Wave Climate and Wave Mixing in the Marginal Ice Zones of Arctic Seas, Observations and Modelling

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LONG-TERM GOALS

The long-term goals of the present project are two: wind/wave climatology for the Arctic Seas and their current and potential future trends; and WAVEWATCH-III and SWAN wave models with new physics, adapted and validated for the Beaufort and Chukchi Seas.

OBJECTIVES

The wind/wave climatology for the Arctic Seas will be developed based on altimeter observations. It will have a major scientific and applied significance as presently there is no reference climatology for this region of the ocean available. The new versions of wave models for Beaufort and Chukchi Seas will include new physics that is already under development, and the novel physics presently unavailable. In particular, it is planned to use a wave boundary layer model to replace traditional wind-input parameterisations. The models will be suitable for operational forecast. Altimeter climatology and the wave models will be used to study the current and future wind/wave and ice trends.

APPROACH

Spaceborne radar altimeters have observed the oceans for more than two decades with an almost continuous record since 1985. Pulse-limited radar altimeters can estimate wave height about every second over a footprint of 1-10km while the precise size depends on various characteristics (i.e. range, pulse width, wave height). Satellite altimetry is also able to provide information on surface winds and on storm events, and on the respective trends in these quantities. Satellites equipped with altimeters operate on various orbits, which determine the repeat cycle, inclination angle, altitude etc. With change in the inclination angle, global coverage and repeat cycle also change. An inclination angle close to 90 degree yields better data coverage in the polar region such as Arctic. In this regard, coverage of instruments operated by NASA/CNES (i.e. JASON1/2, TOPEX) ends at approximately 67 degrees north/south. Altimeters of the European Space Agency cover up to the 80th degree north/south and higher. Starting from ERS1 which was launched in 1991, these are polar areas up to 82 degrees North, with the latest CRYOSAT2 altimeter measuring waves and winds up to 88N (provided these waters are open). Therefore, information on wave climate is available over the entire period of existence of the marginal Arctic ice zones.

PIs of the proposal developed a 23-year database (1985-2008) of calibrated and validated satellite altimeter measurements (Zieger et al., 2009), to investigate global changes in oceanic wind speed and wave height, and found a general global trend of increasing values of wind speed and, to a lesser degree, wave height, over this period (Young et al., 2011). The rate of increase is greater for extreme events as compared to the mean condition. This database was then use to evaluate extreme values of wave height and wind speed (Young et al., 2012). Within this study, a methodology was developed for obtaining trends based on short (4-year) segments of the altimeter records. This technique will be used to investigate wave climate variability in the Arctic Seas whose history is unknown, but whose duration is short by comparison with typical climate-trend research records.

Respective investigations of the wind/wave climate in the Arctic are also urgently needed. The Swinburne altimeter database contains information on the Arctic Seas. It was not used, since the authors were originally interested in annual trends, and these Seas were and still are covered with ice for most of the year. Altimeters record the signal returned from an illuminated surface, which can be over sea, land, or ice. In transition from sea to land, the return signal shows distinct spikes, but this is not the case for sea/ice transition and therefore separating the ice from the ocean/sea is ambiguous. If not accounted for ice, however, statistics and therefore climatology in the Arctic Seas will be biased by surface characteristics due to snow dunes and ice layering.

Separation of measurements over sea ice from measurements over the open ocean is the initial task of this project. The selected algorithm should be versatile and applicable to various missions. It has been demonstrated that sea ice can be detected if brightness temperature data, available from radiometer instruments, is considered (Tran et al., 2009). Radiometers, however, are typically not available on many altimeter platforms. Therefore, in the first year of the project, a more versatile approach (Laxon, 1990, Rinne and Skourup, 2012) was selected and verified against the method proposed by Tran et al. (2009). In order to investigate the wave climate in the Arctic Seas, this algorithm has then been applied to a decade of altimeter data obtained during the ENVISAT mission (2002–2012). At subsequent stages of the project, the same method will be applied to altimeter data at latitudes greater than 67 degrees North (i.e. ERS2, CRYOSAT2). This will allow us to extend the trends for the Arctic Seas wind/wave climate into the past and future.

