An Arctic Ice/Ocean Coupled Model with Wave Interactions

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LONG-TERM GOALS

The overarching long-term goal of Project N00014-131-0279 remains as defined in the original proposal, namely to include two-dimensional (2D) ocean surface wave interactions with sea ice in a contemporary 3D Arctic ice/ocean model. To accomplish this primary goal, the objectives listed in the next section are required to be achieved along the way. Consequential to the primary goal, we aim to

– develop an improved operational ice/ocean model for the Arctic Basin, built upon a recently published model assembled for the Fram Strait region of the Greenland Sea that has collinear wave trains interacting with the ice;
– improve the forecasting capacities of contemporary Arctic climate models.

OBJECTIVES

To make progress with our long-term goals, we will

– further our understanding of the hydrodynamical interactions between polar oceans and sea ice;
– develop new theoretical models and numerical methods with applications to other areas of science;
– model attenuation and directional wave propagation within and in the waters adjoining the marginal ice zone (MIZ), using the conservative multiple wave scattering approach in a medium with random geometrical properties that is specified using remote sensing data products and other data sets;
– test the conjecture that ocean waves are governed by an isotropic directional spectrum in the MIZ, as observed by Wadhams et al. (1986) during field experiments;
– develop novel numerical techniques to limit the computational effort for large scale models;
– advance new parametrizations for dissipative mechanical processes within the MIZ, to account for additional energy loss not captured by conservative wave scattering theory;
– validate the ice/ocean model using experimental data from past and upcoming field and laboratory work, as available; and
– if possible, use the wave scattering model to calibrate viscoelastic-type models that render the MIZ as a continuum.

The work described in this report is the outcome of a collaboration between the PI, AIs: Bennetts, Holt and Williams, and Montiel who is the Postdoctoral Fellow on the project located with the PI at the University of Otago.

APPROACH

There are two complementary approaches to modeling the effects of ocean waves in the Arctic with its present-day reduced summer sea ice cover, and both are actively being investigated in the 'Sea State and Boundary Layer Physics of the Emerging Arctic Ocean' DRI. The first involves substantially improving the way in which sea ice is treated in contemporary third generation operational wave models such as WAVEWATCH® III or WAM, as the current parametrization is poor. In this respect a viscoelastic continuum is a prospective candidate for the 'grid cells' in these numerical models that are either partly or wholly ice-covered (e.g. Wang and Shen, 2010, 2011, noting that the magnitudes of the viscoelastic moduli are undetermined). We are not directly involved in this work, other than by helping to resolve the moduli by means of our model, i.e. calibrating the parametrization. The second approach is the focus of the current project; its aim is to enhance the accuracy of present-day ice/ocean models by directly including the influential contribution that waves make in metamorphosing the sea ice itself and vice versa. In a nutshell, waves break up the sea ice differentially to create the floe size distribution (FSD), thereby allowing individual floes more freedom to move laterally under the action of winds and currents (and the waves themselves) changing local concentration, and they can enhance ice-albedo feedback by bringing warmer water in contact with the decaying ice mass. *Mutatis mutandis*, the waves are attenuated and scattered by the sea ice, which they have modified.

WIFAR (Waves-in-Ice Forecasting for Arctic Operators), a partnership initially between the Nansen Environmental and Remote Sensing Center (NERSC) in Norway and the University of Otago, was the precursor to the project being described here. Work started during WIFAR, which was completed during the tenure of the current award, targets a less ambitious ice/ocean model of the Fram Strait with collinear as opposed to 2D wave-ice interactions (Squire et al., 2013; Williams et al., 2013a,b).

Similarly to the Williams et al. (2013a,b) papers we consider a grid cell from an operational ice/ocean model, in this case TOPAZ: a hybrid coordinate ocean model of roughly 13 km horizontal resolution forced by ECMWF atmospheric fields, as the platform to construct a 3D WIM (waves-in-ice model) for the MIZ. The new WIM will extend the one used by Williams et al. to account for the evolution of directional wave spectra in the MIZ, i.e. the wave-interactions will be 2D as in nature. The model is based on subdividing the ice cover into contiguous strips of designated finite width running parallel to the ice edge, each containing an arbitrary distribution of circular ice floes. The disposition of the ice in each strip, including FSD, can be generated from a random sampling parametrized by mean and standard deviation values of floe diameter, concentration and thickness.

