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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 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 2009) 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 plan 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 of wave energy along the direction of propagation.

A summary of tasks is given below.

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

Task 2. Baseline wave hindcasts (basin-scale). 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. Sensitivity analysis. Determine reasonable range of values for free parameters of new physics using baseline hindcasts.

Task 4. Real part of wavenumber. 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. Baseline wave and ice hindcasts (regional). Similar to Task 2, except that these hindcasts would be for the focus area of the DRI, the Chukchi and Beaufort Seas, nested in the basin-scale simulations. This would provide the basis for further, deterministic modeling. A secondary motivation for these preliminary hindcasts is that they will 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 would include 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 and 2 were completed, and Task 3 was partially completed. During FY14, tasks 3, 4, and 5 were completed, though certain aspects will be revisited in FY15, as explained below. Also, in FY14, Task 10 was initiated. 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 method is expected to be most appropriate for cases where the wave energy is propagating through small ice floes, pancake ice, frazil ice, grease ice, and/or rubble ice.

Work completed during CY2012 was documented in a report, Rogers and Orzech (2012), 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, 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 FY15, 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. 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.

RESULTS

The new physics IC1, IC2, IC3 are applied here to a hindcast for the Beaufort and Chukchi Seas, along with the traditional ice representation of Tolman (2003), denoted as "IC0". The time period used, 1-18 August 2012, corresponds to the "great Arctic cyclone" described in Simmonds and Rudeva (2012). The first two days are taken as spin-up. Wind and ice concentrations are taken from operational NOGAPS fields (Navy Operational Global Atmospheric Prediction System, Hogan and Rosmond 1991). The ice concentrations are based on radiometer analyses by FNMOC. This regional model ingests boundary forcing from a WW3 hindcast for the entire Arctic Ocean, so that wave energy generated in regions west of the Chukchi Sea are fully accounted for. The regional grid is, in fact, a subset of the Arctic grid, designed specifically for multiple, rapid testing of the new source functions. The grids are based on a polar stereographic projection at approximately 16 km resolution (see also Rogers and Campbell 2009).

Results are shown in Figure 1. Figure 1a-d shows wave heights and mean direction for 2100 UTC 6 August 2012 using IC0, IC1, IC2, and IC3. Figure 1f-g shows the differences in wave heights between the control simulation (IC0) and the simulations with new physics (IC1, IC2, and IC3). In the IC0 simulations, regions with ice concentration greater than 0.75 are treated as non-sea points, i.e. significant wave height is zero, and plotted as white area in Figure 1a. In the IC1/2/3 simulations, no such cut-off is used (thus no white area in Figure 1b-d). For IC1, dissipation rate $k_i = 2\times10^{-5}$ rad/m is used; for IC2, eddy viscosity $\nu_{IC2} = 15\times10^{-6}$ m^2/sec; for IC3, effective viscosity $\nu_{IC3} = 1.0$ m^2/sec. Results indicate that with IC3, there is greater suppression of local wave generation in the MIZ, e.g. north of Wrangel Island, consistent with stronger damping of short waves, a known feature of IC3. Correspondingly, there is greater penetration of swells into the central ice pack with IC1, IC2, and IC3, compared with IC0. This is consistent with a weaker damping of long waves, which is again a known feature of IC3. In independent tests (not shown here), it is observed that with these settings, IC3 yields a very steep dependence of dissipation rate k_i on wave frequency σ. IC2 has the same dependence, but it is weaker, i.e. smaller $\partial k_i / \partial \sigma$.

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)".

