# 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
Swinburne University of Technology, PO Box 218, Hawthorn, Victoria 3140 Australia
phone: +61-3-9214-8131 fax: +61-3-9818-3469 email: iyoung@swin.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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## LONG-TERM GOALS

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

## OBJECTIVES

The objectives are to use new observation-based source terms for the wind input and wave-breaking dissipation in the third-generation models WAVEWATCHIII and SWAN. Calibration and performance of the source functions have to satisfy set of physical constraints. 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.

## 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 strong-to-extreme wind forcing. 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. None of these features are present in the currently employed dissipation functions used for 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 the environment of steep-waves/strong-winds). Enhancement of the wind input due to wave breaking was also observed, quantified and parameterised.

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. 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.

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), Lake George (finite depth, no swell), Gulf of Mexico (open sea, deep-to-finite depths, swell, tropical cyclones). Measurement data are available for all the chosen sites.

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

The formulations for the observation-based source terms (wind input, Donelan et al., 2006, dissipation, Young and Babanin, 2006), proposed and quantified in the course of Lake George field campaign (Young et al., 2005), have been 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., 2010a).

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 Gulf of Mexico cases (Bender et al., 2010, Dietrich et al., 2010, Howes et al., 2010, Smith, J.M. et al., 2010). New dynamic wave-bottom friction routine is suggested and tested in SWAN, which accounts for ripple formation and dissolution, grain size of the sediment (Smith, G. et al., 2010). Sensitivity tests for the source functions, including bottom-limited breaking, diffraction, refraction and numerical schemes were conducted by means of simulating Typhoon Krosa (Babanin et al., 2010d) - the simulations were done with SWAN and WWMII (Roland, 2009). Field data sets for further model-testing are selected and prepared: Lake George (Young and Verhagen, 1996a,b, Young et al., 1996, 2005, Babanin and Makin, 2008); Black Sea (Babanin and Soloviev, 1998a,b); global altimeter data base (Zieger et. al., 2009).

Implementation of the source functions into WW3 is started. A set of experimental dependences and physical constraints for academic testing of the new terms in WW3 was selected or prepared. The dependences include: 1) Integral dependences: for the total energy, $f_p$, peak width, peak enhancement (Babanin and Soloviev, 1998a); based on external and internal dimensional scaling (Kitaigorodskii, 1962 and Badulin et al., 2007, respectively); 2) Spectral dependences: levels of $f^{-4}$ (Resio et al., 2004) and $f^{-5}$ (Babanin and Soloviev, 1998a, Babanin, 2010) subintervals, transition between them (Babanin, 2010), transition between inherent- and induced-breaking (Filipot, unpublished); 3) Directional dependences: on wave age, on relative frequency, the narrowest spread, behaviour at low frequencies (Babanin and Soloviev, 1998b). The constraints include: 1) Dependences for the sea-drag coefficient $C_D$ as constraint for the total input (Guan and Xie, 2004, Babanin and Makin, 2008, Babanin, 2010, Ting et al., 2010); 2) Donelan (1998) constraint for the total dissipation as a function of the total input; 3) Formulation for the integral dissipation in the water column (Babanin et al., 2005, Babanin, 2009).

Research on the main topic of the project, wave-breaking and wind-input constraints, continued. Laboratory and numerical studies of wave breaking onset (Babanin et al., 2010b), of mechanisms of the breaking in directional wave fields (Babanin et al., 2010c), of limiting steepness in the oceanic and laboratory three-dimensional waves (Toffoli et al., 2010a), of wave-breaking severity (Galchenko et al., 2010), of evolution of non-linear wave trains (Toffoli et al., 2010b, d, e). were completed. For the wind input, investigation of the sea-drag dependence on wave breaking (Babanin, 2010) and wave directional spreading (Ting et al., 2010) were conducted, new methodology for measuring spray in tropical cyclones was developed in preparation for a field experiment (Toffoli et al.. 2010c).

