Wave-Ice interaction in the Marginal Ice Zone: Toward a Wave-Ocean-Ice Coupled Modeling System

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LONG-TERM GOALS

Our main objective is to improve an operational model for wind-generated surface gravity waves (WAVEWATCH III®) such that it can accurately predict the attenuation and scattering of waves by interaction with ice in the Marginal Ice Zone (MIZ). The wave model physics developed here will later be part of an operational coupled model system, allowing feedback to ice, ocean, and atmospheric models.

OBJECTIVES

The specific objective of this proposal is to fully exploit the theoretical, observational, and ice/ocean/atmosphere numerical modeling work performed by various groups within the MIZ DRI and the "Sea State and Boundary Layer Physics of the Emerging Arctic Ocean" DRI to improve wave predictions.

APPROACH

The WAVEWATCH III model (Tolman 1991, Tolman et al. 2002, Tolman et al. 2014) is a phase-averaged wave model solved by integrating the wave action conservation equation. Local rates of change of wave spectral density is determined by advection in four dimensions (two geographic and two spectral dimensions) and source terms representing various dynamic processes, such as energy transfer from the wind, and energy lost due to wave breaking. The approach in WAVEWATCH III ("WW3") version 3 (Tolman 2009) was to represent the effect of ice on waves as part of the advection, such that under partial ice cover, wave energy is partially blocked, with linear scaling of the blocked fraction according to ice concentration (Tolman 2003). This is a practical approach for an operational model, since present state of knowledge of wave-ice interaction hardly justifies more rigorous methods, especially not at the resolution at which the model is typically applied. In any case, ice concentration is the only ice variable traditionally available for input to the wave model in an operational environment. However, this approach has a number of drawbacks, e.g. it does not allow one intuitive outcome: that the attenuation rate of wave energy as it enters the MIZ should depend on wave frequency. Further, with research efforts such as the aforementioned DRIs now starting, it is reasonable to expect that the state of knowledge will improve soon; enough such that it is reasonable to begin thinking about new ways to represent these physics. Our approach is to implement these effects as source terms, rather than as a partial blocking of advection. The new source terms, S_{ice}, will be implemented in a manner consistent with the real ocean; these interactions consist of both conservative and non-conservative physics, $S_{ice} = S_{ice,c} + S_{ice,nc}$. The former will represent the scattering and reflection of waves by ice, and the latter will represent dissipation of wave energy by the ice, noting that for swell entering the MIZ, both source terms imply a diminishing (attenuation) of wave energy along the direction of propagation.

A summary of tasks are originally proposed are given below.

Task 1. <u>WAVEWATCH-III interface</u>. Implement the framework for the wave attenuation source term in WW3.

Task 2. <u>Baseline wave hindcasts (basin-scale)</u>. Create baseline hindcasts for the entire Arctic basin, initially using traditional treatment of ice (Tolman 2003), and later to be applied with the new source terms.

Task 3. <u>Sensitivity analysis</u>. Determine reasonable range of values for free parameters of new physics using baseline hindcasts.

Task 4. <u>Real part of wavenumber</u>. Incorporate into WW3 the effect of sea ice on the real part of the wavenumber (determined by the physics routines for $S_{ice,nc}$), which produces an effect analogous to refraction and shoaling by bathymetry. (The imaginary part of the complex wavenumber determines the dissipation rate.)

Task 5. <u>Baseline wave and ice hindcasts (regional)</u>. Similar to Task 2, except that these hindcasts is the focus area of the DRI, the Chukchi and Beaufort Seas, nested in the basin-scale simulations. These provide the basis for further, deterministic modeling. A secondary motivation for these preliminary hindcasts is that they establish a limited climatology for the incident swell directions, which can be considered when planning locations for in situ measurements, flight paths, etc. This task includes application of Community Ice CodE (CICE).

Task 6. Deterministic modeling. Using the sub-regional hindcasts, we will use physics-based relationships connecting ice concentration and floe size distribution to the coefficients required by the theoretical models to estimate, again leveraging expertise of external groups participating in the DRI.

Task 7. Breakup investigations. Observations of temporal variation of MIZ geographic extent and floe size distribution will be used with wave information to connect wave events with seasonal ice breakup events.

Task 8. Coupled Modeling System. We will introduce the new WW3 code with the source terms into a coupled modeling system implementation. NRL will perform ice/ocean/wave hindcasts for the Chukchi and Beaufort Seas with tight coupling via Earth System Modeling Framework (ESMF) interfaces in each model.