The second main goal of the project is to advance the physics of wave-forecast models in general, and with respect to the Arctic Seas in particular. Third-generation wave models are about 30 years old, but it is only now that their physics is going through significant updates. Overall forecast of the waves with the present models is reasonable, except non-standard situations, where the balance of the source terms is not satisfied or the parameterisations are not suitable due to some missing physics or due to limits of the range of their original applicability. Such situations are frequent and well known. Waves in marginal ice zones is certainly one of such situations.

Within the proposed project, WAVEWATCH-III and SWAN models with the state-of-art new physics will be used. Apart from new physics, applying the models in polar areas in general and in the Beaufort and Chukchi Seas in particular will require special numerics. Such version of

WAVEWATCH-III (v.4.10), which includes both multigrid and irregular-grid features in WAVEWATCH has been developed in NRL (Rogers et al., 2011), and will be used along with the new physics.

Principal for the wave modelling in the Beaufort and Chukchi Seas is the dissipation term (or terms) to account for the attenuation of waves due to interaction with ice. These terms will also define the ice-fracturing capability of ocean waves and thus the fringe of the open and frozen oceans, and therefore the wave fetch. As described by Bennetts and Squire (2011), Rogers et al. (2011) variety of physical and mathematical models for such wave-due-to-ice attenuation are available to choose from, which include viscous (e.g. Newyear and Martin, 1999), visco-elastic (e.g. Wang and Shen, 2010), turbulence (e.g. Liu et al., 1991), scattering (e.g. Perrie and Hu, 1996, Bennetts and Squire, 2011) theories, among others. Scattering theories appear most physical for the Marginal Ice Zone, but they can be further subdivided into variety of physics, such as scattering by ice floes, cracks, pressure ridges (Bennetts and Squire, 2011). With respect to this project, we will not be duplicating other DRI efforts and rely on the NRL group of Rogers and Posey whose concurrent proposal is dedicated specifically to the developing a module for wave-ocean-ice coupled modelling system based on best physics (see Related Projects). At the same time, the PIs participate in Australian efforts of developing wave-ocean-ice coupled models for Antarctica.

Apart from the implementing WAVEWATCH-III and SWAN, with the new physics described above, for the Beaufort and Chukchi Seas, specific new physics modules are planned to be developed for the wave modelling within this project. They include an update to the whitecapping dissipation parameterisation and a novel term for wind-wave energy/momentum exchange based on explicit physics rather than parameterisations.

Validation of the whitecapping dissipation in field conditions have been particularly difficult up to date (Babanin, 2011). The most successful so far were methods based on remote sensing, either by bubble-acoustic means (Manasseh et al., 2006) or whitecap observations (Melville and Matusov, 2002, Gemmrich et al., 2008). Both of these methods, however, appear to be affected in the polar seas.

From very early observations it is known that lifetime of whitecap foaming depends on the water temperature (Miyake and Abe, 1948). As temperature drops, the lifetime increases. Such trends were mentioned through a number of papers, but never studied systematically, and evidences are sometimes contradictory (Babanin, 2011). Bortkovskii (1997), for example, confirms the above trend, but at the same time concludes that overall whitecap coverage decreases at lower temperatures. This is supported by Stramska and Petelski (2003) who conducted observations of whitecap coverage in north polar waters of the Atlantic. They concluded that, by comparison with the historical relationships of such coverage as a function of wind speed, their measured values were some 8 times smaller. This may be related to the increase of surface tension, and therefore reduction of the bubble size at low temperature, or to different biological surfactants in the polar seas, or to alterations of the breaking severity, or a combination of those. Such issues are very important both for the dissipation function of wave models employed for Arctic and Antarctic, and for interpretation of the remote sensing observations of the surface whitecapping in applications other than wave modelling (e.g. Anguelova and Webster, 2006).

In this project, we plan to investigate the whitecapping dissipation and its relation with the whitecap coverage in the Arctic Seas both in order to update its respective parameterisations for wave models, and to achieve physical understanding of the complicated trends mentioned. This will be done by means of the field observations, and can be complemented by laboratory experiments in wave tanks with water-cooling facilities such as ASIST at the University of Miami, as necessary.

Most essential new contribution to the physics of wave models planned for this project, is that for the wind-input term. Up to date, it seems to be the most developed source function, as it refers to analytical, laboratory and field observation in a greater regard than any other term employed in such models. On the close scrutiny, however, significant issues remain unanswered and even uncovered.

