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 being accomplished along the way. Consequential to the primary goal, we aim to

- develop an improved parametrization of how ocean waves and sea ice interact, for use in operational models of the Arctic Basin and the adjacent seas;
- improve the forecasting capacities of contemporary Arctic climate models.

OBJECTIVES

To make progress with our long-term goals, over the lifetime of the project we will

- further our understanding of the hydrodynamical interactions between polar oceans and sea ice, especially with regard to the marginal ice zone (MIZ), i.e. the typically 10–100 km wide mélange of ice floes that connects open sea to the interior pack ice;
- model the attenuation and spreading of directional seas within and in the waters adjoining MIZs, using a conservative, multiple wave scattering approach in a medium with random geometrical properties that can be specified by means of remote sensing data products and supplementary cognate data sets;
- devise a user-friendly parametrization of directional wave spreading in the presence of sea ice, to be integrated into operational wave and ice/ocean models, and refine the existing parametrization of ocean wave attenuation to one based on 2D multiple scattering as opposed to a 1D paradigm constrained to the primary wave vector;
- model the effect of realistic ocean wave spectra on the structural integrity of the Arctic ice cover;
- explore whether ocean waves are systematically refracted as they enter MIZs, a contemporary open question that is equivocal in current data sets;
- investigate new parametrizations for dissipative mechanical processes within the MIZ that account

for additional energy loss not captured by conservative wave scattering theory, where this has not been done by other investigators in the DRI;
- validate the efficacy of the parametrizations mentioned above using experimental data from past and upcoming field and laboratory work, as available; and
- compare the results of the wave scattering model with the published 1D viscoelastic layer and plate models that render the MIZ as a continuum, in association with Professor Hayley Shen who is a PI on the same DRI.

The work described in this report is the outcome of a collaboration between the PI, the two AIs' Bennetts and Williams, and Montiel and Mosig who are respectively the postdoctoral fellow and doctoral student on the project located with the PI at the University of Otago.

APPROACH

Two complementary methodologies to modeling the effects of ocean waves in the Arctic ice-covered ocean are actively being investigated in the 'Sea State and Boundary Layer Physics of the Emerging Arctic Ocean' DRI. The aim of the first approach is to improve the accuracy of present-day operational ice/ocean models by directly including the influential contribution that ocean waves make in reshaping the Arctic ice-covered ocean. 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, currents and the waves themselves. This dynamical process affects the proximate concentration and therefore supplements positive ice-albedo temperature feedback by bringing warmer water in contact with the decaying ice mass. In tandem, aggregated fetch length may be increased because of the incidence of more leads and polynyas, which raises the possibility of wave generation within the compass of the ice field. What is more, the very presence of this mélange of ice floes influences the way ocean waves propagate in the Arctic Ocean. Dissipative processes and scattering attenuate ocean wave spectra and modify their directional spread. Being the primary focus of the current project, we are developing innovative methods to model these phenomena for realistic wave spectra and FSDs, and are generating prototypical parametrizations of their effects for assimilation in operational models.

The second approach involves substantially improving the way in which sea ice is treated in contemporary third generation operational wave models such as WAVEWATCH® III or WAM, to remedy their existing unphysical parametrization of the action of sea ice on any infiltrating waves. Such models do not resolve phase and are referred to as spectral models. With reference to sea ice, a potential simplifying *aspiration* is to render the entire inhomogeneous ice cover as a surface-floating viscoelastic layer or viscoelastic beam which consolidates the physical properties of the ice/water continuum into a single complex compliance that affects the passage of wave energy flux (see, e.g., Wang and Shen, 2010, 2011; Mosig et al., 2015a). We contend that the magnitudes of the viscoelastic moduli are undetermined and challenging to measure because period, wavelength and attenuation must be found synchronously throughout the MIZ, which cannot be achieved with contemporary wave observation techniques. In principle, such continuum models provide a unified approach to the parametrization of ocean wave dynamics for different types of ice terrain and are therefore a prospective candidate for the 'grid cells' in operational wave models that are either partially or wholly ice-covered. Rogers (2014) has already made some progress but the main challenge will always be to find the relationship between a specific variety of ice cover, invariably observed by a satellite passive microwave or SAR sensor, and the corresponding viscoelastic moduli. Our association with this venture has involved (i) comparing Wang and Shen's 2D viscoelastic layer's predictions with a much simpler viscoelastic beam (Mosig et al., 2015a) where, recognizing that the complex compliance is a 'metaphysical' parametrization, Mosig et al. have shown that the mathematically-rich outcomes, i.e. multiple wave modes, of Wang and Shen (2010, 2011) are superfluous in the MIZ context; (ii) developing non-trivial calibration procedures for Wang and Shen's viscoelastic layer model and the simpler beam model, using wave attenuation data collected in the Southern Ocean (Meylan et al., 2014a); (iii) providing simplified code that can be embedded in WAVEWATCH® III to compare with Wang and Shen's solver, which we have done and is currently being tested; and (iv) possibly using the multiple scattering model, which can accommodate a wide range of ice covers, to 'calibrate' the continuum models.

