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New wave-ice interaction physics in WAVEWATCH III®

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The third generation model for wind-generated surface gravity waves WAVEWATCH III® is modified to represent the effect of ice on waves as a source function. This replaces the existing approach of representing ice via fractional blocking (per grid cell) of wave propagation using ice concentration. We have implemented three alternative formulations of varying complexity. The first dissipative source function is a simplistic model where dissipation rate is specified directly. The second dissipative source function, based on work by A. Liu and others, assumes that dissipation is primarily caused by turbulence at the interface between water and a locally continuous ice layer. The third dissipative source function, based on work by H. Shen and others, treats the ice as a locally continuous visco-elastic layer (i.e. a two-layer model). In all cases, the ice characteristics may be specified as non-homogeneous and nonstationary fields. In the latter two source functions, the dissipation rate is non-uniform in frequency space, which is a highly intuitive and documented feature of wave-ice interaction: shorter waves are damped rapidly within the Marginal Ice Zone (MIZ), while the longest waves can penetrate several kilometers (at least) into the ice pack. These source functions are applied in preliminary hindcasts for August 2012 in the Beaufort and Chukchi Seas.

1. Introduction

During the 1970s and 80s, phase-averaged finite difference wave models were widely adopted for wave hindcasting and forecasting, based on wave energy or wave action conservation equations. This advancement liberated the wave modeler from reliance on grossly unsatisfactory assumptions about the wave state (e.g. fully development, or fetch limited) and the forcing (e.g. winds that are steady and/or uniform over a fetch) used in parametric models. Instead, the model numerically integrates the partial differential equation, simultaneously allowing for unsteady and non-uniform forcing, advection, highly nonlinear source terms (e.g. wave breaking), and treatment of swell. The most recent major advancement in this elegant mathematical treatment was the introduction of the so-called "third generation wave model" or "3GWAM" (Komen et al. 1994). The WAVEWATCH III® model (WW3, Tolman 1991, Tolman et al. 2014), used today by the U.S. Navy, falls into this category.

The mutual interactions between ocean waves and sea ice cover play a crucial role for planning safe operations in the Arctic Ocean. Therefore, wave-ice interactions should be among the center-pieces of the operational wave forecasting system. A research objective of the Naval Research Laboratory (NRL) and the Office of Naval Research (ONR) is to study these interactions in the marginal ice zone (MIZ) of the Arctic Ocean, and develop techniques for modeling the effect of sea ice on wave energy and wavelength. A number of theories and models have been developed to describe this phenomenon. A brief review of these methods is given in Rogers and Orzech (2013, this report is available online and is denoted below as RO13).

The retreating ice cover implies an increase in fetch for generation of waves in the Arctic, which allows waves to grow higher under the same wind conditions. This, combined with more frequent incoming cyclones in the Arctic (Sepp and Jaagus 2011) naturally leads to more severe wave conditions. The reduction of the permanent polar pack ice also implies that regions of the Arctic that could previously be ignored in operational numerical wave models must now be considered. NRL has recently extended the capability of the WW3 model so that it can be applied on irregular grids (Rogers and Campbell 2009). An implementation of WW3 for the Arctic, with two-way nesting to a global model, is now running in realtime on the DoD Supercomputing Resource Center (DSRC) (James Dykes, NRL, personal communication). The curvilinear two-way nested Arctic regional grid addresses the traditional problems associated with extending a regular global grid to high latitudes.

The situation with regard to the physics of wave models in the Arctic has seen less progress until very recently. The key physical process, wave attenuation by interaction with sea ice in the Marginal Ice Zone (MIZ), is traditionally treated within the propagation routine of the model Tolman (2003), with the percent transmission of wave energy through ice being a simple linear function of ice concentration. There is no connection to a physical mechanism for wave attenuation, and so this artificial “dissipation” is not dependent on frequency (see RO13 for detailed discussion). This simple, non-physical approach could nevertheless be justified on the grounds that operational characterization of the ice is limited (ice concentration only) and further that the existing physical mechanisms available from the literature which might be implemented in the forecast model are 1) too numerous and too varied to select from and 2) too poorly informed. Compounding the problem is the limited number of studies estimating attenuation from observations, which would normally be used to calibrate and verify a numerical model.