For each grid cell, our aim is to characterize the propagation of ocean waves arising from a monochromatic directional wave spectrum fully established in the open ocean. For now it is assumed that only conservative wave scattering processes fully govern the evolution of the directional wave spectrum in the cell. The division of the MIZ into strips allows us to represent the wave field at the line interfaces between strips as the coherent superposition of two wave spectra advancing in opposite directions. At their most general, directional wave spectra are continuous sums of plane waves traveling at different angles, so can be seen as the reflected and transmitted components due to the scattering that is occurring within each strip. In a technical sense, the T-matrix associated with each strip can be obtained using a combination of Graf's interaction theory, which is exact for 2D multiple scattering in the plane, and a mapping between circular waves and plane wave fronts. This latter step is novel in offshore hydrodynamics and is based on the plane wave expansion of circular wave components

$$\mathrm{H}_n(kr)\mathrm{e}^{\mathrm{i}n\theta} = \begin{cases} \dfrac{(-\mathrm{i})^n}{\pi} \displaystyle\int_{-\pi/2+\mathrm{i}\infty}^{\pi/2-\mathrm{i}\infty} \mathrm{e}^{\mathrm{i}n\alpha} \mathrm{e}^{\mathrm{i}k(x\cos\alpha + y\sin\alpha)}\,\mathrm{d}\alpha, & (x \geq 0), \\ \dfrac{\mathrm{i}^n}{\pi} \displaystyle\int_{-\pi/2+\mathrm{i}\infty}^{\pi/2-\mathrm{i}\infty} \mathrm{e}^{-\mathrm{i}n\alpha} \mathrm{e}^{\mathrm{i}k(-x\cos\alpha + y\sin\alpha)}\,\mathrm{d}\alpha, & (x \leq 0), \end{cases} \tag{1}$$

proposed by Cincotti et al. (1993) for electromagnetic scattering, where H_n denotes the Hankel function of order n, k is the wavenumber and $(x, y) = (r\cos\theta, r\sin\theta)$ are the coordinates of a field point. A matrix form is then obtained by discretizing the angular spectrum, represented by the variable α, or by means of Fourier series. In any case, the number of angular samples of Fourier modes retained for the numerical evaluation controls the accuracy of the method. Finally, the discrete representations of the reflection and transmission components of the wave field at the strip boundaries can be combined using standard techniques for coherent multiple scattering.

The strip subdivision approach has several advantages, as it provides a complete representation of the directional wave spectrum at the strip interfaces, allowing the evolution of wave characteristics (amplitude, directional spread, etc.) to be tracked with distance traveled from the ice edge. In particular, we expect to be able to test the hypothesis that wave propagation in the MIZ soon becomes directionally isotropic as it moves through the ice field, as formulated by Wadhams et al. (1986) on the basis of a single field experiment that it is intended to repeat during the DRI. In addition, we will be able to analyse the attenuation of wave energy with distance from open water and perform comparisons with field and laboratory experiments. Finally, in regard to the long-term goal, we will be able to provide these results in the form of lookup tables to the TOPAZ ice/ocean model and WAVEWATCH III, and, for the latter, cross-relate to any viscoelastic parametrization of the sea ice to calibrate the material moduli for different types of MIZ.

Apart from a small number of ad hoc field experiments, there have been few in situ data collected relating to wave-ice interactions since the MIZEX campaign of the 1980s. This DRI and the associated 'Emerging Dynamics of the Marginal Ice Zone' one have fieldwork planned that has the capacity to generate significant new data that will intersect majorly with the modeling work that is being reported herein. Laboratory experiments such as those Montiel et al. (2013b,a) reported, are potentially also a rich source of data to test models, noting that they are deceptively difficult to conduct because of challenging scaling problems associated with this kind of work. The other laboratory experiments presently being discussed by DRI participants may likewise aid our understanding. Benefiting from the better technology available now, field experiments supported by an intensive remote sensing program coordinated by Holt at JPL and involving both airplane and satellite data, will furnish a unique set of measurements that will allow validation of theoretical models and provide quantities for parametrizations.

