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 the 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 and are also able to provide information on surface winds and on storm events, and on the respective trends in these quantities (Young et al., 2011, 2012). 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 degrees 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 CRYOSAT altimeter measuring waves and winds up to 88N (provided these

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waters are open). Therefore, information on wave climate is available over the entire period of existence of the marginal Arctic ice zones.

The Swinburne altimeter database does contain information on the Arctic Seas, but it was not utilised, 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 in which ice floes pile up to ridges and keels.

Separation of measurements over sea ice from measurements over the open ocean was 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, as the first aim of the project, a more versatile approach (Laxon, 1990, Rinne and Skourup, 2012) was selected to be verified against the method proposed by Tran et al. (2009). At subsequent stages of the project, the same method is to be applied to altimeter data at latitudes greater than 67 degrees North (i.e. ERS2, CRYOSAT). This should 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 for 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.

Principal for the wave modelling in the Arctic 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 project 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.

Specific new physics modules planned to be developed for the wave modelling within this project 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.

One of the most essential new contributions 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 convert them into pressure working on the ocean surface, without relying on the sea drag or other substitutes for the physics of WBL. An approximation of the 1D version of the Chalikov and Rainchik (2011) WBL model is now available at Swinburne. The major step forward in wave modelling, planned for this project, is implementing a wind-input function based on this WBL in WAVEWATCH-III.

WORK COMPLETED

This is a report for the second year of the project. The remote-sensing part of the project was concentrated on reprocessing, calibration, and validation of CRYOSAT altimeter data. CRYOSAT was launched in 2010 and effectively replaced the retired ENVISAT mission in terms of altimeter and SAR observations. Within the wave modelling part, a new wind-input function was developed for WAVEWATCH-III. Investigation of the Arctic wave climate continued by means of coupled wave, ice and general circulation modelling, and the study of wave-ice interaction in the laboratory and by using field data.

In the first year, the 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. The separation of altimeter measurements over ice from measurements over the open ocean was performed. This allowed preliminary analysis of trends for wave heights over areas of the Arctic Ocean free of ice over the period of 2002-2012 (Babanin et al., 2014). WW3 subroutine for Wave Boundary Layer module was prepared and tested.

In the second year, the CRYOSAT data was quality controlled, and calibrated and validated against NDBC buoys over the period August 2010 to May 2014. In addition to buoys, validation of this data was performed against calibrated JASON1 and JASON2 observations for about four years

(2010-2014). Results from the calibration are presented in section Results. In anticipation of the field experiment in 2015, CRYOSAT ground tracks were forecasted for a field campaign for the concurrent DRI project (MIZ). This was coordinated with the remote sensing group so that synthetic aperture radar observation (TerraSARX) are available for the same region.

An approximation of the WBL model has been implemented as a subroutine in WAVEWATCH-III. The skill of the WBL model in WAVEWATCH is presented later in the Results section.