For the test cases and hindcasting, apart from whitecapping dissipation, the term for non-breaking (swell) attenuation is most essential. For this, both Ardhuin et al. (2009) swell-dissipation term is used (which describes wave attenuation due to ‘friction’ against the turbulent air) and new term was developed in order to account for wave energy spent on generation of turbulence in the water (Babanin, 2010). Among completed and published work on this topic is also the laboratory-numerical study of wave-induced turbulence in stratified waters (Dai et al., 2010), advanced turbulence-mixing scheme with account for wave-caused turbulence diffusion and wave-induced turbulence production (Pleskachevsky et al., 2010).

Collaboration with other NOPP groups was continued. Specifically, another formulation of the dissipation term, which also includes the observational features of the breaking threshold and cumulative dissipation was tested (Ardhuin et al., 2010), and an alternative deep-to-shallow-water dissipation function, based on combination of experimental observations of breaking probability and severity, was proposed (Filipot et al., 2010).

## 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 calibrated observation-based wind-input and dissipation functions in frequency domain are compared in Fig. 1 (left) at different stages of wave development. In Fig.1 (right), the bimodal frequency-directional dissipation function is illustrated.

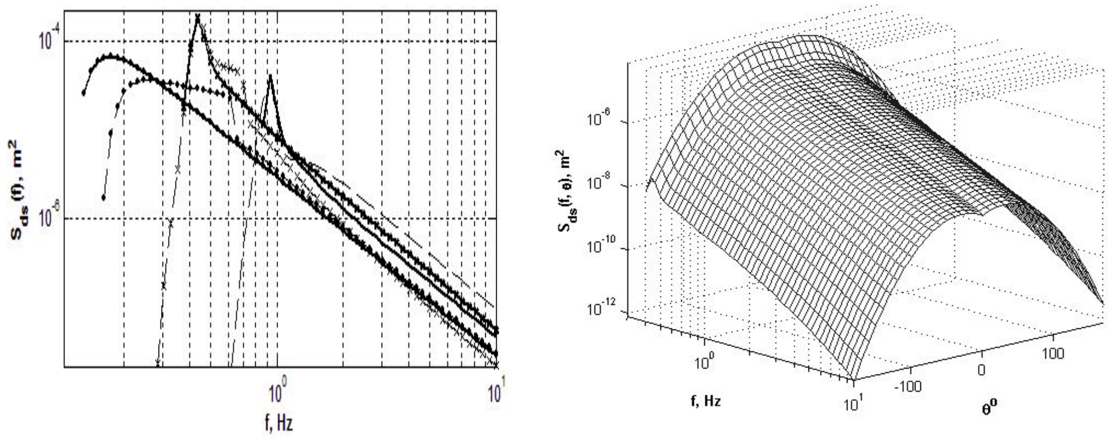


*Fig.1. Calibration of the new source functions for spectral models. (left) Spectral dissipation source function $S_{ds}(f)$ at different stages of the wave development: $U_{10}$ / $c_p$ = 5.7 (bold line), 2.7 (bold line with crosses), 0.83 (bold line with dots), for the wind speed $U_{10}$ = 10 m/s. Respective wind-input source functions $S_{in}(f)$ are also shown with plane lines marked with symbols corresponding to the dissipation functions. As the spectral peak downshifts, the input-dissipation spectral density grows, except for the full development where it drops significantly, both at the peak and across the spectrum. (right) Two-dimensional dissipation function $S_{ds}(f,\theta)$, with the bimodal directional spreading. (Figures are reproduced from Babanin et al., 2010a, copyright of AMS)*

Total dissipation in the water column was used as a verification means for the new observation-based input and dissipation source terms (Fig.2 left). Simulations of Hurricane Ivan were conducted using SWAN and compared with measurements (Fig.2 right). Results are summarised in the caption of Fig.2.