While the models typically take U_{10} or other mean wind speed as an input property, from the atmospheric models or from observations, they ultimately use friction velocity u_*. To convert one into another, so called drag coefficient C_d is employed. This purely empirical property is meant to replace the entire physics of the boundary layer. As a result, it is not a single number and not even a simple function of the wind or wave age, as it is often presented, but depends on very many properties and features of the air flow, boundary layer, ocean surface, wave fields and wave dynamics (Babanin and Makin, 2008, Babanin, 2011, Ting et al., 2012, Toffoli et at al, 2012).

As a result, scatter for parameterisations of the sea drag is formidable and cannot be improved unless the variety of parameters is properly accounted for. It is quite likely that the Arctic environment, particularly the Marginal Ice Zones, will pose another set of parameters for such dependences. Combining all the wind, wave, ocean, ice, boundary-layer and other properties into an accurate parameterisation is not feasible and not practical.

Even more problematic are the observed deviations from the constant-flux layer behavior, which the definition of sea drag relies on. Recently, comparisons of mean wind speeds and wind-momentum fluxes are conducted, based on measurements throughout the wave boundary layer, including wave-follower measurements very near the surface (Babanin and McConochie, 2013). Significant deviations from the constant-flux expectations are found. Near the surface, the fluxes are less than those obtained by extrapolation within the logarithmic-layer assumption, and the mean wind speeds are correspondingly larger.

Therefore, the next logical step in advancing the wave models would be to employ a model of wave boundary layer (WBL) instead of parameterisations of the wind input. Such model would take the mean wind speeds as an input and converted them into pressure working on the ocean surface, without relying on the sea drag or other substitutes for the physics of WBL. 1D version of the Chalikov and Rainchik (2011) WBL model is now available at Swinburne, and it is fast enough to be implemented operationally. The major step forward in wave modelling, planned for this project, is implementing this WBL in WAVEWATCH-III instead of wind-input parameterisations.

The research group includes academics from Swinburne University of Technology (SUT) and Australian National University (ANU). The team is a group of experts on satellite altimetry, statistical analyses, wave and ocean modelling, wave and ocean dynamics, air-sea interactions, atmospheric boundary layer, with a track record of joint research. Thus, they cover all the diverse areas of the project involved. They also lead the ONR N00014-101-0418 project and together with PI Zieger participate in implementing the new physics in WAVEWATCH-III and SWAN. PIs also conduct a number of research projects funded by the Australian Research Council, CSIRO and offshore industry, relevant for the current proposal (see Relevant Projects below).

WORK COMPLETED

This is a report for the first year of the project. The previous altimeter database at Swinburne covered the period 1985-2008, and it has been extended to 2012, end of the mission for ENVISAT whose observations cover the Arctic region. CRYOSAT altimeter mission was launched in 2012, and work on calibration and quality control of its data is in progress. As described in Results below, separation of altimeter measurements over ice from measurements over the open ocean has been conducted. This allowed preliminary analysis of trends for wave heights over areas of the Arctic Ocean free of ice over the period of 2002-2012.

WW3 subroutine for Wave Boundary Layer module has been prepared and is being tested. Two-dimensional spectra of the wave-energy input and two components of the wave-momentum input obtained with this module are shown in the results.

A number of new collaborations and related research have been established. With the University of Plymouth (England), laboratory tests were conducted to evaluate wave attenuation and scattering due to imitated ice floes. Simulations of the future Arctic wave climate were conducted by means of coupled wave/climate/ice models, in collaboration with the Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences.

RESULTS

One of the initial objectives was a comprehensive testing of an ice detection classifier in order to separate wave-height data in the open ocean from invalid observations in the presence of sea ice. ENVISAT mission covered areas up to 81.5° North, and apart from radar altimeter, ENVISAT was equipped with a radiometer that measures brightness temperature. Information about brightness temperature in combination with Ku-band radar backscatter can be utilised in a cluster algorithm to map various types of sea ice, for example first-year ice, wet ice, multi-year ice, and the open ocean (Tran et al. 2009).