Reflection and transmission of ocean waves by ice floes were investigated by laboratory means. To understand the future trends for winds and waves in the Arctic, coupled modelling was conducted by means of WAVEWATCH-III forced by winds and sea ice concentration produced within the regional model HIRHAM, under the anthropogenic scenario SRES-A1B.
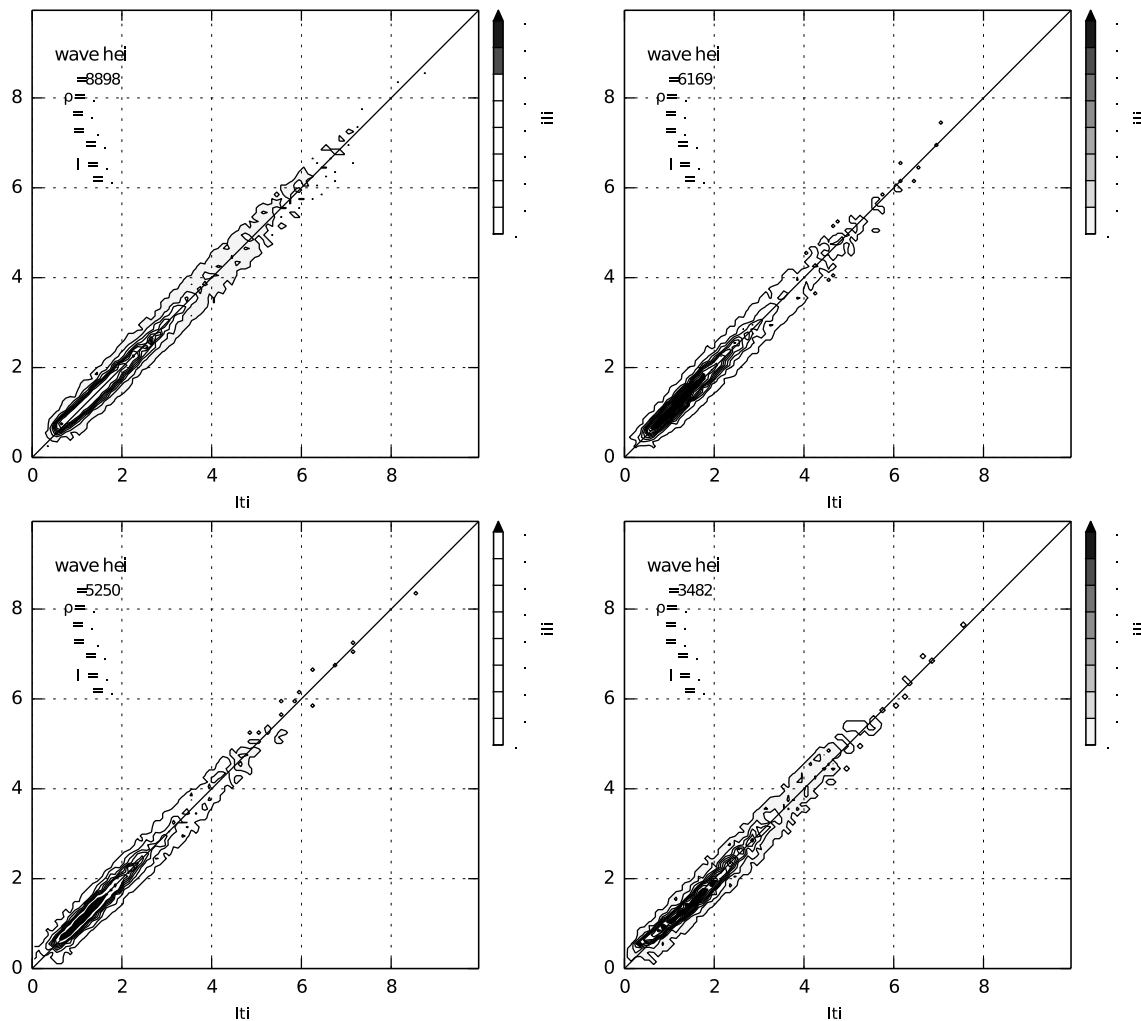

Figure 1. Altimeter calibration against NDBC buoys. Results are shown in the form of scatter density for various altimeters. Collocated measurements are considered within 50 km radius and 30 minutes different in time. Error statistics for number of points (n), correlation (ρ), rms error, bias (b), standard deviation (σ_b), scatter index (SI) and slope (m_o) are given in the legend.