Seeding work for project N00014-131-0279 took place during WIFAR (Waves-in-Ice Forecasting for Arctic Operators), a partnership between the Nansen Environmental and Remote Sensing Center (NERSC) in Norway and the University of Otago that partly supported one of the AIs (Williams) financially until early 2014 and resulted in two key papers of particular relevance to the current project (Williams et al., 2013a,b). Building upon the work of Williams et al., our aim is to enhance the way wave-ice interactions are absorbed into waves-in-ice models (WIMs) and ice/ocean models. Two avenues are currently being investigated that will each be included in a new 2D WIM in due course: (i) an augmented scattering model that considers the directional evolution of ocean wave spectra and their spreading due to the presence of the fragmented ice cover (Montiel and Squire, 2015a; Montiel et al., 2015b,c), from which we hope to produce a simple parametrization; and (ii) an improved parametrization of wave-induced ice breaking under realistic irregular wave spectra (Squire and Montiel, 2015; Montiel and Squire, 2015b). Our immediate plan is (i) to use legacy MIZEX data to see whether the model's predictions are in accord with the few data that are available (e.g. Wadhams et al., 1986) — plus any relevant data that arise out of the 2015 Beaufort Sea field programme, of course; (ii) to investigate refraction at the ice edge and as a continuous process within the ice cover; (iii) to develop ideas of wave-induced breakup further with the ultimate aim of creating a FSD and comparing it with observations if this is practicable; and (iv) to consider potential parametrizations of non-conservative wave-ice interactive processes that dissipate wave energy in the ice-covered ocean if work on this by colleagues requires our input. Feeding into the long-term goals of the current project, the WIM developed as part of the WIFAR project is independently also being integrated in Arctic Basin scale operational forecasting and global models by Williams at NERSC who is partly funded independently but is also supported by ONR Global on project N00014-131-0279.

Our strategy has been to develop a new 2D scattering model that replicates the way ocean waves and sea ice floes interact in Nature. The model subdivides the ice field (composed of a large but finite number of floes) into contiguous "slabs" (strips) of designated finite width running parallel to the ice edge, with each slab containing a random distribution of circular ice floes. The FSD in each slab may be generated from a random sampling of floe diameter and thickness, parametrized by ice concentration and observed statistical power law distributions. Our aim is to characterize the evolution of a monochromatic directional ocean wave spectrum fully as it makes its way in an ice-covered ocean with specified (observed) mean properties. The new *slab-clustering method* offers significant improvements in terms of computational efficiency for the solution of the multiple scattering problem, as described technically by Montiel et al. (2015b) for the analogous problem of acoustic waves interacting with many hard scatterers. It also provides a natural framework to track the evolution of directional wave properties with distance from the ice edge, as reported by Montiel et al. (2014) and Montiel and Squire (2015a), and in a substantial manuscript due to Montiel et al. (2015c) recently submitted to *J. Fluid*

Mech.; arguably the most prestigious fluid dynamics journal in the world (h5-index = 50). Therein, wave energy attenuation and directional wave spreading are characterized by estimating the angular spreading function between the slabs. Assuming, without loss of generality, that the ice edge is perpendicular to the x-axis, the directional wave spectrum may then be described by

$$E(x,\theta) = E_0(x)\mathscr{S}(x,\theta),$$

where $E_0(x)$ is the total energy and $\mathscr{S}(x,\theta)$ is the angular spreading function with unit energy. At a distance x from the ice edge, attenuation and directional spreading are given by

$$E_0(x) = E_0(0)\mathrm{e}^{-\alpha x} \quad \text{and} \quad \mathscr{S}(x,\theta) = \int_{-\pi}^{\pi} f(x,\theta,\theta')\mathscr{S}(0,\theta')\mathrm{d}\theta',$$

with $f(x,\theta,\theta')$ a function specifying the directional spreading of an arbitrary wave field in the system. In this manner, exponential attenuation of the wave energy is parametrized by a single attenuation coefficient α, similarly to the 1D scattering model. An appropriate parametrization of the function f is now also required to assimilate the effects of directional spreading in the WIM. Our current thinking consists of using the slab-clustering method for ensembles of random realizations of the MIZ defined by a prescribed FSD. Ensemble averaging then allows us to examine the way the directional content of the wave fields in the ice cover change spatially. To quantify how the waves spread within the MIZ, we use a variation on the basic directional spread parameter (see, e.g. Krogstad, 2005). Namely, for each slab q of S slabs, define