Two other tasks were mentioned in the FY13-15 proposal as possible out-year tasks. Under revised plans, these will be at least partially addressed during FY13-15, though most likely at the expense of some progress with tasks 7 and 8 above. They are:

Task 9. Inversion for ice characteristics. We will utilize satellite, airborne and in situ wave observations to invert for necessary parameters (e.g. effective viscosity) using selected mathematical models and WW3 hindcasting for the DRI region.

Task 10. Non-dissipative scattering. Implement conservative source term $S_{ice,nc}$. This will be a diffusive scattering mechanism, whereby for each model frequency, there are two free parameters, controlling the strength of diffusion and fraction reflected, with both being quantified as "per unit time" or "per distance travelled".

WORK COMPLETED

During FY13, Tasks 1 (interface) and 2 (baseline hindcasts) were completed, and Task 3 (sensitivity) was partially completed. During FY14, tasks 3, 4 (real wavenumber), and 5 (improved hindcasts) were completed. Also, in FY14, Task 10 (scattering) was initiated. During FY15, Task 9 (inversion) was completed, but similar work may be performed later with additional datasets. Also, Tasks 3 (sensitivity) and 5 (improved hindcasts) were extended. Task 7 (breakup investigation) was performed through a collaboration, with most of the work done by Clarkson U. (more info below). Additional tasks not included in the original proposal were performed, as explained below.

WW3 was modified to allow up to eight new ice-related parameters to be read in from external files. The parameters are allowed to vary in time and space. Three methods were implemented for representation of $S_{ice,nc}$, for which we use shorthand notation IC1, IC2, and IC3 corresponding to WW3 code notations:

IC1. A simple routine in which the wave dissipation rate $k_i(x,y,t)$ is prescribed. With this method, k_i does not vary with wave frequency.

IC2. The method of Liu et al. (1991). This approach is based on the assumption that dissipation is caused by turbulence at the ice/water interface. The input parameters are ice thickness and an "eddy viscosity in the turbulent boundary layer beneath the ice". This method is expected to be most appropriate for cases with continuous or semi-continuous shore-fast ice, large ice floes, and inside the central ice pack.

IC3. The method of Wang and Shen (2010). This routine was provided by Prof. Hayley Shen (Clarkson University), who is also participating in the Sea State DRI. In this approach, sea ice is represented as a visco-elastic layer. Inputs are effective viscosity and a modulus of elasticity. This is intended as a “unified” approach where different ice types are possible by varying these two inputs.

Work completed during CY2012 was documented in a report, Rogers and Orzech (2013), summarized in the FY13 Annual Report. Also during FY13, the Science Plan for the Sea State DRI was published by the DRI PIs (Thomson et al. 2013).

During FY14, for Tasks 3 and 5, a nested hindcast was designed for the Beaufort Sea, allowing rapid, repeated testing of the new physics routines for a realistic case. Reasonable expected ranges for input variables were determined based on these results.

Since 2010, WW3 is managed as a community model, with invited participation from over a dozen researchers around the world. All WW3 code developed by NRL under this project is maintained on a NOAA/NCEP (National Centers for Environment Prediction) SubVersion (version control) server and is accessible to others in the WW3 community. Starting in FY14, there were valuable contributions to the wave-ice interaction routines from Dr. F. Ardhuin (Ifremer, France) via this server. Reconciliation of internal (i.e. by NRL and USM) with external (i.e. by Ifremer and others) changes to the code was required. This represents a considerable effort, but is essential for such collaborations.

During FY14, method IC3 was optimized by NRL following recommendations by Clarkson U., and extended to optionally allow runtime selection of IC3 vs. a simple variant of IC2 provided by Ifremer. Selection is made using a proxy variable for ice type; at present, ice thickness (e.g. from the ice model CICE) is used for this purpose. This method was applied to the nested hindcast described above and results were presented in a conference paper (Rogers and Zieger 2014). This hindcast used ice concentration and thickness from the NRL Arctic Cap Nowcast Forecast System (ASNFS), improved for the 2012 hindcast using the Multisensor Analyzed Sea Ice Extent (MASIE) product of the National Snow and Ice Data Center (NSIDC).

Task 4 was completed in FY14, so that when IC3 is used, the dispersion relation of IC3 is used to calculate ice-modified values of wave length, phase velocity, and group velocity, thus producing effects analogous to shoaling and refraction by currents or bathymetry. This was validated to work properly using simple, idealized tests. During FY16, it will be tested for realistic applications. Also in FY14, the open water source functions (input by wind, dissipation by whitecapping) were modified to scale with ice concentration. Further, a preliminary representation of scattering by sea ice (Task 10 above) was implemented in WW3.