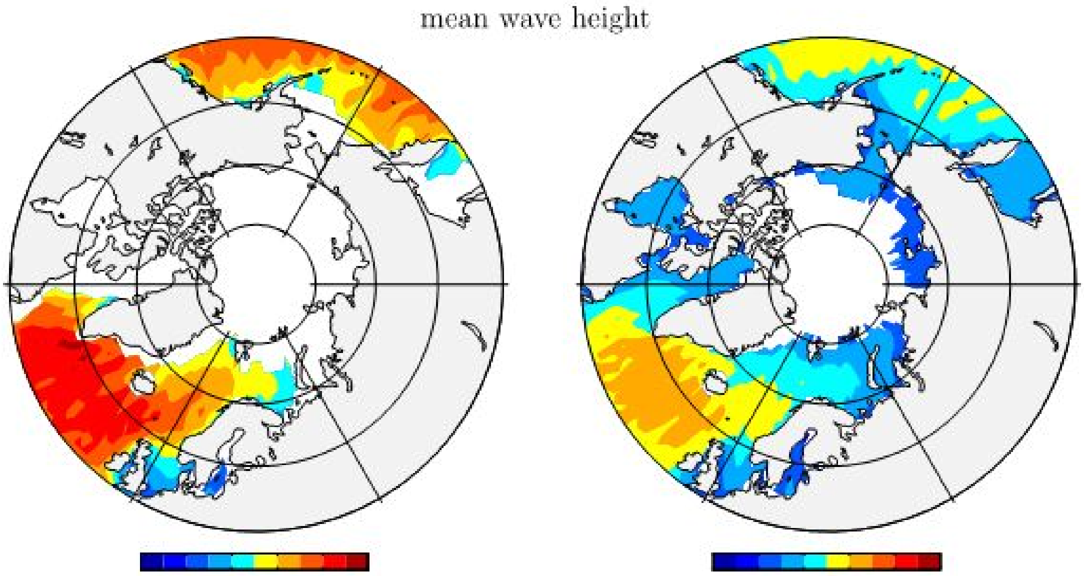

Figure 1. Mean wave height in the Arctic Seas, over 2002-2012. (left) March, (right) September

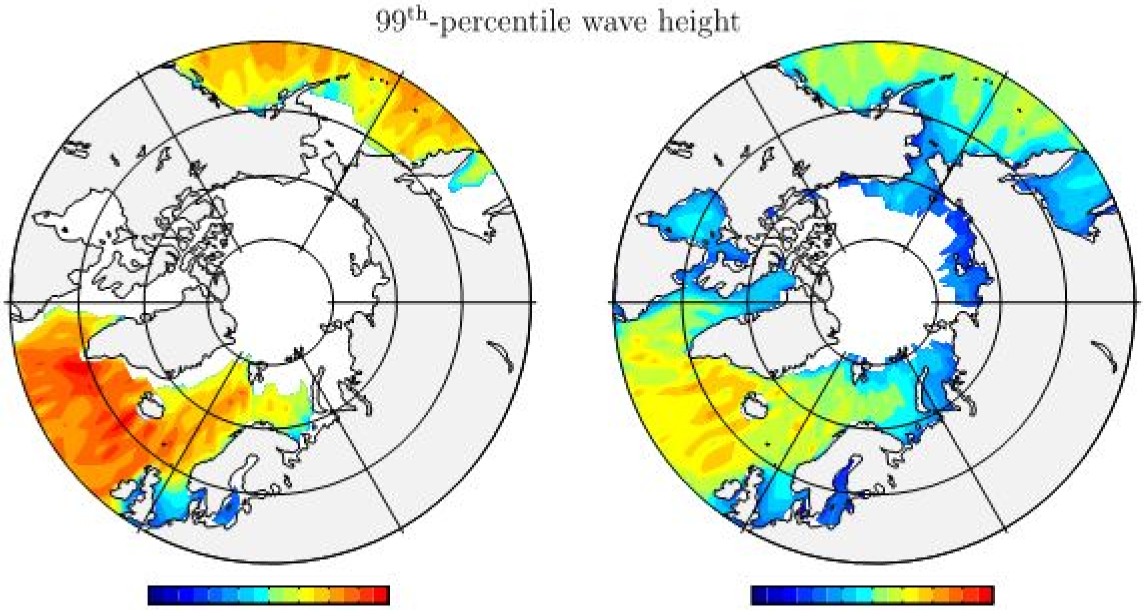

Figure 2. Extreme wave heights (top 1%) in the Arctic, 2002-2012. (left) March, (right) September

Wave climatology derived from ENVISAT data (2002-2012) is based on a calibrated data source from the GlobWave database. It is shown in Figures 1 and 2 for mean significant and extreme wave heights (i.e. highest 1% or 99-th percentile), respectively. The climatology is derived from altimeter data binned across two-square-degree regions for each calendar month. At the beginning of Boreal summer, wave heights about 4.5m dominate the condition in the North Atlantic. In the Norwegian Sea, average wave heights between 2.5-3.5m were observed. In September, at the end of summer, waves in the Chukchi Sea can grow up to about 2m. Similar wave climate is observed in the Baffin Bay located between Canada and Greenland.