$$\sigma_1(x_q) = \sqrt{2\left(1 - r_1(x_q)\right)} \quad q = 0,\ldots,S,$$

for the normalised forward energy density at $x = x_q$, so our definition for σ_1 is the forward-only spectrum version of the standard definition in which the integrals range from $-\pi$ to π to account for the full directional range (Krogstad, 2005, Equation 2.16). The original definition of σ_1 is the standard deviation of a random variable with periodic probability density function, in this case the energy spreading function. The theoretical value of σ_1 for an isotropic field is then $\sqrt{2(1-2/\pi)} \approx 0.8525$. Simulations performed for a range of ice covers and directional forcing will be conducted to characterize the evolution of the directional spread σ_1 through the MIZ and the conditions under which isotropy is reached. This will in turn dictate a reasonable parametrization (in matrix form) for the discretized spreading function $f(x,\theta,\theta')$.

A vital aspect of the wave attenuation and directional spreading model that we have constructed is its use of circular ice floes. We justify this approximation by conjecturing that the specific shape of the individual ice floes is irrelevant to the large scale scattering behavior of a random array of randomly shaped ice floes and, as such, it can be assumed that all floes are cylindrical. This hypothesis needs to be tested, however. PhD student Mosig is investigating a new technique to describe random quantities such as shape, thickness, and the floes' elastic properties, etc., in the ice floe model directly. The method makes use of generalized polynomial chaos (gPC), as part of which the stochastic solution of the wave scattering problem with random parameters is expanded in a basis of orthogonal polynomials, with coefficients corresponding to the moments of the random solution. The governing equations can then be recast (using, e.g., the stochastic Galerkin method) as a system of deterministic governing equations to solve for these moments. The solution of the system follows from standard wave scattering techniques.

Few in situ data relating to wave-ice interactions have been collected since the MIZEX campaign of the 1980s, aside from a small number of ad hoc field experiments. This DRI and the associated 'Emerging

Dynamics of the Marginal Ice Zone' DRI include associated fieldwork that has the capacity to generate significant new data that will intersect appreciably with the modeling work that is being synopsized herein. Laboratory experiments (e.g. Montiel et al., 2013a,b; Bennetts and Williams, 2014; Bennetts et al., 2014; Bennetts et al., 2015; Meylan et al., 2014b; Meylan et al., 2015a; Skene et al., 2015b) potentially provide a rich source of data to test models. While scaling undoubtedly creates major challenges for this type of work, as phenomena observed in a wave tank may not necessarily scale up to Nature, the data sets produced are invaluable. Other laboratory experiments presently being discussed by DRI participants may aid our understanding as well, e.g. those conducted in the Hamburg Ship Model Basin.

Our theoretical advances benefit from the better technology and analysis tools now available, including those related to the field experiments supported by an intensive remote sensing program coordinated by Holt at JPL, an AI funded by NASA. We anticipate a unique set of measurements, which will expedite the validation of models generally and provide quantities for parametrizations. The approach of this effort is to utilize multiple remote sensing data sets to quantify the impact of waves on Arctic Ocean sea ice. NASA/JPL activities have been planned to align closely with modeling projects to seek the optimum and most reliable methods to quantify the impacted sea ice cover and produce analyzed fields for comparison with coupled WIMs for sensitivity testing and potential improvement of the ice parameters that go into the models. The key sea ice parameters of interest are FSD and ice morphology at < 100 m resolution, the latter essentially specifying the distribution of ridges and cracks along with thickness or a proxy such as ice type. The primary data to be utilized will be from SAR and optical sensors flown on both satellite and aircraft platforms. Holt will fill an on board science position on RV Sikuliaq to provide ship-board validation of interpreted satellite remote sensing data provided by land-based investigators. In this position, he will analyze the satellite data in comparisons to ship-based observations of ice and ocean conditions and will assist with the near-term planning of ship science observations and future satellite collections.