All of these new features are documented by the PIs in the user’s manual which is maintained as part of the WW3 “package”. Also, simple tests such as the refraction/shoaling test above, and 1d and 2d demonstrations of dissipation by sea ice are included with the model package so that users can experiment with the features themselves.

All changes to the code, build system, documentation, and test cases that had been rolled into the “trunk” of the version-control repository prior to March 2013 were included in the version 4 public release of WW3 (Tolman et al. 2014). This is a significant milestone, since such releases occur infrequently (WW3 versions 1, 2, and 3 were released to the public in 1997, 2002, and 2009 respectively). Version 4 included all work done in FY13 and most of the work done in FY14 for this project.

WW3 hindcasts were performed for the Arctic in support of collaborations with other DRI participants. For example, one hindcast was featured in Thomson and Rogers (2014), a paper which received positive attention from a number of large media outlets. The hindcasts are also used by the "remote sensing" DRI participants to assist in interpretation of imagery. NRL performed "recent history" hindcasts/nowcasts every two weeks during August and September 2014 to assist in interpretation of contemporaneous field observations taken in the Beaufort Sea.

New work in FY15

An opportunistic study was performed for a wave-in-ice event near Svalbard in 2010, in collaboration with Aleksey Marchenko (Svalbard University). This involved making the most of limited ice and wave measurements during a wave event, with fracturing of an ice sheet by large waves (Collins et al. 2015) (Figure 1).

Inversion analysis was performed using large numbers of inexpensive simulations for Beaufort and Chukchi Seas in 2012, to determine the implied frequency-dependent dissipation rates for time period that MIZ was retreating (August) and advancing (October) past the "Beaufort Gyre" AWAC mooring. (Figure 2).

WAVEWATCH III hindcasts were performed for east Asian and North American sector of the Arctic for late August to early November, 2013 and 2014. These were on 16 km resolution polar stereographic grids (Rogers and Campbell 2009), and were similar to the hindcast performed for 2012: winds were taken from NAVGEM (Hogan et al. 2014) and ice concentration and thickness were taken from the Arctic Cap Nowcast/Forecast System (ACNFS), based on the Los Alamos Community Ice Code (CICE) with blending of AMSR2 and MASIE. (Note: MASIE is now replaced in the operational system by an equivalent product, the National Ice Center's Interactive Multisensor Snow Ice Mapping System, IMS.) The wave hindcasts were used for: a) test cases for new source functions, e.g. for sensitivity analyses, b) anticipating wave climate for 2015 cruise, c) validation exercises using moored data and MIZ DRI data, and d) opportunistic investigations with DRI collaborators, e.g. Thomson and Rogers (2014). Hindcast results were shared with the Sea State DRI via an (approved for public release) NRL ftp site.

In late FY15, substantial work was performed in anticipation of participation of Rogers in the Sea State cruise, planned for Oct. 1 to Nov. 11 2015. Special grids for WW3 were created which can run on a laptop and were tested during the mock "Plan of the Day" exercises prior to the cruise. An automated system was developed to deliver the following to a password-protected ftp site hosted by U. Victoria, where files for support of the cruise are aggregated: a) NAVGEM winds and ice analyses (0.5° regular global grid), b) COAMPS (Hodur 1997) winds and ice analyses (a higher resolution Navy meteorology product, on a 16 km polar stereographic Arctic grid), c) ice concentration, ice thickness, and surface currents, on a 5 km grid, from a modeling system operated by NRL-Stennis (D. Hebert) natively run at 2 km resolution, based on CICE and HYCOM. These files will be pulled from the U. Victoria ftp site from the ship by Rogers for forcing wave model forecasts run on the ship.

A number of other contributions were made by our team in collaboration with other Sea State PIs:

1. Modeling support for comparison to TerraSAR-X and buoy measurements. This effort is led by J. Gemmrich (U. Victoria). Gemmrich presented these results at three conferences and the analysis will later be used in a paper (not yet written).
2. Modeling support for a paper on regime change in the Beaufort and Chukchi Seas. This effort is led by J. Thomson (U. Washington). Co-I Y. Fan contributed significantly to this. At time of writing, this group paper is circulating in draft form and will be submitted prior to the cruise, Oct. 1 2015.
3. Modeling support for a paper on connections between wave events and floe size distributions and leads. This paper is led by Clarkson U. (Shen and Yu). As with (2), this group paper is circulating in draft form and will be submitted prior to the cruise, Oct. 1 2015.