RESULTS

Preliminary Arctic wave climatology from the 2002-2012 ENVISAT altimeter measurements, shown in the 2013 report, was not calibrated and validated against in-situ data observed from the NDBC buoy network. Note that the existed Swinburne database (Zieger et al., 2009) was calibrated up to the year 2008.
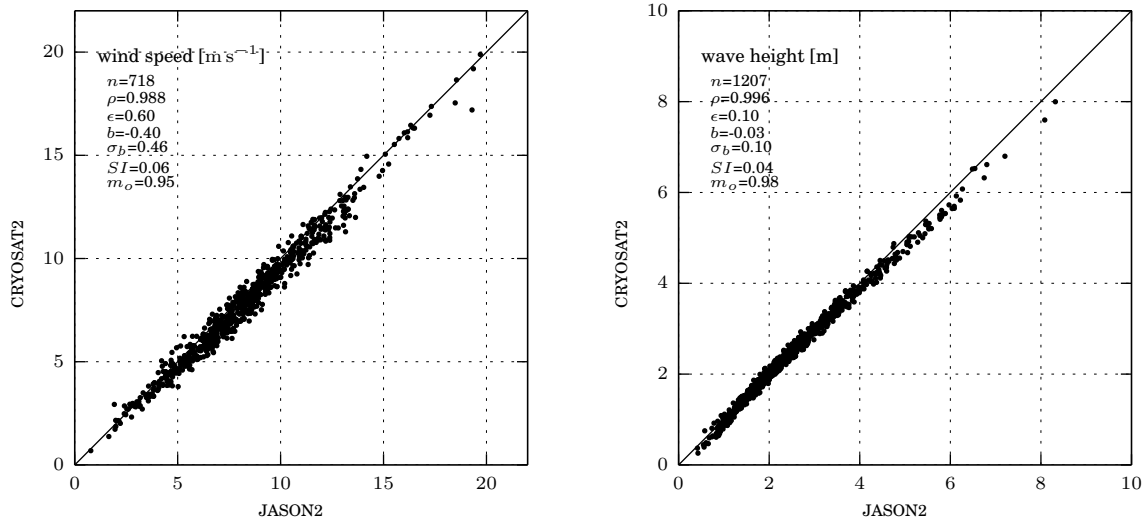
Figure 2. Scatter plots of altimeter crossover wind speed (left panel) and wave height (right panel) over the period 2010 to 2014. Calibrated crossovers are considered within 50 km radius and 30 minutes difference in time. Error statistics for number of points (n), correlation (ρ), rms error, bias (b), standard deviation (σ_b), scatter index (SI) and slope (m_o) are given in the legend.

Zieger et al. (2009) also developed a calibration procedure that was now applied to the global dataset of the ENVISAT mission and then extended to the CRYOSAT data. Another problem with the CRYOSAT data was identified by Zieger et al. (2013). They pointed out that in the default geophysical data product from the CRYOSAT mission wave height information was missing over vast areas such as the Central Pacific and North Atlantic, the latter being particularly essential for the current project. It appeared that the missing data occurs when the altimeter switches to a different mode. It was found that by using the waveform re-tracking in post-processing routines it is possible to recover wave height estimate in those areas from the fast delivery product (Smith et al., 2011). The disadvantage of the waveform re-tracking is that the data is typically available with a lag of 30 to 60 days. As a result, the CRYOSAT altimeter is not the instrument of choice for near real time observations for waves in the MIZ and the Arctic Oceans. Scatter density plots of calibrated wave height against NDBC buoys are shown in Figure 1. For the available CRYOSAT data (2010-2014) the correlation of 0.983 is high when compared with buoys, and root-mean-square error of 0.18 m is close for the concurrent altimeters (see legend in Figure 1).

The scatter in wind speed estimates from altimeters is much broader than for wave height. Applying the procedure outlined in Zieger et al. (2009) to CRYOSAT for surface wind speed yields a correlation coefficient of 0.930 with an estimate of root-mean-square error of 1.16 m·s^{-1}. This is in excellent agreement to the calibration statistics listed in Zieger et al. (2009, their Table 4). The calibration functions are for wave height H_s: $H_s = 0.949 H_s - 0.004$ and for 10 m surface wind speed U_{10}: $U_{10} = 1.050 U_{10} - 0.369$ (with $\Delta\sigma = -0.008$). Here, the corrected value is formatted in italic. Scatter plots of calibrated wind speed and wave height of simultaneously operating altimeters of JASON2 and CRYOSAT is depicted in Figure 2. In contrast to buoy observations, the scatter in Figure 2 is significantly smaller, with scatter index of 0.06 and 0.04 for wind speed and wave height, respectively. The root-mean-square error of the altimeter crossovers is 50% of the error estimate from buoys. These results are consistent with findings in Zieger et al. (2009).