With respect to the Williams et al. (2013a,b) study, the first step is to diversify its reach from the Greenland Sea into the Arctic Basin and the other seas bounding the Arctic Ocean. Progress has already been made with this and will be illustrated later in this report (Figure 1). This is work under way towards the longer term goal of embedding the 3D WIM described above into the TOPAZ framework, by so doing allowing fully directional seas generated by WAVEWATCH III as inputs, for example.

It is also observed that the 3D WIM will provide a testing platform which can be built upon to include additional physical non-conservative processes. Dissipation of wave energy in the MIZ is controlled by many nonlinear phenomena that are not represented by a conservative scattering formulation. Two avenues will be considered to study these processes:

- the introduction of an artificial dissipation numerically by combining two approximations: (i) an iterative procedure for the interaction between floes that effectively replaces Graf's interaction theory, which can be truncated arbitrarily to neglect high order negligible interactions (Twersky, 1952); and (ii) a limited-range approximation for floe-floe interactions whereby a radius of action is designated that controls the extent to which a particular floe influences the remainder of the MIZ. In addition to introducing additional dissipation, this approach has the attractive spinoff of curbing the computational cost significantly.
- The second approach will consist of parametrizing dissipative effects in terms of known ice and wave properties, by modeling the physical processes of interest in a simple setting. This work will be done by a PhD student. Sensitivity analyses will then be conducted to generate lookup tables used in the large scale context.

WORK COMPLETED

To the 30th September 2013, Project N00014-131-0279 has been operational for just 10 months, but we can report the following accomplishments to date:

- **Setting up the 3D WIM.** The theory of wave scattering by multiple strips of randomly distributed scatterers is new and, as such, has been studied *sui generis* before being applied to ocean waves and sea ice. We considered a simple planar sound wave propagation medium governed by the Helmholtz equation containing circular totally reflective obstructions with a Neumann edge condition. In this context, the full scattering problem was solved and tested for wave attenuation and evolution of the directional spread. Comparisons were also made with an existing model (Bennetts, 2011) by imposing the same assumptions made in the Bennetts model on our more general approach. The implementation of the 3D WIM is currently under way for interactions between ocean waves and sea ice.
- **Validation of the Williams et al. (2013a,b) WIM.** A paper seeking to validate the Williams et al. model against data is currently in preparation, led by AI: Williams, and co-investigators on the project (the PI, AI: Bennetts and Dumont who is an affiliate). Simulations have been performed for a 2-year period at NERSC, and ice charts from DMI analysed for a 1-year period to compare the MIZ width, which is one of the main outputs of the model. Further confirmation of the actual MIZ width is currently being sought from SAR images.
- **Wave tank experiment.** In July 2013 a wave-tank experiment was carried out, which looked into wave attenuation by the MIZ and the drift motion in the presence of currents and waves. In the wave attenuation experiments, between 35 and 80 'ice floes' (0.99 m diameter wooden disks) were moored with springs to the tank floor and plane waves were sent down, with an array of wave probes to measure the reflected and transmitted waves. In the rheology experiments, to provide collisions similar numbers of floes were subjected to currents with different structures and to waves. Although not formally part of Award N00014-131-0279, data from the experiment will form a valuable addition to verifying theoretical predictions.
- **Wave attenuation experiment.** From about 25 July to 6 August 2013, a joint experiment between

Martin Doble and NERSC (Yngve Kristoffersen) took place, using NERSC's hovercraft to travel from Longyearbyen to the ice edge at about (9°E, 81°N). Six wave-buoys (measuring vertical accelerations) were deployed for about 10 hours in total. Although the waves were relatively small, it is hoped that some attenuation is apparent in the data. The buoys also had GPS receivers with a 10 Hz frequency of positional acquisition, so it will be interesting to look at these from an ice-rheological point of view. Previous drift measurements have had a 3-hour temporal resolution so we hope to obtain information about smaller time scales.

– **Artificial dissipation.** We have implemented the iterative method for multiple scattering and the limited-range approximation for an array of O(100) randomly distributed, randomly sized ice floes. Preliminary tests were conducted for a wide range of parameters.