The full Arctic ice/ocean model built by (AI) Tim Williams and colleagues runs well, but awaits a parametrization of directional spreading of waves within the sea ice. Having now completed and submitted the overarching *J. Fluid. Mech.* paper (i.e. Montiel et al., 2015c), our focus for the immediate future after finishing some outstanding spin-off projects that arise from the Montiel et al. analysis, will be to make progress with that simplified parametrization. There is a serendipitous overlap here with another project at NERSC which also partly supports Williams, namely SWARP (Ships and Waves Reaching Polar Regions) funded by the European Union, from which each project benefits. In the context of both N00014-131-0279 and SWARP, Williams has set up a full-Arctic sea ice forecast as a practice run for a complete waves-in-ice forecast. It is based upon the TOPAZ system using the same domain, and weekly restart files from MET Norway that include assimilation. A free run is then completed daily using atmospheric forecasts from ECMWF, with 3-hourly outputs of variables that are of interest to ship navigation. A waves-in-ice forecast has also been set up using WAM forecasts provided by MET Norway for the Barents and Greenland Seas. This will be upgraded to a full Arctic domain using the WAVEWATCH® III forecasts from Ifremer in due course. Validation of the existing WIM continues, with 2 months of MIZ outlines drawn on Radarsat 2 images by Stefan Muckenhuber at NERSC, and being processed for MIZ width in order to compare with the predicted break-up from the model. A contextual paper is in press (Aksenov et al., 2015). Williams is also working on an entirely new ice/ocean model known as neXtWIM in which wave-ice interactions are elemental (see http://www.nersc.no/project/nextwim). The aim is to couple a waves-in-ice model, i.e. a WIM, with the neXtSIM sea ice model (Bouillon and Rampal, 2015), focussing on wave-induced ice drift and lateral melting. First results ‘Modeling wave-ice interactions with ice dynamics’ were presented by Williams at a floe size distribution workshop at the Scottish Association for Marine Science in Oban during July 2015.

Last year we reported that Williams and Squire (2014) had investigated wave-induced ice breakup from the perspective of building a parametrization of the length dependence of strains in a 1D ice floe. While more work is necessary, we have continued to pursue this general theme with two papers relating to ice floe breakup being presented at the *7th International Conference on Hydroelasticity in Marine Technology* in September 2015. The first investigates how the brine volume gradient between the surface and underside of the sea ice affects its rigidity and flexural strength and, consequently, the strain necessary for it to fail. The second uses the multiple scattering model developed by Montiel et al. (2015c) to investigate breaking of circular floes in an MIZ. A breaking criterion is tested for each floe in the MIZ, such that failure occurs if the maximum principal strain over the surface of a floe exceeds the theoretical breaking strain. The two approaches will be combined in an attempt to recreate an FSD observed by remote sensing tools.

Evidently, this all remains work underway towards the longer term goal of inserting the 2D WIM described above into the TOPAZ framework and neXtSIM to create neXtWIM. The WIM originally developed by Williams et al. (2013a,b) should also be extended to include additional physical non-conservative processes, which we have signalled as one of our objectives. Dissipation of wave energy in the MIZ is controlled by many nonlinear phenomena that are not represented by a conservative scattering formulation, e.g. turbulence, drag due to vortex shedding, collisions between ice floes including ridge building and rafting, overwashing near the ice edge, and sea ice inelasticity; some of which are being investigated by Bennetts (AI) and other PIs across the DRI, e.g. Professor Fabrice Ardhuin at Ifremer. Any approach will need to be a parametrization that is easily and efficiently assimilated into a WIM for inclusion in an ice/ocean model. In due course, sensitivity analyses of these models will then be conducted to generate lookup tables used in the WIM.

WORK COMPLETED

To the 30th September 2015, the following accomplishments can be reported as part of project N00014-131-0279:

- **Directional wave scattering.** A method has been developed to simulate the propagation of directional wave spectra in large random arrays of scatterers (led by the PI and postdoctoral fellow Montiel). The so-called slab-clustering scheme allows the directional properties of a wave field to be tracked deterministically through large arrays of scatterers with random sizes and locations. Due to its potential impact in several areas concerned with wave scattering (e.g. acoustics, electromagnetism, hydrodynamics), a paper describing the method for a canonical related acoustic problem has been published in *SIAM Journal on Applied Mathematics* (Montiel et al., 2015b). The method was validated by comparison with the infinite multiple-row array method of Bennetts (2011) in the case of regular arrays and Foldy’s method for mean field attenuation in random media. This canonical theory has now been developed further to the case where the scatterers are ice floes in a MIZ, as now follows.
- **3D model for wave attenuation and directional spreading in the MIZ**. A 3D model for wave attenuation and directional spreading in the MIZ due to 2D conservative multiple scattering has been devised, utilizing slab-clustering grounded in the mathematics outlined by Montiel et al. (2015b). This work has been submitted to *J. Fluid Mech.* (Montiel et al., 2015c). An example of its use is

provided in figures 1 through 5, which show how a simple monochromatic wave train with power cosine spread is attenuated and redistributed angularly as it travels through a 50-km-wide swath of thousands of ice floes. (See the figure captions for more information.) While a case study, the aim of the numerical experiment is to replicate work done at the end of MIZEX, which observed that the seas entering an ice field become directionally isotropic as they penetrate farther into the MIZ with the distance to full isotropy depending on the wave period. Of particular note is Figure 5b, which shows the distance the waves must travel to become fully isotropic. Evidently, the model at least qualitatively affirms the observations of Wadhams et al. (1986). Moreover, the analysis has also led to the major finding that the directional spread of a wave field in the MIZ increases linearly with distance from the ice edge, so a simple parametrization of this effect can be determined.