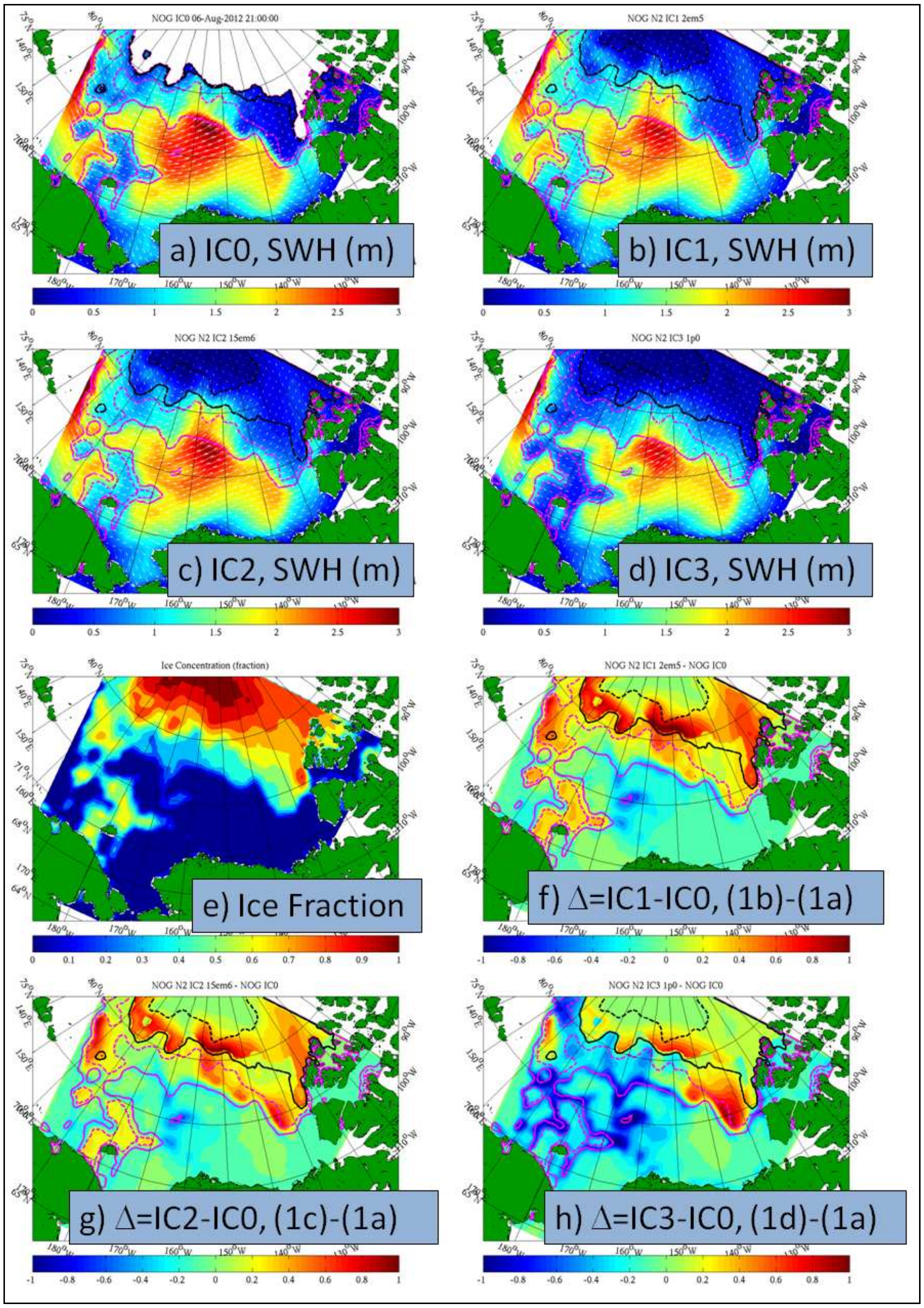

Figure 1. From Rogers and Zieger (2014). Hindcast for the Beaufort and Chukchi Seas for 2100 UTC 6 August 2012 using IC0, IC1, IC2, and IC3. Panels a-d indicate significant wave height (SWH), in meters (colors) and mean direction (arrows). Panel e indicates ice concentration (fraction) from operational analysis. Panels f-h indicate differences between SWH of the new routines (IC1, IC2, IC3) and the control (IC0). Contours indicate ice fraction of 0.25 (solid magenta), 0.50 (dashed magenta), 0.70 (solid black), and 0.95 (dashed black).

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PUBLICATIONS

Rogers, W. E., M. D. Orzech, 2013. Implementation and testing of ice and mud source functions in WAVEWATCH III®. NRL Memorandum Report, NRL/MR/7320-13-9462, 31pp. (http://www7320.nrlssc.navy.mil/pubs.php)
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INVITED TALK

New wave-ice interaction physics in WAVEWATCH III®, invited plenary talk at 22nd IAHR International Symposium on Ice, Singapore, Aug. 11 to 15 2014.