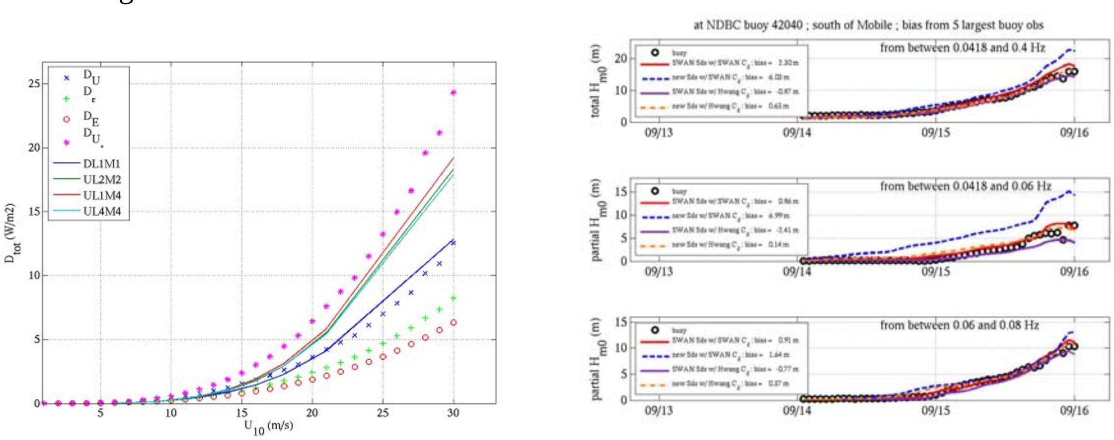


*Fig.2. Implementing the new source functions in SWAN model. (left) Verification of new observation-based numerical model against independent parametric models: variation of integrated dissipation with 10m wind speed. Solid lines: from four variants of the new model,*

*computed at the end of single-point (duration-limited) simulations at a number of wind speeds. Points: Four different parametric models:* $D_U$ *and* $D_\varepsilon$ *are taken from Hwang and Sletton (2003);* $D_E$ *is from Hanson and Phillips (1999);* $D_{U_*}$ *is a variant of* $D_U$ *which scales with* $u_*$ *rather than* $U_{10}$*. (right) Verification of models for Hurricane Ivan (Gulf of Mexico, September 2004) against a buoy near landfall location (NOAA NDBC 42040). Top panel: time series of waveheight. Center and lower panels: time series of energy for 2 frequency bands. "SWAN* $S_{ds}$*" refers to default physics of the SWAN model (input and dissipation). "new* $S_{ds}$*" refers to new observation-based physics (input and dissipation). "SWAN* $C_d$*" refers to drag formula used by default in SWAN, a modified version of Wu (1982). "Hwang* $C_d$*" refers to a new drag formula proposed by Hwang (JGR, 2010) which is based on new measurements of wind stress at high wind speeds, including during Hurricane Ivan. With antiquated* $C_d$*, the new model performs very poorly, severely overpredicting low-frequency energy. The default input and dissipation of SWAN perform better using antiquated* $C_d$ *than with a modern* $C_d$*. With a modern* $C_d$ *formula, the new model out-performs the other 3 models.*

Main constraint for the wind input is the total stress $\tau$ which is obtained from the wind speed $U_{10}$ by using the sea drag coefficient $C_D$: $\tau = \rho_a C_D U_{10}^2$. For the dissipation, the constraints are due to energy lost in the course of a breaking event. New developments are illustrated in Fig.3.