- **Model of ice break-up in the MIZ.** Ice floe break-up in the MIZ has been modelled using the 3D model of Montiel et al. (2015c). We determined qualitatively the potential for breakup in a homogeneous array of circular ice floes and found that multiple scattering decreases the likelihood of ice floe breakup and does not affect the location of breakup. Also the likelihood of breakup is enhanced close to the ice edge because of reflected wave energy but decreases with distance from the ice edge. This analysis has been published in Montiel and Squire (2015b).
- **Validation of the Williams et al. (2013a,b) 1D WIM.** The paper seeking to compare predictions from the Williams et al. model with data, led by the AI, is still underway. The intention is to validate against MIZ width and a student (Muckenhuber) has been assigned to extracting MIZ outlines from Radarsat 2 images to achieve this. Simulations have been performed over a short period in September 2013 when a ship was near the Greenland Sea ice edge with Williams aboard. The analysis is supported by two types of passive microwave imagery to provide concentration, high resolution SAR imagery, the usual atmospheric, ocean and ice inputs, plus WAM significant wave height and peak period. The SAR allows predictions of MIZ width and other parameters to be verified.
- **Experiments with supporting validations.** (i) Associate Investigator Bennetts calculated the rate of energy attenuation of the spectral components of ocean waves, with respect to distance traveled into the Antarctic marginal ice zone. He showed that the attenuation rate is functionally dependent on wave period and that the attenuation rates of short-period components depend on wave amplitude. (ii) Bennetts also designed an experimental model of wave transmission by a group of ice floes, which was conducted in a large wave basin. He used the experimental data to show that the linear scattering model accurately predicts transmission for small incident wave amplitudes and well separated floes, which is a reassuring step forward. Notwithstanding this result, he also identified the unmodeled processes of wave overwash of floes and collisions between floes, as primary sources of discrepancy between current models and data when incident amplitudes are large and ice floes are tightly packed together. These results are in concert with current thinking. (iii) Pursuing his interests in waves of larger amplitude, acknowledging the results of Young et al. (2011) which suggests a trending upwards of significant wave height globally and especially at higher latitudes, Bennetts analysed data from an experimental model of regular incident wave interactions with a solitary ice floe. He showed that the floe creates a highly irregular transmitted wave field for steep incident waves but also showed that the linear scattering model accurately predicts the flexural motion of the floe. (iv) Finally Bennetts developed the first mathematical model of wave overwash of an ice floe, testing the range of validity of the model using laboratory experimental data. These experimental campaigns with their associated models were written up as journal papers and refereed conference proceedings (Bennetts et al., 2015; Bennetts and Williams, 2014; Bennetts et al., 2014; Meylan et al., 2015a; Meylan et al., 2014a,b; Skene et al., 2015a,b; Skene et al., 2015c) and presented at conferences.
- **Continuum models.** A comparative analysis of wave propagation properties between the

viscoelastic layer model of Wang and Shen (2010, 2011) and the standard thin elastic plate model, augmented by an energy dissipative loss modulus, was completed using Mathematica by Mosig and published in J. Geophys. Res. (Mosig et al., 2015a). While all models of this kind are arguably problematical in regard to modeling MIZs composed of a collection of discrete ice floes present at some concentration, some specific issues became evident with the Wang and Shen model when the two models were provided with identical parameters as reported by Mosig et al. (2015a). As can be deduced from Figure 6, very promising results suggest that the more complicated Wang and Shen dispersion relation can be replaced by a much simpler one which is numerically expeditious to solve — especially in the deep ocean so its use in WAVEWATCH® III can be made more efficient with less code furcation. A Matlab solver based on the Mosig et al. thin elastic plate has been provided to Erick Rogers at NRL-SSC for assimilation in WAVEWATCH® III.

