model. *J. Phys. Oceanogr.*, 26, 2497--2518

Tsagareli, K.N., A.V. Babanin, D.J. Walker, and I.R. Young, 2010: Numerical investigation of spectral evolution of wind waves. Part 1. Wind input source function. *J. Phys. Oceanogr.,* 40, 656-666

Tracy, B.A., and D.T. Resio, 1982: Theory and calculation of the nonlinear energy transfer between sea waves in deep water. U.S. Army Engineer Waterways Experiment Station, Rep. N11, Vicksburg, U.S.A., 54p

Young, I.R. and L.A. Verhagen, 1996a: The growth of fetch limited waves in water of finite depth. Part I: Total energy and peak frequency. *Coast. Eng.*, 28, 47-78

Young, I.R. and L.A. Verhagen, 1996b: The growth of fetch limited waves in water of finite depth. Part II: Spectral evolution. *Coast. Eng.*, 28, 79-100

Young, I.R., L.A. Verhagen, and S.K. Khatri, 1996: The Growth of fetch limited waves in water of finite depth. Part III: Directional spectra. *Coast. Eng.*, 28, 101-122

Young, I.R., M.L. Banner, M.A. Donelan, A.V. Babanin, W.K. Melville, F. Veron, and C. McCormick, 2005: An integrated system for the study of wind wave source terms in finite depth water. *J. Atmos. Oceanic Tech.,* 22(7), 814–828

Young, I.R., 2006: Directional spectra of hurricane wind-waves. *J. Geophys. Res.*, 111, C08020, 14p

Young, I.R., and A.V. Babanin, 2006a: Spectral distribution of energy dissipation of wind-generated waves due to dominant wave breaking. *Journal of Physical Oceanography*, 36(3), 376–394

Young, I.R., and A.V. Babanin, 2006b: The form of the asymptotic depth-limited wind wave frequency spectrum, *Journal of Geophysical Research*, 111, C06031, doi:10.1029/2005JC003398, 15p

Young, I.R., and A.V. Babanin, 2009: The form of the asymptotic depth-limited wind wave frequency spectrum. Part II – The wavenumber spectrum. *Coastal Engineering*, 56, 534-542

Young, I.R., 2010, The form of the asymptotic depth-limited wind-wave spectrum: Part III: Directional spreading, Coastal Engineering, 57, 30-40

Zieger, S., J. Vinoth, I. R. Young, 2009: Joint Calibration of Multiplatform Altimeter Measurements of Wind Speed and Wave Height over the Past 20 Years. *J. Atmos. Oceanic Technol.*, 26, 2549–2564

PUBLICATIONS

Journals, book and theses

Babanin, A.V., 2011a: Breaking and Dissipation of Ocean Surface Waves. *Book,* Cambridge University Press, 480p [published, refereed]

Babanin, A.V., T.-W. Hsu, A. Roland, S.-H. Ou, D.-J. Doong, and C.C Kao, 2011a: Spectral modelling of Typhoon Krosa. *Natural Hazards and Earth System Sciences*, 11, 501-511 [published, refereed]

Babanin, A.V, T. Waseda, T. Kinoshita, and A. Toffoli, 2011b: Wave breaking in directional fields. *Journal of Physical Oceanography,* 41, 145-156 [published, refereed]

Chalikov, D., and A.V. Babanin, 2011: Simulation of breaking in spectral environment. *Journal of Physical Oceanography* [under review]

Dietrich, J.C., J.J. Westerink, A.B. Kennedy, J.M. Smith, R. Jensen, M. Zijlema, L.H. Holthuijsen, C. Dawson, R.A. Luettich, Jr., M.D. Powell, V.J. Cardone, A.T. Cox, G.W. Stone, H. Pourtaheri, M.E. Hope, S. Tanaka, L.G. Westerink, H.J. Westerink, and Z. Cobell, 2011: Hurricane Gustav (2008) Waves, Storm Surge and Currents: Hindcast and Synoptic Analysis in Southern Louisiana, *Monthly Weather Review*, 139, 2488-2522 [published, refereed]

Galchenko, A., 2011: Numerical and physical modelling of breaking of fully nonlinear surface waves. *PhD Thesis*, Swinburne University of Technology [published, refereed]

Galchenko, A., A.V. Babanin, D. Chalikov, I.R. Young, and B.K. Haus, 2011: Influence of wind forcing on modulation and breaking of deep-water groups. *Journal of Physical Oceanography* [under review]

Le Roy, P., 2011: Effects of gustiness, humidity and stratification on the drag coefficient. *Master Thesis*, Swinburne University and Meteo France [published, refereed]