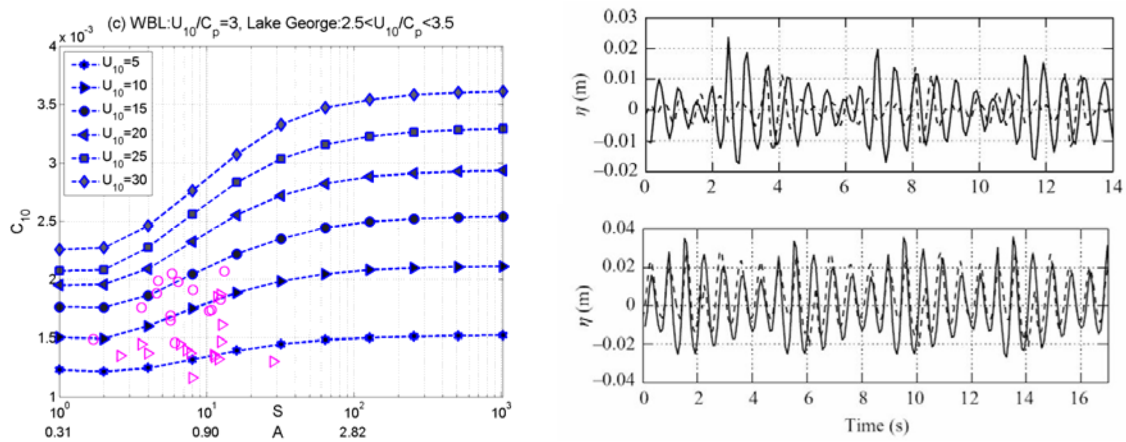


*Fig.3. Experimental and numerical investigation of physical constraints for the new source functions. (left) Dependence of sea drag on directional spreading described in terms of cosine power S (Longuet-Higgins et al, 1963) and directional-spectrum integral A (Babanin and Soloviev 1998b).* $C_d$ *is shown for wind speeds* $U_{10}$*=5, 10, 15, 20, 25 and 30m/s, and it grows significantly as a directional spread narrows. Corresponding Lake George measurements (pink data points, Babanin and Makin, 2008) agree well with the model. (Figure is reproduced from Ting et al. (2010)) (right) Wave trains before (solid line) and after (dashed line) a breaking, mechanically-generated waves: (top) no wind, most of the energy is lost from the wave group; (bottom) strong wind forcing U/c=3.9, breaking strength is marginal, the group survived. (Figure is reproduced from Babanin et al., 2010b, copyright of CUP)*

Investigation of the nature of wave breaking, as a key component of the wave-energy dissipation studies also continued. In Fig.4, limiting steepness of the waves in directional wave fields is shown in the left panel, and separation of linear-focusing and modulation-instability breaking in the right panel.