RESULTS

After 33 months the major outcomes from the project are

- continued modifications to the Arctic wide WIM code in association with advances relating to a new ice/ocean model known as neXtWIM in which wave-ice interactions are structural, primarily due to Williams who is a named AI on project N00014-131-0279 supported by ONR Global;
- development of the slab-clustering scheme for multiple scattering by large random arrays of obstructions, including redaction, submission and publishing of a paper (Montiel et al., 2015b), primarily due to Montiel with oversight and direction from the PI and AI (Bennetts), as required;
- development of the slab-clustering scheme for multiple scattering by large random arrays of ice floes in an MIZ, including redaction and submission of a paper (Montiel et al., 2015c), primarily due to Montiel with oversight and direction from the PI and AI (Bennetts), as required;
- a comparative analysis of the wave propagation properties of the viscoelastic layer model of Wang and Shen (2010, 2011) and an augmented standard thin elastic plate model completed and published in *J. Geophys. Res.* (Mosig et al., 2015a), primarily due to Mosig with supervision from the PI and Montiel;
- three papers presented at, and appearing in the Proceedings of, the 7th Hydroelasticity in Marine Technology International Conference, two relating to the breakup of sea ice by waves in the MIZ (Montiel and Squire, 2015b; Squire and Montiel, 2015) and one relating to further analysis of continuum models (Mosig et al., 2015b);
- a number of laboratory experiments with associated modeling done by AI Luke Bennetts and his students (Bennetts et al., 2015; Bennetts and Williams, 2014; Bennetts et al., 2014; Meylan et al., 2015a; Meylan et al., 2014a,b; Skene et al., 2015a,b; Skene et al., 2015c).

IMPACT/APPLICATIONS

There is little doubt that the massive adjustments in extent and thickness of the summer Arctic sea ice originating at least from the beginning of the satellite era are due to ice-albedo temperature feedback. Notwithstanding this, as the Arctic opens up to become more MIZ-like, it is now accepted that ocean waves will have a much greater prominence that can supplement this feedback by breaking up the sea ice to create more open water and moving ice floes about. Waves can also now be generated within the Arctic basin to a much greater extent as the aggregated fetch lengths are longer (Thomson and Rogers, 2014) and global wave heights are larger (Young et al., 2011). These considerations, together with the performance of climate models in predicting the rate of disappearance of Arctic sea ice (Jeffries et al., 2013), are fuelling considerable interest in the sea ice community.

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

SWARP (Ships and Waves Reaching Polar Regions), http://swarp.nersc.no/, is a NERSC-led project funded by the European Union FP7 programme, which now partly supports Williams, an AI on the current project, with remuneration that takes his salary to 1 FTE. SWARP will develop downstream services for sea ice and waves forecasting in the MIZ in the Arctic, integrating new met-ocean services into software for contingency planning and onboard navigation that contributes positively and synergistically to the current project. Dr Bennetts was awarded a 3-year Australian Research Council fellowship as part of the Discovery Program before attaining his permanent position at the University of Adelaide, and he has a more recent Discovery grant with Australian collaborators at Newcastle and Swinburne. These investments are also commensurate with the work of the ONR DRI.

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Talks presented by University of Otago based investigators during the reporting period

Montiel, F. Modelling the Propagation of a Directional Wave Spectrum in the Marginal Ice Zone, *22nd IAHR International Symposium on Ice*, Singapore, August 2014.

Montiel, F. Modelling waves in ice: a new approach to scattering by large random arrays, Invited plenary keynote presentation, *2014 AUT Mathematical Sciences Symposium*, Auckland, December 2014.

Montiel, F. Transmission of ocean waves through a row of randomly perturbed circular ice floes. Minisymposium on Wave Motions of Fluid-Loaded Structures and Multiple Scattering, *12th International Conference on Mathematical and Numerical Aspects of Waves*, Karlsruhe, Germany, July 2015.

Montiel, F. Hydroelastic perspectives of ocean wave / sea ice connectivity II. *7th International Conference on Hydroelasticity in Marine Technology*, Split, Croatia, September 2015.

Mosig, J. E. M. Rheological models of flexural-gravity waves in an ice covered ocean on large scales, *2014 AUT Mathematical Sciences Symposium*, Auckland, December 2014.

Mosig, J. E. M. Rheological models of flexural-gravity waves in an ice covered ocean on large scales. *7th International Conference on Hydroelasticity in Marine Technology*, Split, Croatia, September 2015.

Squire, V. A. Ongoing development of ice/ocean models and OGCMs: a case for including ocean wave interactions. Invited plenary keynote presentation, *22nd IAHR International Symposium on Ice*, Singapore, August 2014.