Pleskachevsky, A., M. Dobrynin, A.V. Babanin, H. Gunther, and E. Stanev, 2011: Turbulent diffusion due to ocean surface waves indicated by suspended particulate matter. Implementation of satellite data into numerical modelling. *Journal of Physical Oceanography*, 41, 708-724 [published, refereed]

Rogers, W.E., A.V. Babanin, D.W. Wang, 2011: Observation-based input and whitecapping-dissipation in a model for wind-generated surface waves: Description and simple calculations. *Journal of Atmospheric and Oceanic Technology* [under review]

Smith, G., 2011: Sediment mobility modelling: bedforms, sediment suspension and sediment transport. *PhD Thesis*, Swinburne University of Technology [under review]

Smith, G., A.V. Babanin, P. Riedel, I.R. Young, S. Oliver, and G. Hubbert, 2011: Introduction of a new friction routine into the SWAN model that evaluates roughness due to bedform and sediment size changes. *Coastal Engineering*, 58, 317-326 [published, refereed]

Ting, C.-H., A.V. Babanin, D. Chalikov, and T.-W. Hsu, 2011: Dependence of drag coefficient on the directional spreading of ocean waves. *Journal of Geophysical Research* [under review]

Toffoli, A., L. Cavaleri, A.V. Babanin, M. Benoit, E.M. Bitner-Gregersen, J. Monbaliu, M. Onorato, A.R. Osborne, and C.T. Stansberg, 2011a: Occurrence of extreme waves in three dimensional mechanically generated wave fields propagating over an oblique current. *Natural Hazards and Earth System Scie.*, 11, 895-903 [published, refereed]

Toffoli, A., A.V. Babanin, M.A. Donelan, B.K. Haus, and D. Jeong, 2011b: Estimating sea spray concentration with the laser altimeter. *Journal of Atmospheric and Oceanic Technology*, 28, 1177-1183 [published, refereed]

Vinoth, J., 2011: Study of the global wave climate by means of altimeter satellite data base. *PhD Thesis*, Swinburne University of Technology [published, refereed]

Vinoth, J., and I.R. Young, 2011: Global estimates of extreme wind speed and wave height. *J. Climate*, 24, 1647-1665 [published, refereed]

Young, I.R., S. Zieger, and A.V. Babanin, 2011: Global trends in wind speed and wave height. *Science*, 332, 451-455 [published, refereed]

Zieger, S., 2011: Determining changes in the global ocean wind and wave climate as observed by satellite altimeter. *PhD Thesis*, Swinburne University of Technology [published, refereed]

Other

Babanin, A.V., 2011b: Change of regime of air-sea interactions in extreme weather conditions. *Proc. 20th Australasian Coastal and Ocean Eng. Conf. and 13th Australasian Port and Harbour Eng. Conf., 28-30 September 2009, Perth, Western Australia,* 5p [published, refereed]

Babanin, A.V., T. Waseda, I. Shugan, H.-H. Hwung, 2011c: Modulational instability in directional wave fields and extreme wave events. *Proc. ASME 2011 30th Int. Conf. on Ocean, Offshore and Arctic Eng. OMAE2011, July 19-24, 2011, Rotterdam, The Netherlands*, 7p [published, refereed]

Das, H.S., H.-S. Jung, J. Smith, and T. Wamsley, 2011: A high resolution unstructured model to study storm surge in the Pacific Island of Guam. *Proc., Solutions to Coastal Disasters 2011*, ASCE, 22-29 [published, refereed]

Massey, T.C., M.E. Anderson, R. Jones, J. Gomez, and J.M. Smith, 2011: STWAVE: Steady-state spectral wave model user's manual for STWAVE, Version 6.0, ERDC/CHL SR-11-01, U.S. Army ERDC, Vicksburg, MS, 88p [published]

Smith, J. M., J.J. Westerink, A.B. Kennedy, A.A. Taflanidis, K.F. Cheung, and T.D. Smith, 2011: SWIMS Hawaii hurricane wave, surge, and runup inundation fast forecast tool. *Proc., Solutions to Coastal Disasters 2011*, ASCE, 77-88 [published, refereed]

Taflanidis, A.A., A.B. Kennedy, J.J. Westerink, M. Hope, S. Tanaka, J. Smith, and K.F. Cheung, 2011: Online hurricane surge risk estimation for coastal regions by response surface methodologies. *Proc., Int. Conf. on Applications of Statistics and Probability in Civil Eng.* [published]

Ratcliff, J. and J. Smith, 2011: Sea level rise impacts to military installations in lower Chesapeake Bay. *Proc., Solutions to Coastal Disasters 2011*, ASCE, 740-751 [published, refereed]