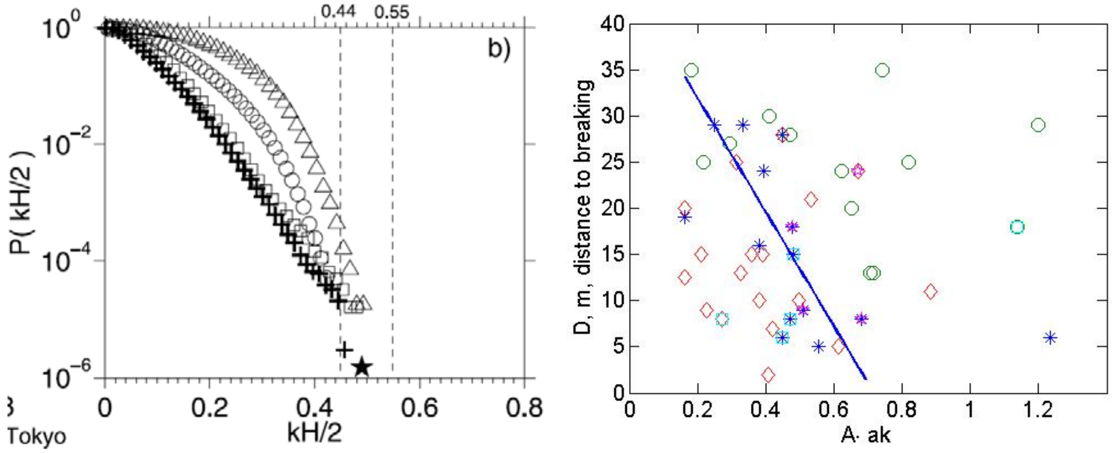


*Fig.4. Nature of the wave-breaking onset and physics. (left) Wave-steepness probability distribution in directional wave fields. Four diverse data sets are used, obtained in directional wave tanks (University of Tokyo, triangles, and Marintek, circles) and two field sites (Black Sea, squares, and tropical Indian Ocean, pluses). The star indicates the minimal possible probability level which could have been detected if existed. Each of the data subsets indicate the steepness limit of Hk/2≈0.46-0.48 for the up-crossing wave steepness. (Figure is reproduced from Toffoli et al., 2010a, copyright of AGU) (right) Distance to breaking D versus directional modulation index ak*A where ak is mean wave steepness and A is the directional-spread parameter (Babanin and Soloviev, 1998b, same as in Fig.3 (left)). Circles correspond to the breaking due to modulational instability, diamonds to linear focusing, and stars to transitional cases. Solid line is regression drawn through the transitional cases, it separates the modulational-instability and linear-focusing breaking. The Figure demonstrates that the instability breaking does exist in wave fields with typical steepness and directional spread, and that it is more likely than the linear-superposition breaking. (Figure is reproduced from Babanin et al., 2010c)*

## 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.

Results of Ardhuin et al. (2010), Babanin et al. (2010a), Filipot et al. (2010), Tsagareli et al. (2010) formulate and test new source functions, based on advanced physics, which have a potential to become operational for wave-forecast models. Babanin et al. (2010a), Tsagareli et al. (2010) suggest new approach to testing the source functions individually and separately, before including them into wave models, which approach has a potential to replace the existing tradition of testing the models based on bulk performance of the energy sources together.

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., 2010). Simulations of Typhoon Krosa by means of SWAN and WWMII revealed bottom-limited-breaking terms as most problematic in finite depths (Babanin et al., 2010d). These results have essential implications for finite-depth modelling.

Publications of Babanin (2010), Babanin et al. (2010a,b,c), Galchenko et al. (2010), Toffoli et al. (2010a,b,d,e) scrutinise evolution of non-linear waves, including that leading to wave breaking, the breaking onset, breaking strength. They clarify mechanisms responsible for the breaking in directional wave fields, define limiting wave steepness, parameterise the breaking severity.

Potential impact of this research is significant across variety of related topics, including modelling the wave dissipation.

Research of the wave-induced turbulence is most important for the upper-ocean mixing, and in the context of the present project for the swell dissipation (Babanin, 2010, Dai et al., 2010, Pleskachevsky et al., 2010).

The sea-drag was shown to be affected by wave breaking (Babanin, 2010) and to depend strongly on the directional spreading (Ting et al., 2010). Also most important are measurement of the drag in extreme weather conditions (Toffoli et al., 2010c). In the context of the present project, this is important as the drag is used as a wind-input constraint, but impact of potentially improved sea-drag parameterisation is much broader in the air-sea interaction modelling of all scales.

## 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, see also Work Completed).

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, 2010, Dai et al., 2010, Pleskachevsky et al., 2010)

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., 2010a, Ting et al., 2010)

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 (Zieger, 2010, Vinoth and Young, 2010)

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., 2010d)

## REFERENCES

*References to the 2010 publications by PIs and Research Fellow are in Publications below*

Ardhuin, F., B. Chapron, B., and F. Collard, 2009: Observation of swell dissipation across oceans. *Geophys. Res. Lett.*, 36, L06607, doi:10.1029/2008GL037030, 4p

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. Oceanography*, 28(4), 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(2), 89-101

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., and V.K. Makin, 2008: Effects of wind trend and gustiness on the sea drag: Lake George study, *J. Geophys. Res.,* 113, C02015, doi:10.1029/2007JC004233, 18p

Babanin, A.V., 2009: Breaking of ocean surface waves. *Acta Physica Slovaca,* 59(4), 305-535

Badulin, S.I., A.V. Babanin, V.E. Zakharov, and D. Resio, 2007: Weakly turbulent laws of wind-wave growth. *J. Fluid Mech.,* 591, 339-378

Donelan, M.A., 1998: Air-water exchange processes. *Physical Processes in Lakes and Oceans. Coastal and Estuarine Studies*, 54, Ed. J.Imberger, 19-36