In any case, these early methods represent the dissipation of waves by interaction with sea ice using the propagation terms of the governing equation of WW3 (known as the radiative transfer equation), and our objective here is to do the same thing via source function (i.e. dynamics). In the present effort, we utilize modeling codes that are currently used operationally—WW3 in the case of the wave model—distinguishing our aim from more detailed process-based modeling investigations, such as models of individual waves and ice floes.

The last two years have seen progress on the ice source function problem. Doble and Bidlot (2013) have implemented a non-conservative source function S_{ice} in the WAM model and have applied it to a hindcast of the Weddell Sea, and compared with observations from a wave buoy. RO13 implemented two non-conservative S_{ice} routines in WW3, and applied and verified using simple tests. Since then, a third S_{ice} formulation has been added to WW3 by NRL using routines provided by H. Shen, a viscoelastic model. The WW3 code is maintained on the development repository at NCEP (National Centers for Environmental Prediction) and these features are included in the recent public release of the model, v4.18 (Tolman et al. 2014). Since the public release, Ifremer (France) has made significant contributions to the wave-sea ice interaction routines; this paper focuses on capabilities that exist in the public release.

2. Description of modifications to the model

The WW3 model (Tolman 1991, Tolman et al. 2014) is a phase-averaged model for wind-generated surface gravity waves based on the radiative transfer equation. In this approach, the dependent variable is the wave spectrum (denoted *E* for wave energy or *N* for wave action), which is a function of wavenumber or frequency (k or σ), direction (θ), space (x,y), and time (t), with spectral density being defined on frequency and direction. The left hand side of the radiative transfer equation includes terms for time rate of change and propagation, while the right hand side includes source functions (dynamics):

$$\frac{\partial N}{\partial t} + \nabla \cdot \vec{c} N = \frac{S}{\sigma} \qquad \textbf{[1]}$$

where $\vec{c}$ describes the propagation velocities in x, y, k, and θ. The sum of all source functions is denoted as S, and individual source functions are denoted with appropriate subscript, for example dissipation by whitecapping is S_{wc}, and dissipation by ice (new in v4.18) is S_{ice}. For more detailed description of the model, we refer the reader to Tolman et al. (2014); a concise description of aspects of the model relevant to this study can be found in RO13. In WW3, the traditional ice representation is denoted as IC0, and that notation is used here. The new source functions are denoted as IC1, IC2, and IC3 and are described below.

Treatment of open water source functions

The treatment of partial ice coverage (ice concentration) in the source term follows the concept of a limited air-sea interface. This means that the momentum transferred from the atmosphere to the waves is limited. Therefore, input and dissipation terms are scaled by the fraction of ice concentration. The nonlinear wave-wave interaction term can be used in areas of open water and ice (Polnikov and Lavrenov, 2007). The scaling is implemented so that it is independent of the

S_{ice} source term selected. With the ice source functions, ice concentration is not a required input, but if ice concentration has been read in, the S_{ice} source functions are scaled by ice concentration.

Conservative vs. non-conservative source functions

In the real ocean, the effect of ice on waves can be split into two categories: 1) scattering, which is strictly energy-conserving and we denote as $S_{ice,c}$ and 2) various non-conservative processes which we denote as $S_{ice,nc}$. This paper deals with the latter type. In principle, any number of non-conservative terms can be included simultaneously, provided that they represent unique physical processes, e.g. turbulence at the ice/water interface vs. quasi-continuous frazil ice represented as a viscous layer vs. energy losses from collisions of floes. However, during the development process which we are in now, we allow for only one representation of $S_{ice,nc}$ in a particular simulation, i.e. the user must select one of IC0, IC1, IC2, or IC3. We anticipate that our representations will evolve toward greater sophistication in this regard.