Linear trends for the wave climatology were estimated for the months of March and September, over the entire duration of the ENVISAT mission (2002-2012). For each location, both Mann-Kendall test (MKT) and Sen estimate for trend were used. These are shown in Figure 3.

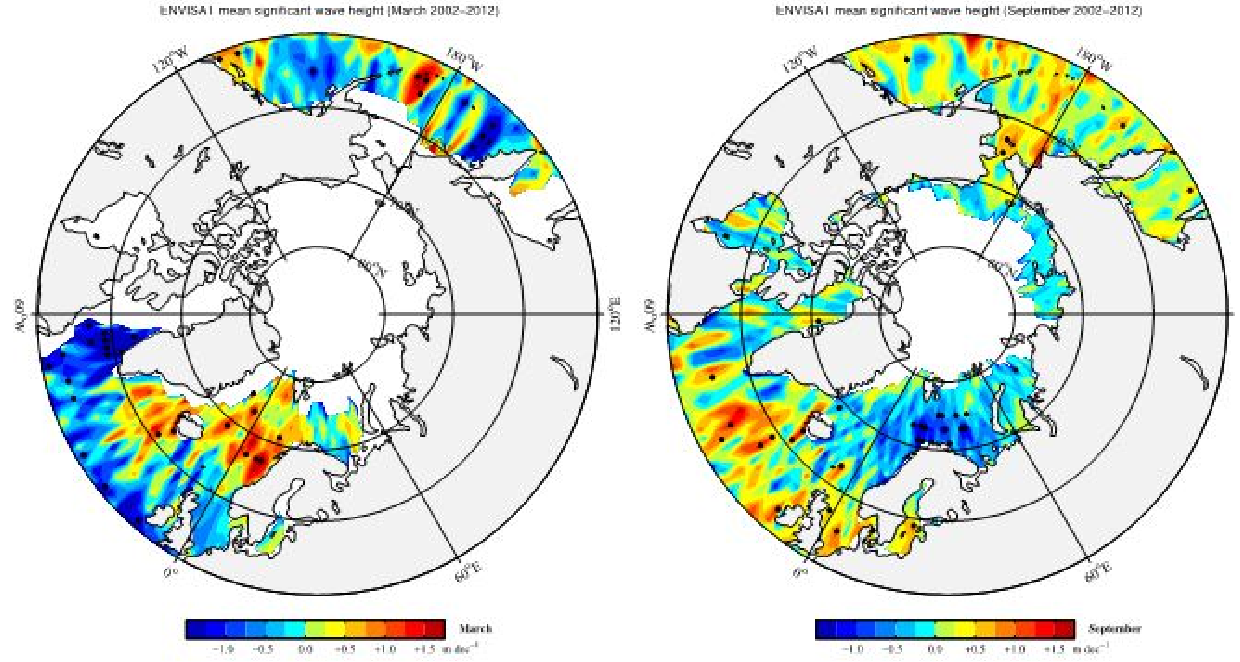

Figure 3: Changes of mean wave height in the Arctic, over 2022-2012. (left) March, (right) September. Dots mark significant trends at the 95% level and the contour interval is 0.25m/decade