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. *Journal of Physical Oceanography*, 36(8), 1672-1688

Guan, C., and L. Xie, 2004: On the linear parameterisation of drag coefficient over sea surface. *J. Phys. Oceanogr.*, 32, 2847-2851

Hanson, J. L., and O. M. Philips (1999), Wind sea growth and dissipation in the open ocean. *J. Phys. Oceanogr.*, 29, 1633–1648

Hwang, P. A., and M. A. Sletten (2008), Energy dissipation of wind-generated waves and whitecap coverage. *J. Geophys. Res.,* 113, C02012, doi:10.1029/2007JC004277.

Hwang, P.A., 2010: A note on the ocean surface roughness spectrum. *J. Geophys. Res.*, under review

Kitaigorodskii, S.A., 1962: Applications of the theory of similarity to the analysis of wind-generated wave motion as a stochastic process. *Bull. Acad. Sci. USSR, Geophys. Ser., Engl. Transl*., N1, 105-117

Longuet-Higgins, M.S., D.E. Cartwright, and N.D. Smith, 1963: Observations of the directional spectrum of sea waves using the motions of the floating buoy. *Proc. Conf. on Ocean Spectra*., Prentice-Hall, Englewood Cliffs, NJ, 111-136

Resio, D.T., C.E. Long, and C.L. Vincent, 2004: Equilibrium-range constant in wind-generated wave spectra. *J. Geophys. Res*., 109, C01018, doi:10.1029/2003JC001788, 14p

Roland, A., 2009: Development of the WWM II -Spectral Wave Modeling on Unstructured Meshes. *PhD Thesis*, Institute for Hydraulic and Water Resources Engineering, University of Technology Darmstadt

Wu, J., 1982: Wind stress coefficients over sea surface from breeze to hurricane. *J. Geophysical Res.*, V.87, C12, 9704-9706

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

**PUBLICATIONS**

***Journals, book and thesis***

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 [published, refereed]

Babanin, A.V., 2010: Breaking and Dissipation of Ocean Surface Waves. *Book*, Cambridge University Press [in press, refereed]

Babanin, A.V., K.N. Tsagareli, I.R Young, and D.J. Walker, 2010a: Numerical investigation of spectral evolution of wind waves. Part 2. Dissipation function and evolution tests. *J. Phys. Oceanogr.,* 40(4), 667-683 [published, refereed]

Babanin, A.V., D. Chalikov, I.R. Young, and I. Savelyev, 2010b: Numerical and laboratory investigation of breaking of steep two-dimensional waves in deep water. *J. Fluid Mech.,* 644, 433-463 [published, refereed]

Babanin A.V, T. Waseda, T. Kinoshita, and A. Toffoli, 2010c: Wave breaking in directional fields. *J. Phys. Oceanogr.* [in press, refereed]

Babanin, A.V., T.-W. Hsu, A. Roland, S.-H. Ou, D.-J. Doong, and Y.-M. Fan, 2010d: Spectral modelling of Typhoon Krosa. *Natural Hazards and Earth System Scie.* [under review]

Dai, D., F. Qiao, W. Sulisz, L. Han, and A.V. Babanin, 2010: An experiment on the non-breaking surface-wave-induced vertical mixing. *J. Phys. Oceanogr.*, 2180-2188 [published, refereed]

Dietrich, J.C., M. Zijlema, J.J. Westerink, L.H. Holthuijsen, C. Dawson, R.A., Luettich Jr, R.E. Jensen, J.M. Smith, G.S. Stelling, and G.W. Stone, 2010: Modeling hurricane waves and storm surge using integrally-coupled, scalable computations. *Coast. Eng.* [in press, refereed]

Filipot, J.-F., F. Ardhuin, and A.V. Babanin, 2010: A unified deep-to-shallow-water spectral wave-breaking dissipation formulation. *Journal of Geophysical Research,* 115, C04022, doi:10.1029/2009JC005448, 15p [published, refereed]