RESULTS

After 10 months the major outcomes from the project are (i) completion of the Williams et al. (2013a,b) papers, which admittedly were begun prior to the award but represent the first time wave-ice interactions have been included in an ice/ocean model so accord with our purpose; (ii) modification of the code to be Arctic wide (Figure 1), which has been worked on primarily by AI: Williams under the aegis of the award; (iii) the development of the mathematics to simulate multiple scattering from a random array of circular disks, by deconstructing the medium into a finite number of adjacent parallel strips, primarily due to Montiel at the University of Otago with direction from the PI; and (iv), led by AI: Bennetts (Bennetts and Peter, 2013), is complementary work that may feed into the current project in due course.

Method (iii) offers great promise as a fundamental component of ice/ocean models, as illustrated by Figure 2, but also as a tool for modeling and explaining wave-ice interaction data. The next step is to reconfigure the mathematics to solve for ocean waves propagating in the MIZ as opposed to the acoustic wave solution shown. This outcome offers significant new capabilities for tracking fully directional seas through real ice fields in a physically robust deterministic way without recourse to parametrization.

IMPACT/APPLICATIONS

The primary impact of the research outcomes from this project relate to better forecasting of Arctic and Subarctic sea ice conditions, as a major deficiency in the current models being used, namely the absence of destructive ocean waves, will be overcome. Oceanic GCMs and fully coupled climate models will also benefit, for although direct ocean wave effects are unlikely to be subsumed in global scale simulations because of the models' large demands on computing resources, FSD and MIZ width can potentially parametrize the involvement of waves.

RELATED PROJECTS

The WIFAR project, http://www.nersc.no/project/wifar, led from NERSC and funded primarily by the Research Council of Norway, involved many of the scientists participating in Project N00014-131-0279 and leads directly into our project. The July 2013 wave-tank experiment mentioned above was supported by Total E&P. The SWARP (Ships and Waves Reaching Polar Regions) is a new NERSC-led project that will be funded by the European Union. It will develop downstream services for sea ice and wave forecasting in the Arctic MIZ. Each of these research programmes contributes positively and synergistically with the current project.