Two other items are significant enough to mention:

1. The "ice effects on waves" code was maintained in the NCEP SubVersion repository. The code was kept in sync with the development "trunk" code; minor updates to the code and inline documentation were made.
2. Work was initiated toward bringing the "ice effects on waves" model of Fox and Squire (extended by Sea State PI Squire (personal communication); see a similar model in Mosig et al., 2015) into WAVEWATCH III as a new source function, possibly IC4. The model is not yielding sensible solutions for all expected values of input parameters, so this work is not finished. It will continue through collaboration with Squire, who has been very helpful so far.

RESULTS

The 2010 Svalbard study mentioned above is described in detail in Collins et al. (2015), but a brief summary is given here. A large wave event southeast of Svalbard May 1 to May 3 2010, with significant waveheights (SWH) of 6 m offshore resulting in the fracturing of ice near Svalbard, observed by the R/V Lance, which was in the ice at the time. After fracturing, SWH up to 4 m were observed, estimated from the ship's motion reported by GPS. To our knowledge, this is the largest SWH ever measured in substantial ice cover in the Northern Hemisphere. A binary behavior was observed with respect to the dominant waves, where energy at the spectral peak is either completely damped by the ice cover (prior to ice fracturing) or the ice was essentially invisible to these waves (after the ice fracturing). As shown in Figure 1, we also noticed that the broken sea ice acted as a low-pass filter on wave energy at frequencies higher than the spectral peak. As the event progressed, and as the ship was in ice of floe size which was reducing over time (captured by the ship's camera, as shown in the paper), progressively more higher frequency wave energy was observed by the ship. In other words, the low pass filter in Figure 1 shifted from left to right over time.

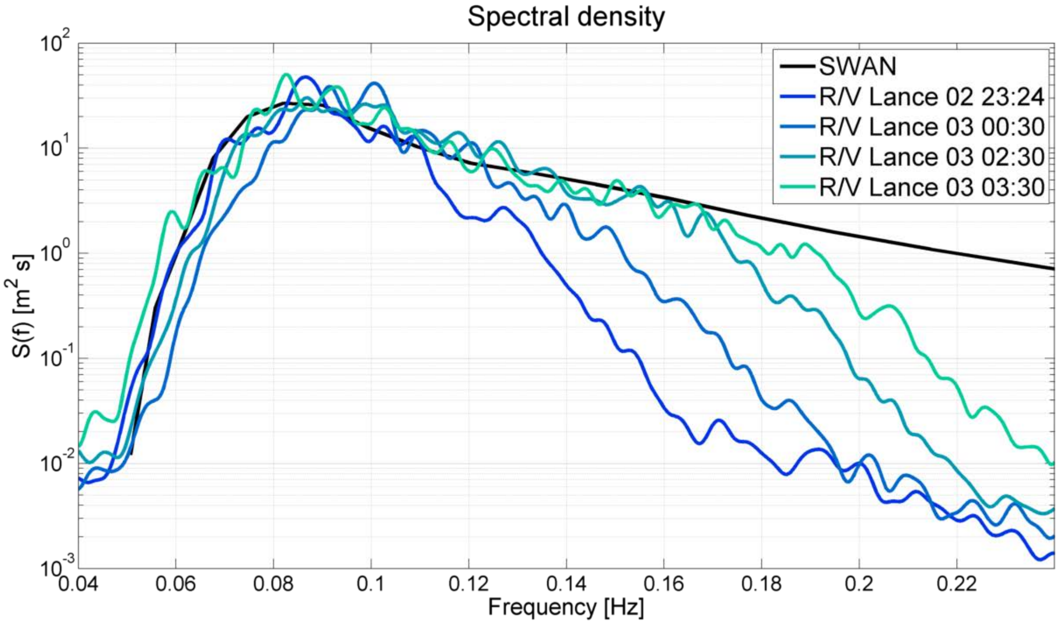

Figure 1. From Collins et al. (2015). The evolution of spectral energy density S(f) over the course of 5 hours as the ship encountered smaller ice floes. The first spectra is shown in dark blue and later spectra transitioning to aqua. SWAN spectra at this time, with no ice representation, is shown in black for reference.

Figure 2 below shows the dissipation rate as a function of frequency by several different models and observation-based fittings. The lines shown are explained in the caption. The inversion analysis mentioned in the prior section is shown with the black lines. These estimates are created using large numbers of inexpensive simulations for Beaufort and Chukchi Seas in 2012, to determine the implied frequency-dependent dissipation rates for time period that MIZ was retreating (August) and advancing (October) past the “Beaufort Gyre” AWAC mooring. Because the MIZ was over the mooring for only brief periods in either case, the resulting disspation rate could be divided into only three “bins”.