Squire, V. A. Perspectives of ocean wave / sea ice connectivity relating to climate change and modelling. Invited plenary keynote presentation, *Royal Society of London Conference on Arctic Sea Ice Reduction: the Evidence, Models, and Global Impacts - Further Discussion*, Chicheley Hall, Buckinghamshire, UK, September 2014.

Squire, V. A. Hydroelastic perspectives of ocean wave / sea ice connectivity I. *7th International Conference on Hydroelasticity in Marine Technology*, Split, Croatia, September 2015.

Squire, V. A. How ocean wave spectra proceed through fields of sea ice, a new model. Invited session talk. *The Mathematics of Sea Ice*, Pacific Institute for the Mathematical Sciences, Vancouver, Canada, September 2015.

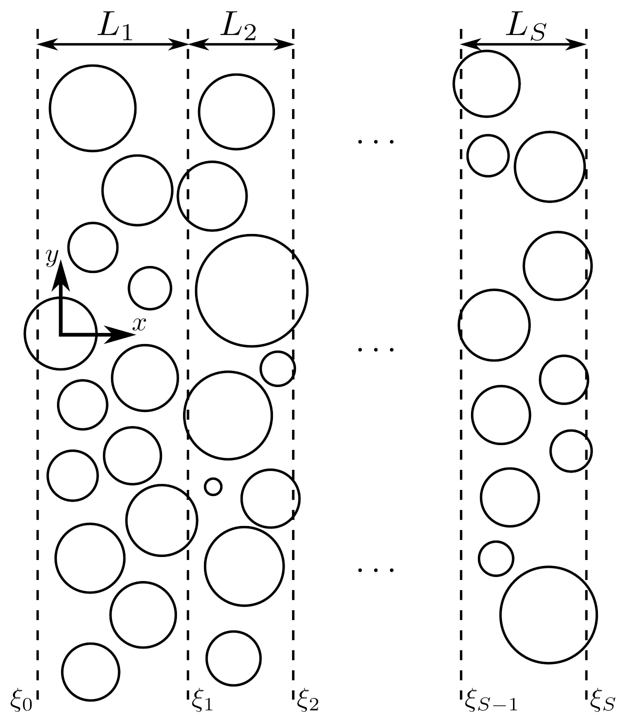

Figure 1: Schematic of the geometry in the horizontal plane.

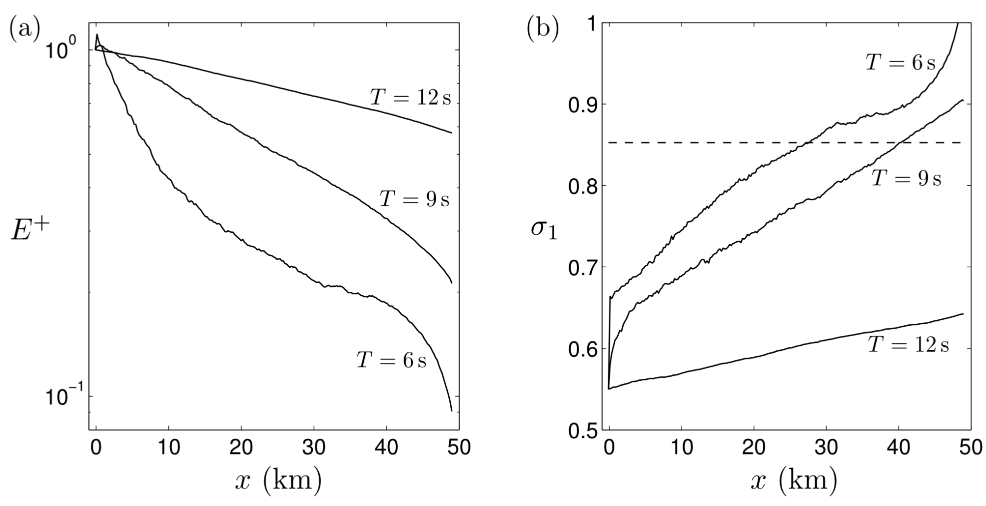

Figure 2: (a) Ensemble average of the forward propagating wave energy and (b) the directional spread σ_1 through approximately 50 km of simulated MIZ for 6, 9 and 12 s period waves. The dashed line in panel (b) corresponds to the theoretical value of σ_1 characterizing an isotropic directional wave field.