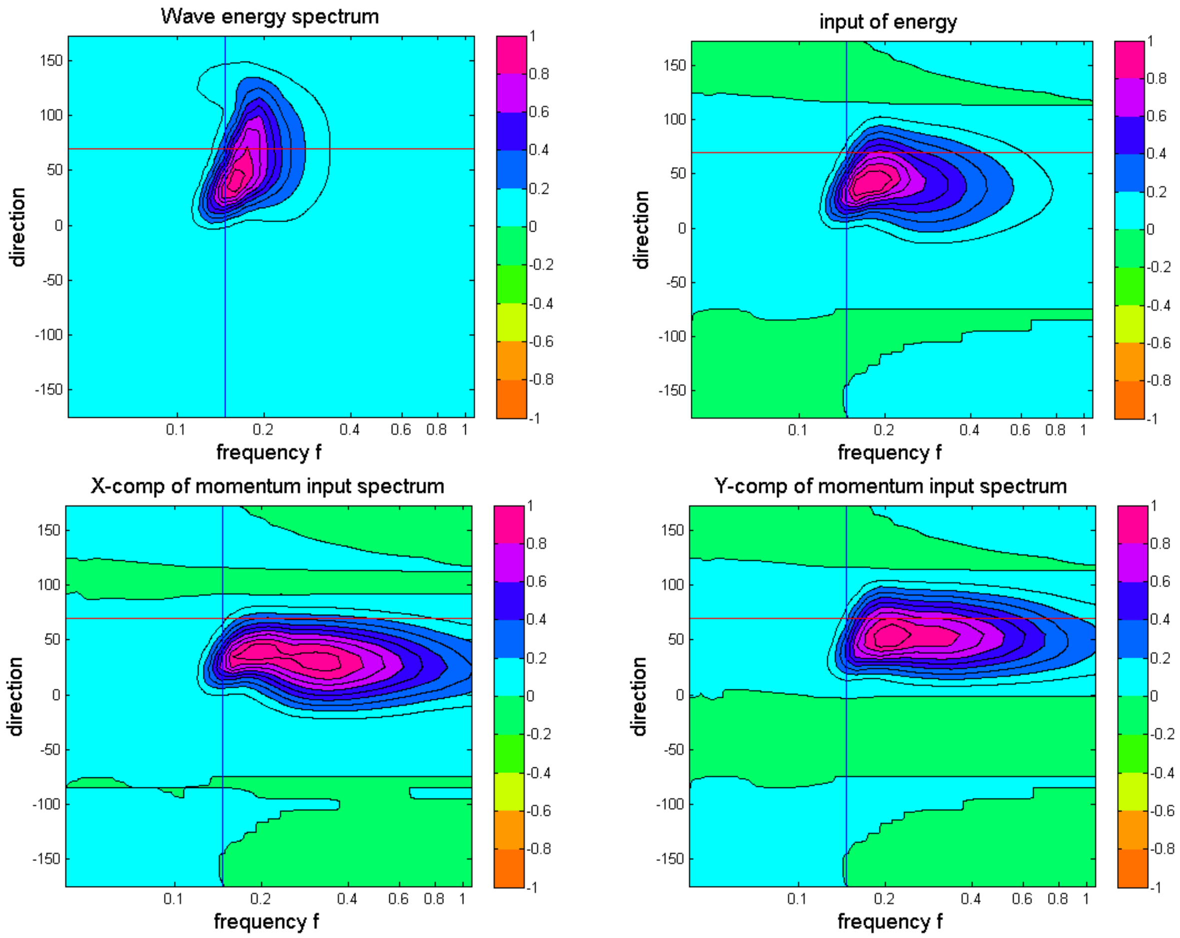

Figure 4 demonstrates testing the WBL module for WAVEWATCH-III. Realistic hindcast spectra are used (top left), for the U_{10} wind speed of 10.6m/s. The wind energy-input spectrum (right) is is shown in top right, and the two components of the wind momentum-input spectra at the bottom. All the input spectra have positive and negative lobes. All spectra are normilised for the comparison.

IMPACT/APPLICATIONS

The existing Swinburne altimeter database was used to quantify trends for 100-year return values of wind speeds and wave heights (Young et al., 2013b). This data were extended with the SSM/I database in order to study regional trends for surface winds in particular months (Zieger et al., 2013). Laboratory experiments were conducted in order to isolate and understand different aspects of wave-ice interaction physics (presentation at WISE-20 meeting in Washington, DC by A.Toffoli, L.Bennetts, A.Albarello, M.Meylan, and A.V.Babanin “Assessing Ice-Induced Attenuation of Water Waves in a Directional Wave Basin”). Physics of the Wave Boundary Layer very near the surface was studied experimentally. Babanin and McConochie (2013) showed that wave-induced influences essentially alter the constant-flux layer near the water interface, and thus the parameterisations used in wave models for the wind input should be corrected. PI Babanin and PI Shen of a concurrent DRI project organised a session on wave-ice interactions at the 22nd IAHR International Symposium on Ice to be held in Singapore in August 2014.