The scattering of waves from sea ice, $S_{ice,c}$, is not considered in the public release version 4.18 (Tolman et al. 2014). This is an important physical process (Wadhams 1975). At time of writing, a preliminary scattering routine has been implemented for WW3, but for the current paper, we focus on the source functions available in v4.18, i.e. $S_{ice,nc}$.

Input methods

Input methods are described in detail in RO13. Variables required by the new source functions (e.g. ice thickness, effective viscosity) are allowed to be non-stationary and non-uniform.

Real and imaginary wavenumbers

In absence of ice cover, the relation between wavenumber k_r and wave frequency is traditionally calculated using the linear dispersion relation in 3GWAMs. In a number of theoretical derivations of the non-conservative term $S_{ice,nc}$, e.g. Liu and Mollo-Christensen (1988), Keller (1998), Wang and Shen (2010), the problem is presented a solution of a modified dispersion relation in which the wavenumber is complex $k = k_r + ik_i$. This is related to the source term in a very simple way. The energy dissipation rate $D = -2C_g k_i = S/E$. Thus, k_i is an exponential decay coefficient $k_i = k_i(x, y, t, \sigma)$ (depending on location, time and frequency, respectively), producing wave attenuation.

The real part of the wavenumber solved in the presence of ice in this fashion is different than that from linear wave theory, but should converge to that value as ice cover (either as concentration or thickness) approaches zero. This modified real wavenumber—representing impact of the sea ice on the physical wavelength and propagation speeds—produces an effect analogous to refraction and shoaling by bathymetry.

With IC1, k_i is specified a priori, uniform in frequency space, whereas with IC2 and IC3, k_i and k_r are calculated using a modified dispersion relation, so obviously, it is non-uniform in frequency space. The effect of sea ice on k_i is used for all three of the source functions IC1, IC2, IC3. The effect of sea ice on k_r has so far, been implemented and tested for IC3 only.

Source function descriptions

IC0: IC0 is used to denote the traditional methods of Tolman (2003), which was updated and improved by F. Ardhuin (Ifremer) in the WW3 public release v4.18. For description of this method and these improvements, see RO13.

IC1: As noted already, the first implemented method is for the user to specify $k_i(x, y, t)$ which is uniform in frequency space. In this case, the amount of information read in has not changed from the Tolman (2003) method of using ice concentration.

IC2: The second method for representing wave-ice interaction is based on the papers by Liu and Mollo-Christensen (1988) and Liu et al. (1991, denoted as LHV below). This is a model for attenuation by a sea ice cover, derived on the assumption that dissipation is caused by turbulence in the boundary layer between the ice floes and the water layer, with the ice modeled as a continuous thin elastic plate. Input ice parameters are ice thickness (in meters) and an eddy viscosity in the turbulent boundary layer beneath the ice, ν. The solution method for IC2 is very efficient and overall computation time is not significantly more than that with IC1. Key equations for the new dispersion relation are given in the Liu references (above), RO13 and Tolman et al. (2014). The IC2 form of $S_{ice,nc}$ is most appropriate for situations of large floes and flexible continuous ice. Applicability to smaller floes or pancake ice is doubtful. The eddy viscosity term ν given by LHV is unfortunately "highly variable" (their words), and "not a physical parameter", which suggests that it is difficult to specify in practice. In LHV, many values are referenced and used (for a summary, see RO13). Since the public release v4.18, Dr. Fabrice Ardhuin (Ifremer) has implemented in WW3 the option to replace the IC2 eddy viscosity with a Reynolds number-based calculation that uses the wave orbital velocity. This is arguably a more physically credible method of parameterization, and has the substantial benefit of simplifying input. This method is not used here, but will likely be adopted for future modeling efforts.