Galchenko, A., A.V. Babanin, D. Chalikov, I.R. Young, and T.-W. Hsu, 2010: Modulation depth and breaking strength for deep-water wave groups. *J. Phys. Oceanogr.* [in press, refereed]

Pleskachevsky, A., M. Dobrynin, A.V. Babanin, H. Gunther, and E. Stanev, 2010 : Turbulent diffusion due to ocean surface waves indicated by suspended particulate matter. Implementation of satellite data into numerical modelling. *J. Phys. Oceanogr.* [in press, refereed]

Smith, G., A.V. Babanin, P. Riedel, I.R. Young, S. Oliver, and G. Hubbert, 2010: Introduction of a new friction routine into the SWAN model that evaluates roughness due to bedform and sediment size changes. *Coast. Eng.* [under review]

Toffoli, A., A.V. Babanin, T. Waseda, and M. Onorato, 2010a: The maximum steepness of oceanic waves. *Geophys. Res. Lett.*, 37, L05603, doi:10.1029/2009GL041771, 4p [published, refereed]

Toffoli, A., L. Cavaleri, A.V. Babanin, M. Benoit, E.M. Bitner-Gregersen, J. Monbaliu, M. Onorato, A.R. Osborne, and C.T. Stansberg, 2010b: Occurrence of extreme waves in three dimensional mechanically generated wave fields propagating over an oblique current. *Natural Hazards and Earth System Scie.* [under review]

Toffoli, A., A.V. Babanin, M.A. Donelan, B.K. Haus, and D. Jeong, 2010c: Estimating sea spray concentration with the laser altimeter. *J. Atmos. Oceanic Tech.* [under review]

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(4), 656-666 [published, refereed]

Vinoth, J. and I.R. Young, 2010: Global estimates of extreme wind speed and wave height. *J. Climate* [under review]

Zieger, S., 2010: Determining changes in the global ocean wind and wave climate as observed by satellite altimeter. *PhD Thesis*, Swinburne University of Technology [under review]

***Other***

Bender, C., J.M. Smith, J.M., and A. Kennedy, 2010: Hurrican Ike (2008) nearshore waves: simulations and measurements. *Proc. ICCE 2010*, Shanghai, China [published]

Howes, N.C., D.M. Fitzgerald, Z.J. Hughes, I.Y. Georgiou, M.A. Kulp, M.D. Miner, J.M. Smith, and J.A. Barras, 2010: Hurricanes-induced failure of low salinity wetlands. *Proc. National Acad. Scie. USA*, 107(32), http://www.pnas.org/content/107/32/14014.full.pdf+html [published]

Smith, J.M., R.E. Jensen, A. Kennedy, J.C. Dietrich, and J.J. Westerink, 2010: Waves in wetlands: Hurricane Gustav. *Proc. ICCE 2010*, Shanghai, China [published]

Ting, C.-H., A.V. Babanin, D. Chalikov, and T.-W. Hsu, 2010: Dependence of drag coefficient on agular spreading of sea waves. *Proc. 32nd Taiwan Ocean Eng. Conf., November, 2010*, 6p. [in press]

Toffoli, A., A.V. Babanin, F. Ardhuin, M. Benoit, E.M. Bitner-Gregersen, L. Cavaleri, J. Monbaliu, M. Onorato, A.R. Osborne, J. Fouques, V. Moe, C. Pakozdi, and C.-T. Stansberg, 2010d: Extreme waves in sea states crossing an oblique current. *Proc. Int. Conf. Offshore Mech. Arctic Eng.(OMAE),* June 6-12, 2010, Shanghai, China, paper OMAE2010-20619, 8p [published, refereed]

Toffoli, A., F. Ardhuin, A.V. Babanin, M. Benoit, E.M. Bitner-Gregersen, L. Cavaleri, J. Monbaliu, M. Onorato, A.R. Osborne, 2010e: Extreme waves in directional wave fields traversing uniform currents. *Proc. HydralabIII Joint User Meeting*, 2-4 February, 2010, Hannover, Germany, 4p [published]