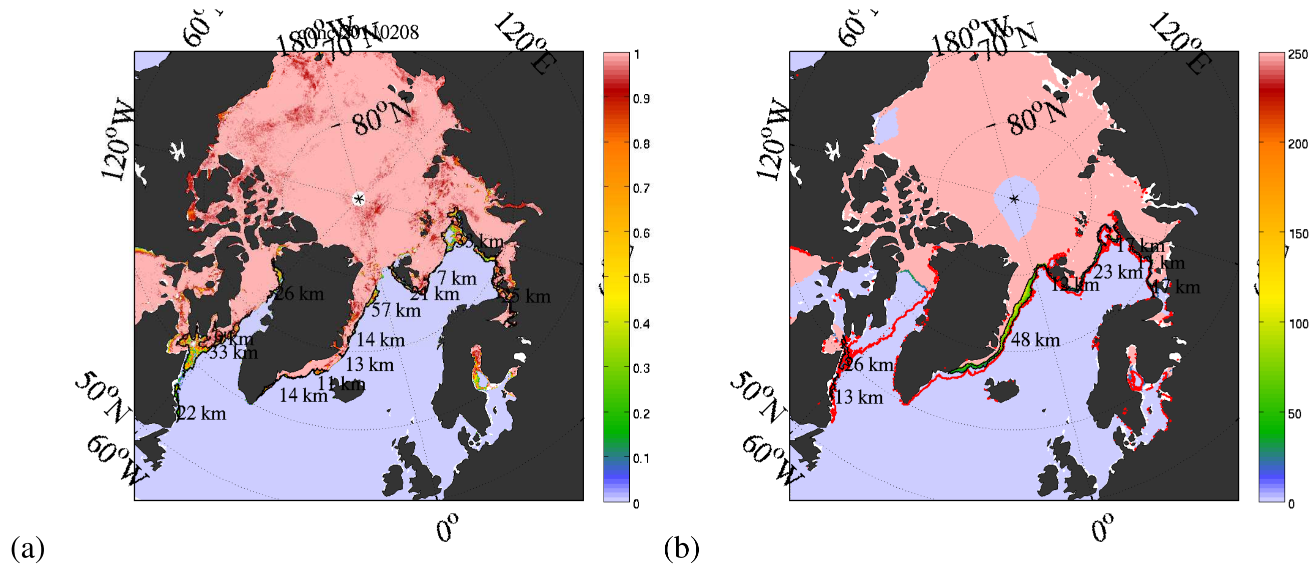

Figure 1: (a) MIZ regions from AMSR-E using 0.2 < concentation < 0.8 to define it. (b) MIZ regions defined by 0 < maximum floe size < 200 m with SMOS and AMSR-E inputs to WIFAR. MIZ width is also shown. In (b) the red boundary is the AMSR-E ice edge used as the mask, within which SMOS is used for ice thickness and AMSR-E for concentration. Waves from WAM then propagate into the MIZ for the day, starting with a (large) maximum floe size value of 250 km.

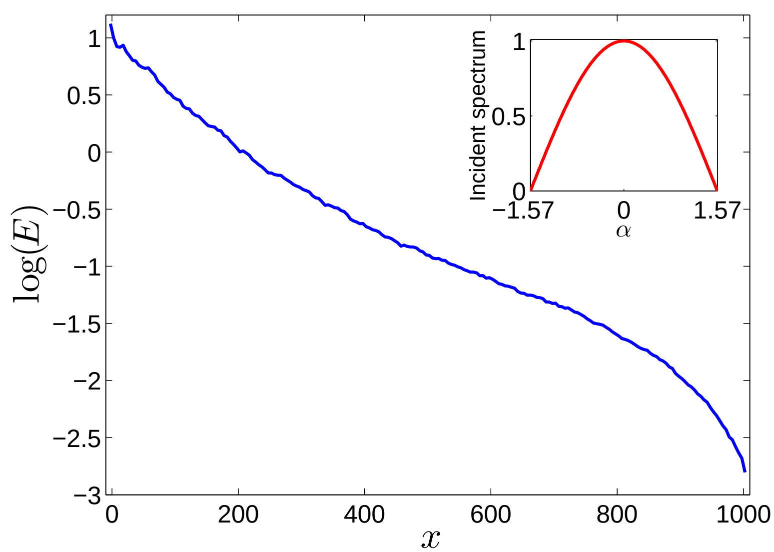

Figure 2: Ensemble average for 30 simulations of wave attenuation due to 200 parallel adjoining strips of 150 scatterers each. Inset is the directional spectrum entering the scattering medium, which is defined over $[-\pi/2, \pi/2]$. The central portion of the curve is roughly linear indicating exponential decay, and appears to become straighter as the number of scatterers is increased. The start and finish of the curve express hyperexponential behaviour because the width of the aggregated 200 slabs is finite ($0 \leq x \leq 1000$) and allows waves to leave the medium rather than being reflected back into it.

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PUBLICATIONS

The final three papers listed below were started before Award N00014-131-0279 began but completed during the tenure of the award. Each is highly relevant to the objectives of the award and is a precursor to the current work being done and longer term goals.

L. G. Bennetts and M. A. Peter. Spectral analysis of wave propagation through rows of scatterers via random sampling and a coherent potential approximation. *SIAM J. Appl. Math.*, In Press, 2013.

V. A. Squire, T. D. Williams, and L. G. Bennetts. Better operational forecasting for contemporary Arctic via ocean wave integration. *J. Offshore Polar*, 23(2):81–88, 2013.

T. D. Williams, L. G. Bennetts, V. A. Squire, D. Dumont, and L. Bertino. Wave-ice interactions in the marginal ice zone. part 1: Theoretical foundations. *Ocean Model.*, In Press, 2013a.

T. D. Williams, L. G. Bennetts, V. A. Squire, D. Dumont, and L. Bertino. Wave-ice interactions in the marginal ice zone. part 2: Numerical implementation and sensitivity studies along 1d transects of the ocean surface. *Ocean Model.*, In Press, 2013b.