IC3: The third method for representing wave-ice interaction is taken from Wang and Shen (2010). This model treats the ice as a visco-elastic layer. It requires four inputs: ice thickness, effective viscosity, ice density, and effective shear modulus. As noted above, this routine is implemented such that k_r is passed back to the main program, modifying wave length and velocities, producing effects analogous to shoaling and refraction by bathymetry. The IC3 form of $S_{ice,nc}$ is most appropriate for situations of frazil, grease, and pancake ice. As implemented in the public release v4.18 of WW3, this method of $S_{ice,nc}$ was much more expensive than IC1or IC2. The code has since been optimized (credit to Clarkson U.), and the computation time is now comparable to IC1 and IC2.

3. Testing

Simplified 1-d and 2-d testing

Simple one- and two-dimensional testing of IC1 and IC2 was performed by RO13. The primary objective was to verify the proper functioning of the model i/o and to quantify sensitivity to geographic resolution. It was found that cases with coarse resolution and strong dissipation are affected by numerical (discretization) error, yielding practical guidelines for how the model should be applied. The reader is referred to RO13 for details. Simplified tests cases demonstrating and verifying the effect of the real part of the wave number on wave direction and energy (analogous to refraction and shoaling) with IC3 were performed. These are not reproduced here, but are included as test cases with the public release of WW3 v4.18.

New tests for the Beaufort and Chukchi Seas

The new physics IC1, IC2, IC3 are applied here to a hindcast for the Beaufort and Chukchi Seas. 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. Wave energy incoming from the adjoining basins (Bering Sea and north Atlantic) is expected to be small and is disregarded here. Traditional ice representation (Tolman 2003) is used in the Arctic Ocean grid, since the hindcast for that larger grid was run only twice. 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).

These hindcasts were repeated using ice concentrations and ice thickness from the Arctic Cap Nowcast Forecast System (ACNFS, Posey et al. 2010), but those results are not presented here. It is worth repeating: both IC2 and IC3 require ice thickness as an input, and this variable is available from ACNFS but not NOGAPS.

These hindcasts presented here are very preliminary. The source functions IC2 and IC3 are applied with uniform thickness (20 cm for IC2 and 10 cm for IC3) which is typically thinner than the thickness predicted by ACNFS. Also, as noted above IC2 and IC3 are expected to be valid only for specific ice types, whereas it must be assumed that the actual situation being modeled (because of the large geographic extent) includes a variety of ice types. In a subsequent study, we plan to incorporate a selection of IC2 vs. IC3 based on ice thickness.

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, $k_i = 2\times10^{-5}$ rad/m is used; for IC2, $\nu = 15\times10^{-6}$ m^2/sec; for IC3, $\nu = 1.0$ 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 k_i on wave frequency. IC2 has the same dependence, but it is weaker, i.e. smaller $\partial k_i / \partial \sigma$.