The effects of airflow in the wave boundary layer over a wavy sea surface have been studied by utilising the approximation of the Chalikov and Rainchik (2011) WBL model (Bahoday Paskyabi et
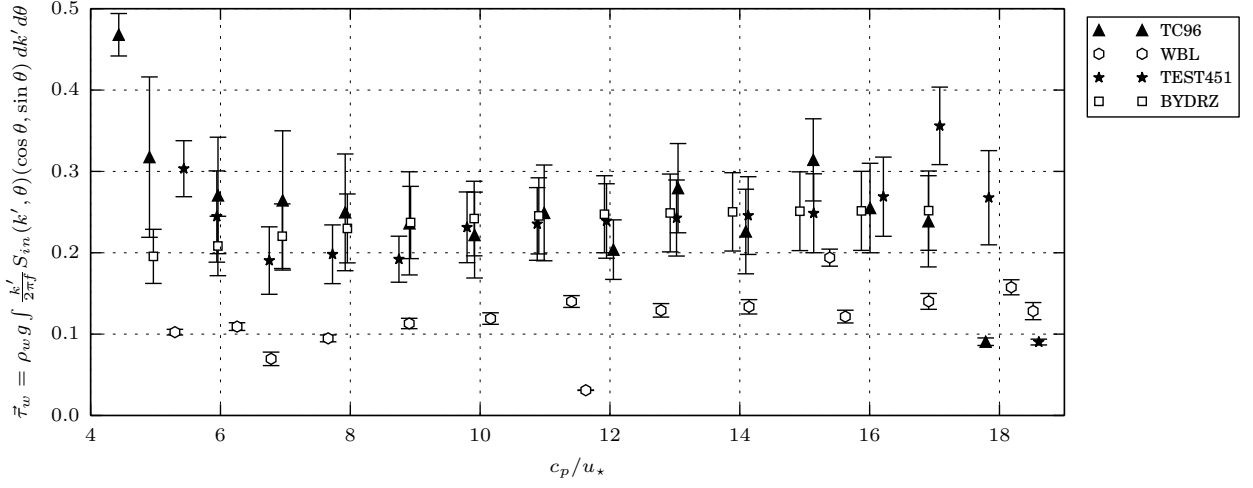
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Figure 3. Wave-supported stress τ_w computed for various wave ages c_p/u_* binned by wave age, where markers indicate the mean and the whiskers represent the standard deviation. Stresses are computed for various source terms: TC96 (Tolman and Chalikov, 1996), WBL (Chalikov and Rainchik, 2011), TEST451 (Ardhuin et al., 2010) and BYDRZ (Zieger, 2014).
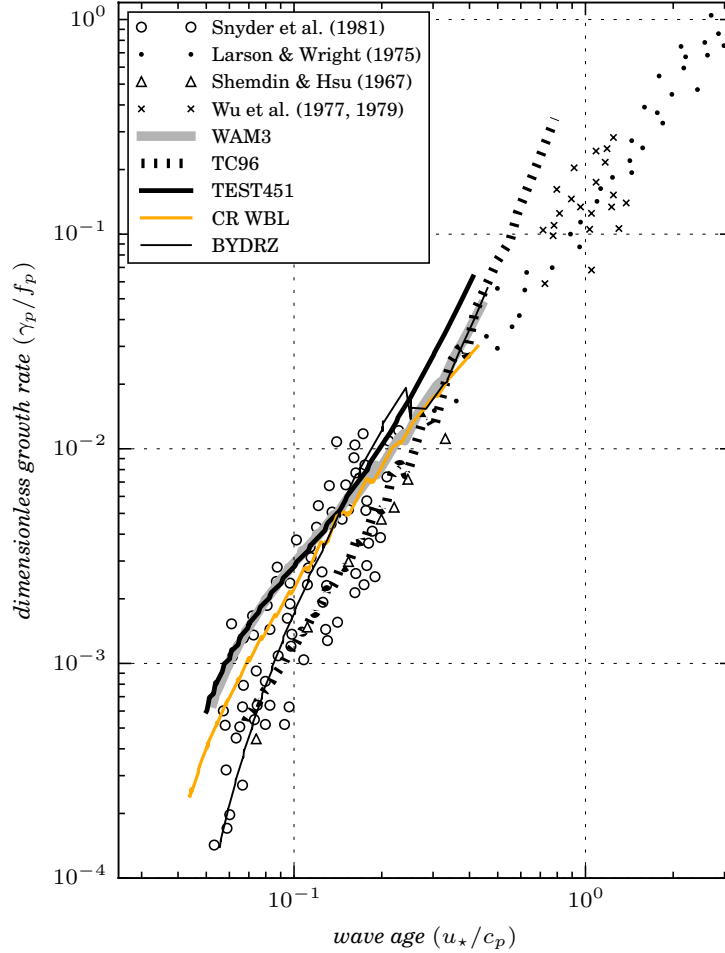