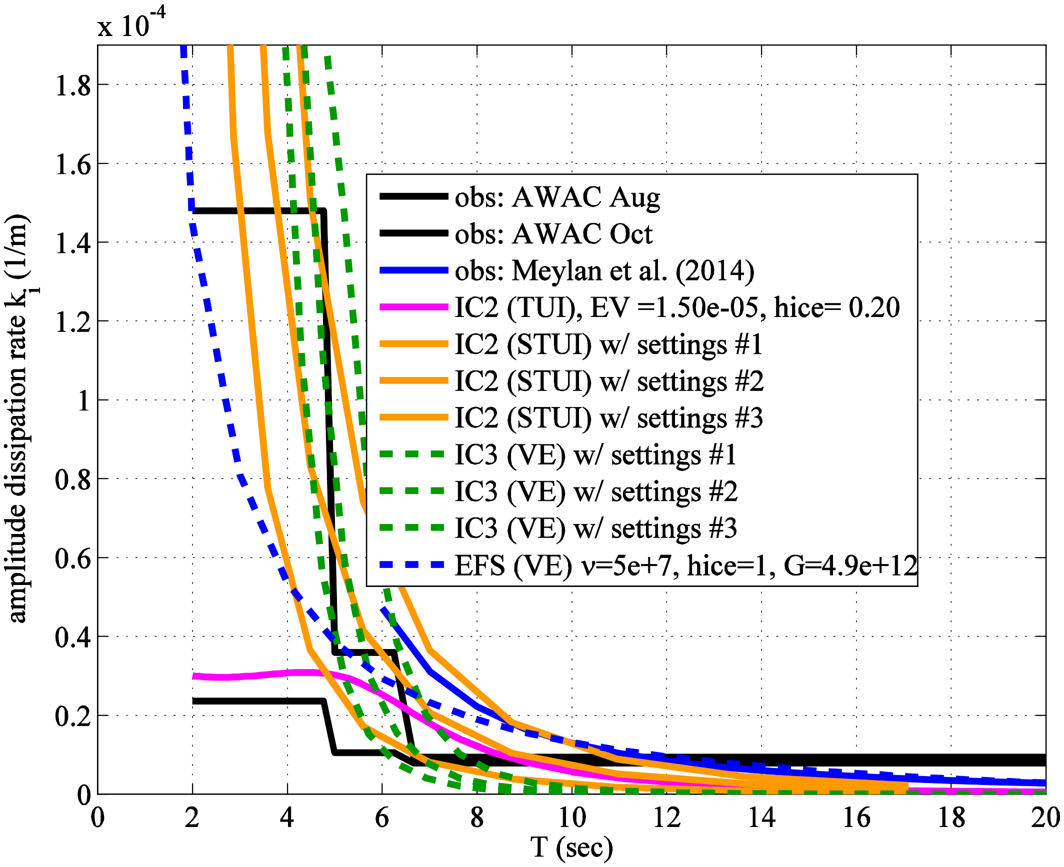

Figure 2. Dissipation rate as a function of wave period. Black: Based on simple inversion from 2012 AWAC mooring obs in MIZ using WW3 (3 frequency bins, ice retreat in August and ice advance in October); Blue (solid): Based on observations near Antarctica by Meylan et al. (2014); Pink: Liu et al. Turbulence-under-ice model; Orange: Simplified turbulence-under-ice model (Ardhuin); Green: Wang and Shen visco-elastic model; Blue (dashed): "extended Fox and Squire (1991)" visco-elastic model.

IMPACT/APPLICATIONS

Improvement of the wave model skill in the Arctic is a goal on its own, but this improvement also enables and facilitates other research within the DRIs. The modified WW3 model will be a tool for studying the changing wave climate in the Beaufort and Chukchi Seas, and for interpreting observations collected via the DRIs. This is discussed in the summary of tasking above, and greater detail can be found in Thomson et al. (2013).

RELATED PROJECTS

PIs Rogers and Posey are funded by a separate project concurrent with the proposed project. This project is an NRL Core Advanced Research Initiative (ARI) led by Richard Allard (Section Head, NRL Code 7322) entitled, "Determining the Impact of Sea Ice Thickness on the Arctic's Naturally Changing Environment (DISTANCE)".

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PUBLICATIONS

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