RELATED PROJECTS

This project is part of ONR Sea State DRI whose projects are all related. Particularly closely related are

Rogers, W.E, Posey, P.G. "Wave-ice interaction in the Marginal Ice Zone: toward a wave-ocean-ice coupled modeling system"

Gemmrich, J., Lehner, S. "Wave processes in Arctic Seas, observed from *TerraSAR-X*"

Shen, H. "An Integrative Wave model for the Marginal Ice Zone based on a Rheological Parameterization"

Other Related Projects

Babanin, A.V., Young. I.R., Rogers, W.E., Smith, J.M., Tolman, H.L. "Observation-based dissipation and input terms for spectral wave models, with end-user westing". Wave modelling NOPP project, funded by ONR. Update of deep-water physics for WAVEWATCH-III and SWAN (Iafratti et al., 2013)

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 (Ghantous and Babanin, 2013)

Babanin, A.V., Hemer, M.A., Schulz, E. "Revisiting wave-induced mixing and current effects: observations and modelling based on the Southern Ocean Flux Station", CSIRO (Commonwealth Science and Industry Research Organisation) Flagship Wealth from Oceans. Field observations of extreme wave conditions and wave-current interactions in the Southern Ocean (Babanin, 2013)

Babanin, A.V., Phillips, W.R.C., Ganopolski, A. "Wave-induced upper-ocean mixing", ARC Discovery grant. Investigation of the wave-induced turbulence and non-breaking dissipation (Babanin and Chalikov, 2012, Babanin et al., 2012)

Young, I.R., Babanin, A.V., Hemer, M.A., Aster, R.C. "Global trends in oceanic wind speed and wave height", ARC Discovery grant. Creation of the global satellite wind and wave database and investigation global and regional trends (Young et al., 2013a,b)

REFERENCES

References to the 2013 publications by PIs are in Publications below

Anguelova, M.D. and F. Webster, 2006: Whitecap coverage from satellite measurements: A first step toward modeling the variability of oceanic whitecaps, *J. Geophys. Res.*, 111, doi:10.1029/2005JC00315, 23p

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

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., 2011: *Breaking and Dissipation of Ocean Surface Waves*. Cambridge University Press, 480p

Bennetts, L.G. and V. A. Squire, 2011: On the calculation of an attenuation coefficient for transects of ice covered ocean. *Proc. Roy. Soc. A*, doi:10.1098/rspa.2011.0155, 27p

Bortkovskii, R. S. 1997: On the influence of water temperature on the ocean-surface state and transfer processes. *Izvestiya Akademii Nauk SSSR. Fizika Atmosferi i Okeana*, 33, 266-273 (in Russian, English abstract)

Chalikov, D. and S. Rainchik, 2011: Coupled numerical modelling of wind and waves and the theory of the wave boundary layer. *Boundary-Layer Meteorol.*, 138 (1), 1–41

Laxon, S., 1990: Seasonal and inter-annual variations in antarctic sea ice extent as mapped by radar altimetry. *Geophys. Res. Lett.*, 17 (10), 1553–1556, doi:10.1029/GL017i010p01553.

Liu, A.K., B. Holt, and P.W. Vachon, 1991: Wave propagation in the Marginal Ice Zone: Model prediction and comparisons with buoy and Synthetic Aperture Radar data. *J. Geophys. Res.*, 96, 4605–4621.

Manasseh, R., A.V. Babanin, C. Forbes, K. Rickards, I. Bobevski, and A. Ooi, A., 2006: Passive acoustic determination of wave-breaking events and their severity across the spectrum. *J. Atmos. Ocean. Technol.*, 23, 599-618

Melville, W.K. and P. Matusov, 2002: Distribution of breaking waves at the ocean surface. *Nature* 417, 58-63

Miyake, Y. and T. Abe, 1948: A study on the foaming ofthe water. Part 1. *J. Mar. Res.*, 7, 67-73

Newyear, K. and S. Martin, 1999: Comparison of laboratory data with a viscous two-layer model of wave propagation in grease ice. *J. Geophys. Res.*, C104, 7837–7840.