Figure 4. Dimensionless growth rate as a function of wave age as compiled by Plant (1982). The curves mark various input source terms: WAM3 (Snyder et al., 1981; Komen et al., 1984), TC96 (Tolman and Chalikov, 1996), TEST451 (Ardhuin et al., 2010), BYDRZ (Zieger, 2014) and CR WBL (Chalikov and Rainchik, 2011).

al., 2014). The wave-induced stress plays a significant role in the momentum transport. Figure 3 shows the wave-supported stress τ_w as a function of wave age, calculated for a number of different source terms in WAVEWATCH-III based on a number of different prescribed spectra. The stresses computed with the Chalikov and Rainchik (2011) WBL model are about half in magnitude compared to the observation-based source terms BYDRZ (Zieger, 2014). Bahoday Paskyabi et al. (2014) also showed that there is a substantial difference between cases of wind sea and swell. The dimensionless growth rates for a variety of input terms calculated in WAVEWATCH are plotted in Figure 4. The WBL model follows the trend of various observations (see legend in Figure 4) closer and corrects for the overestimation of the growth rate at wave age $u_* / c_p = 0.5$-1.0 for input terms based on the Miles theory (WAM3 and TEST451) as well as TC96.

Simulations of future wave climate was conducted by means of coupling wave, ice and climate models (Khon et al., 2014). To understand the future trends, WAVEWATCH-III was forced by winds and sea ice concentration produced within the regional model HIRHAM, under the anthropogenic scenario SRES-A1B. It was found that significant wave height and its extremes will increase over most of the inner Arctic areas due to reduction of sea ice cover and regional wind intensification in the 21st century. The opposite tendency, with a slight reduction in wave height appears for the Atlantic sector and the Barents Sea. Figure 5 illustrates such variations.
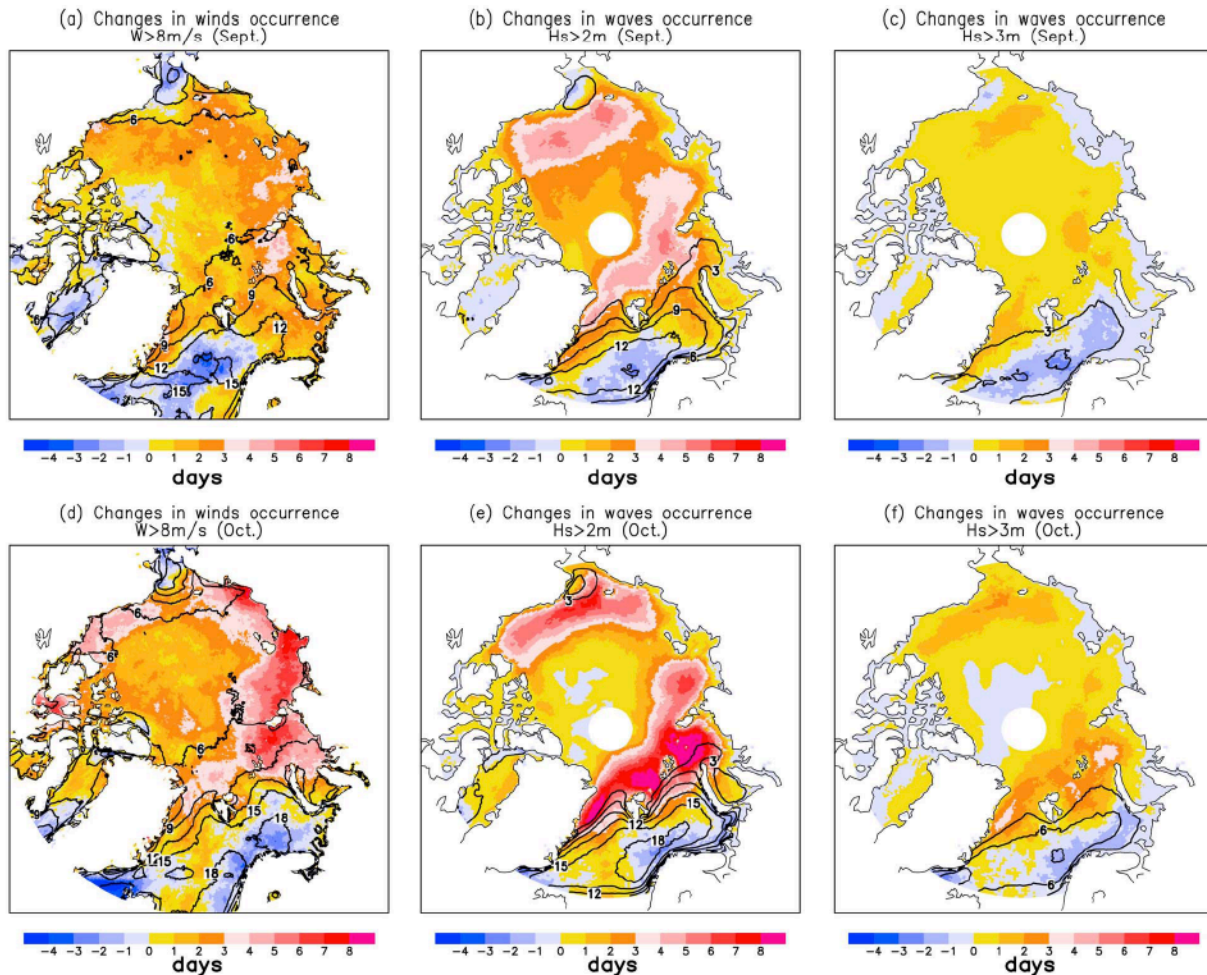