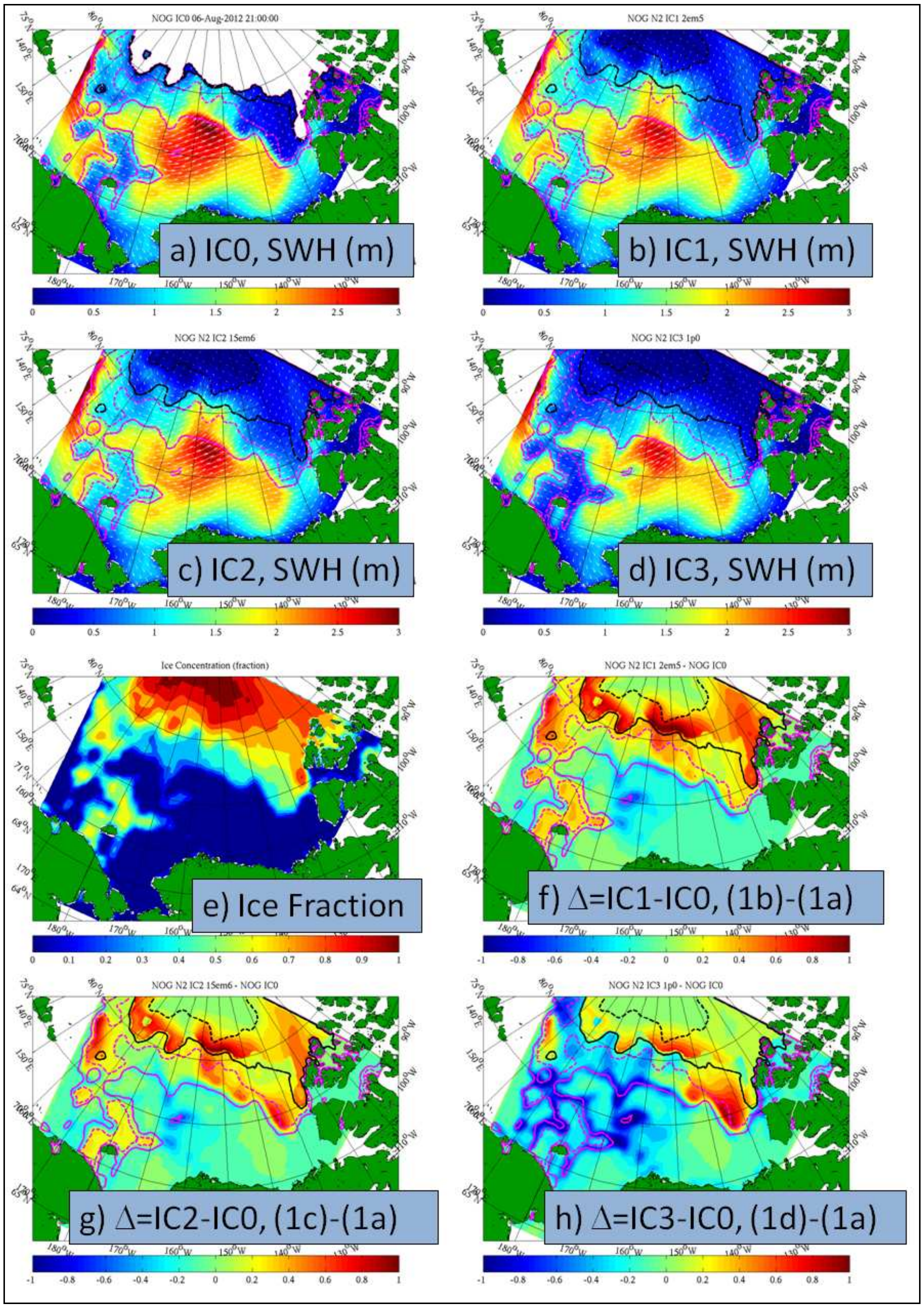

Figure 1. Hindcast for the Beaufort and Chukchi Seas for 2100 UTC 6 August 2012 using IC0, IC1, IC2, and IC3. Panels a-d indicate significant wave height (SWH), in meters (colors) and mean direction (arrows). Panel e indicates ice concentration (fraction) from operational analysis. Panels f-h indicate 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).

These results are very preliminary, and specific needs have been identified for further work. 1) Comparison with observations is a major priority. There are limited data for the MIZ presently, but ONR-supported field programs have been initiated to resolve this deficiency. Suitability and accessibility of altimeter-derived wave heights in the MIZ will be accessed. 2) Inconsistencies in the ice edge for different operational products will be addressed. For example, for the hindcast presented here, the U.S. National Ice Center estimate of the ice edge indicates a MIZ that is approximately twice as large as the operational estimate of ice concentration. We hypothesize that the region where the differences exist might have contained ice types (e.g. frazil, grease, pancake) for which detection by radiometer may not be as reliable. 3) As noted above, we will allow for simultaneous use of IC2 and IC3 (and others that may be added), based on our best estimate of ice type. 4) Scattering by ice, i.e. $S_{ice,c}$ will be added to the simulations, as discussed above. 5) ice concentration and thickness from ACNFS will be used, as noted above. 6) Improved treatment of IC2, without a priori specification of eddy viscosity, will be used (see above).

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