Perrie, W. and Y. Hu, 1996: Air-ice-ocean momentum exchange. Part I: Energy transfer from waves to ice floes. *J. Phys. Oceanogr.,* 26, 1705–1720

Rinne, E. and H. Skourup, 2012: Sea ice detection using ENVISAT radar altimeter 2. *AGU Fall Meeting*, San Francisco, CA, December 3–7, eposter

Rogers, W.E., D. Wang, A.V. Babanin, T. Campbell, and J. Dykes, 2011: On use of internal constraints in recently developed physics for wave models. *Proc. 12th Int. Workshop on Wave Hindcasting and Forecasting and 3rd Coastal Hazards Symp.*, Big Island, Hawaii, October 30 – November 4, presentation slides

Stramska, M. and T. Petelski, 2003: Observations of oceanic whitecaps in the north polar waters of the Atlantic. *J. Geophys. Res.*, C108, doi:10.1029/2002JC001321, 10p

Ting, C.-H., A.V. Babanin, D. Chalikov, and T.-W. Hsu, 2012: Dependence of drag coefficient on the directional spreading of ocean waves. *J. Geophys. Res.*, 117, doi:10.1029/2012JC007920, 7p

Toffoli, A., L. Loffredo, P. Le Roy, J.M. Lefevre, and A.V. Babanin, 2012: On the dependence of sea drag in finite water depth. *J. Geophys. Res.*, 117, doi:10.1029/2011JC007857, 10p

Tran, N., F. Girard-Ardhuin, R. Ezraty, H. Feng, and P. Féménias, 2009: Defining a sea ice flag for envisat altimetry mission. *IEEE Geosci. Rem. Sens. Lett.*, 6 (1), 77–81

Wang, R. and H.H. Shen, 2010. Gravity waves propagating into an ice-covered ocean: A viscoelastic model. *J. Geophys. Res.*, 115, doi:10.1029/2009JC005591, 12p

Young, I.R., J. Vinoth, S. Zieger, and A.V. Babanin, 2012: Investigation of trends in extreme value wave height and wind speed. *J. Geophys. Res.*, 117, doi:10.1029/2011JC007753, 13p

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

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 and thesis

Ghantous, M., and A.V. Babanin, 2013: One-dimensional modelling of upper ocean mixing by turbulence due to wave orbital motion. *Nonlin. Proc. Geophys.* [under review]

Iafrati, A., A.V. Babanin, and M. Onorato, 2013: Modulational instability, wave breaking and formation of large scale dipoles. *Phys. Rev. Lett.*, 110184504, 5p [published, refereed]

Ribal, A., 2013: On the Alber Equation for random water waves. *PhD Thesis*, Swinburne University of Technology [published, refereed]

Ribal, A., A.V. Babanin, I.R. Young, A. Toffoli, M. Stiassnie, 2013: Recurrent solutions of Alber equation initialized by JONSWAP spectra. *J. Fluid Mech.*, 719, 314-344 [published, refereed]

Smith, T.A., S. Chen, T. Campbell, E. Rogers, S. Gaberšek, D. Wang, S. Carroll, and R. Allard, 2013: Ocean-wave coupled modeling in COAMPS-TC: A study of Hurricane Ivan (2004), *Ocean Modelling*, 69, 181-194 [published, refereed]

Young, I.R., A.V. Babanin, and S. Zieger, 2013a: The decay rate of ocean swell observed by altimeter. *J. Phys. Oceanogr.* [in press, refereed]

Zieger, S., A.V. Babanin, and I.R. Young, 2013: Changes in ocean surface winds with a focus on trends of regional and monthly mean values. *Deep Sea Res. P. 1* [under review]

Other

Babanin, A.V., 2013: Physics-based approach to wave statistics and probability. *Proc. ASME 2013 32nd Int. Conf. on Ocean, Offshore and Arctic Eng. OMAE2013, July 9-14, 2013, Nantes, France*, 12p [published, refereed]

Babanin, A.V. and J. McConochie, 2013: Wind measurements near the surface of waves. *Proc. ASME 2013 32nd Int. Conf. on Ocean, Offshore and Arctic Eng. OMAE2013, July 9-14, 2013, Nantes, France*, 6p [published, refereed]

Chalikov, D. and A.V. Babanin, 2013: Three-dimensional periodic fully-nonlinear potential waves. *Proc. ASME 2013 32nd Int. Conf. on Ocean, Offshore and Arctic Eng. OMAE2013, July 9-14, 2013, Nantes, France*, 8p [published, refereed]

Young, I.R., S. Zieger, J. Vinoth, and A.V. Babanin, 2013b: Global trends in extreme wind speed and wave height. *Proc. ASME 2013 32nd Int. Conf. on Ocean, Offshore and Arctic Eng. OMAE2013, July 9-14, 2013, Nantes, France*, 10p [published, refereed]

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)