Figure 5. (a,d) Simulated changes in occurrence of winds exceeding 8 m/s, significant wave heights exceeding (b,e) 2m and (c,f) 3m for the period 2046–2065 relativeto 1980–1999, for September and October. Contours show mean values for the reference period.

Other results were obtained by means of laboratory studies of evolution of mechanically-generated regular waves in presence of synthetic ice floes. They confirm and quantify dependence of reflection and transmission on the period of the incident wave. Results also indicate that wave

overwash on the floe affects both reflection and transmission and serves as an extra dissipation source.

IMPACT/APPLICATIONS

The existing Swinburne altimeter database was extended with the SSM/I database in order to study regional trends in surface wind speed across the globe (Zieger et al., 2014a). The study concluded that the pattern of trend in wind speed between altimeter and SSM/I is similar although the magnitude of trends differs. Wave height in the Arctic modelled under a future climate projection was published in Khon et al. (2014). These results showed tendency of an increase and decrease of the wave climate in different Arctic sectors, which is in support of the observations from altimeters. An increase in wave height has played an important role on coastal processes particularly for communities in Alaska. The combined calibrated altimeter database can be used to validate numerical models by means of wave height and wind speed.

TRANSITIONS

Thompson and Rogers (2014) created a wave model setup for the Beauford and Chuckchi Seas to which wave observations can be applied. Track estimates of significant wave height are subject for comparison of synthetic aperture radar images for different areas of interest (PI Gemmrich, remote sensing group). The version of the WBL model implemented in WAVEWATCH-III has been added to the NCEP/NOAA repository and can be shared for additional validation and testing of the source terms. CRYOSAT data was utilized to validate the observation-based source terms in a global wave model hindcast (Zieger et al., 2014b) that is part of a concurrent project funded by the Office of Naval Research through Naval Research Grant N00014-101-0418.

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

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

Marusic, I., Monty, J.P., Hutchins, N., Soria, J., Ooi, A., Babanin, A.V., Kentish, S.E., Young, I.R., Phillips, W.R., Honnery, D.R., "Experimental Facility for Extreme Air/Sea Interaction Studies", ARC Linkage Infrastructure and Facility grant

Monty, J., Babanin, A.V., Meylan, M., Bennetts, L., Toffoli, A., Marusic, I., Klewicki, J., Hutchins, N., Suslov, S., Walker, D., Chung, D., "A Thermally Stratified Sea-Ice-Wave Interaction Facility", ARC Linkage Infrastructure and Facility grant

Shats, M., Babanin, A.V., Marusic, I., Young, I.R., Punzmann, H., Xia, H, Toffoli, A., Chalikov, D., Klewicki, J., Hutchings, N., Monti, J., "Wind profiler network for planetary boundary layer research", ARC Linkage Infrastructure and Facility grant

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

REFERENCES
References to the 2014 publications by PIs are in Publications below

Ardhuin, F., E. Rogers, A.V. Babanin, J.-F. Filipot, R. Magne, A. Roland, A. Van der Westhuysen, P. Queffeulou, J.-M. Lefevre, L. Aouf, and F. Collard, 2010: Semiempirical Dissipation Source Functions for Ocean Waves. Part I: Definition, Calibration, and Validation. *J. Phys. Oceanogr.*, 40(9), 1917–1941, doi:10.1175/2010JPO4324.1

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

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

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

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

Gemmrich, J.R., M.L. Banner, and C. Garrett, 2008: Spectrally Resolved Energy Dissipation Rate and Momentum Flux of Breaking Waves. *J. Phys. Oceanogr.*, 38(6), 1296–1312. doi:10.1175/2007JPO3762.1

Komen, G.J., S. Hasselmann, K. Hasselmann, 1984: On the Existence of a Fully Developed Wind-Sea Spectrum. *J. Phys. Oceanogr.*, 14(8), 1271–1285

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, 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

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

Plant, W.J., 1982: A relationship between wind stress and wave slope. *J. Geophys. Res.*, 87, 1961–1967

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

Smith, W.H., R. Scharroo, J.L. Lillibridge, E.W. Leuliette, 2011: Retracking CryoSat waveforms from near-real-time ocean forecast products, platform altitude and other applications. . *AGU Fall Meeting*, San Francisco, CA, December 5–9

Snyder, R.L., F.W. Dobson, J.A. Elliott, and R.B. Long, 1981: Array measurements of atmospheric pressure fluctuations above surface gravity waves. *J. Fluid. Mech.*, 102, 1–59

Thomson, J. and W.E. Rogers, 2014: Swell and sea in the emerging Arctic Ocean. *Geophys. Res. Lett.*, 41(9), 3136–3140

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

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

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

Bakhoday Paskyabi, M.B., S. Zieger, A.D. Jenkins, A.V. Babanin, and D. Chalikov, 2014: Sea Surface Gravity Wave-wind Interaction in the Marine Atmospheric Boundary Layer. *Energy Procedia*, 53, 184-192, doi:10.1016/j.egypro.2014.07.227 [published, refereed]

Ghantous, M. and A.V. Babanin, 2014: One-dimensional modelling of upper ocean mixing by turbulence due to wave orbital motion. *Nonlin. Processes Geophys.*, 21, 325-338 [published, refereed]

Khon, V.C., I.I. Mokhov, F.A. Pogarskiy, A.V. Babanin, K. Dethloff, A.Rinke and H. Matthes, 2014: Wave heights in the 21st century Arctic Ocean simulated with a regional climate model. *Geophys. Res. Lett.*, 41, 2956-2961, doi:10.1002/2014GL059847 [published, refereed]

Zieger, S., A.V. Babanin, and I.R. Young, 2014a: Changes in ocean surface winds with a focus on trends of regional and monthly mean values. *Deep Sea Res. P.1,* 86, 56-67 [published, refereed]

Zieger, S., A.V. Babanin, and I.R. Young, 2014b: Observation-based source terms in the third-generation wave model WAVEWATCH. *Ocean Mod.* [under review]

Other

Babanin, A.V., S. Zieger and A. Ribal, 2014: Satellite observations of waves in the Arctic Ocean. *Proc. 22nd IAHR Int. Symp. on Ice*, Singapore, August 11-15 [refereed]

Rogers, W.E. and S. Zieger, 2014: S_{ice}: Damping by sea ice. In *User manual and system documentation of WAVEWATCH III(R),* H. Tolman (eds.), Technical Note MMAB No. 316, NOAA/NWS, College Park, MD, Section 2.3.19-21, 3pp.

Zieger, S., 2014: $S_{in} + S_{ds}$: BYDRZ. In *User manual and system documentation of WAVEWATCH III(R),* H. Tolman (eds.), Technical Note MMAB No. 316, NOAA/NWS, College Park, MD, Section 2.3.10, 5pp.

Zieger, S., A.V. Babanin, and A. Ribal, 2013: Wave climate in the marginal ice zone as observed by altimeters. *AGU Fall Meeting*, San Francisco, CA, December 9–13, eposter