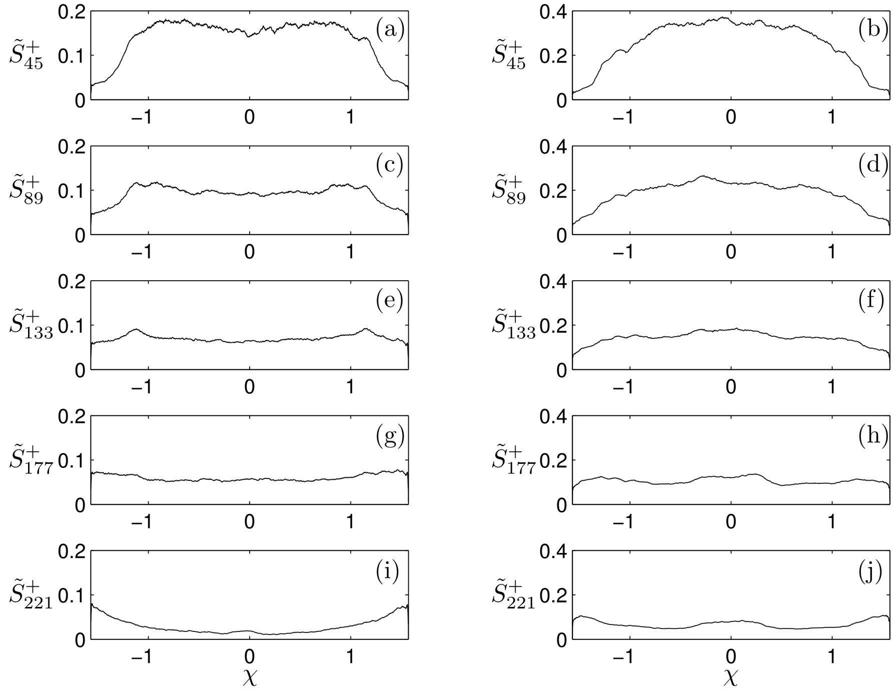

Figure 3: Ensemble average of normalised forward energy density function for 6 s (left panels) and 9 s (right panels) wave period. The energy densities are plotted at approximate penetrations of 10, 20, 30, 40 and 50 km.

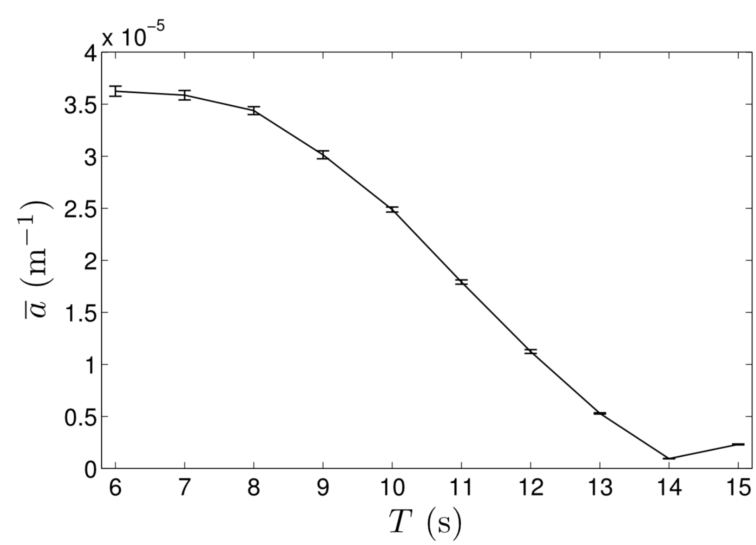

Figure 4: Wave energy attenuation coefficient as a function of wave period in the range 6–15 s.

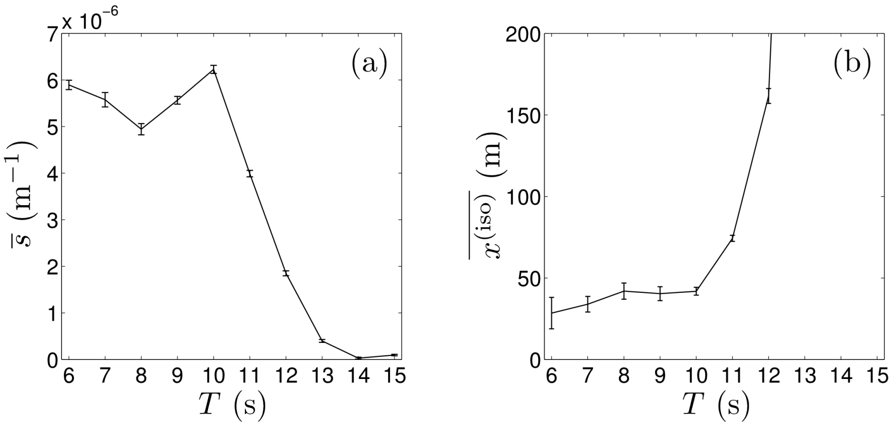

Figure 5: (a) Rate of directional spreading as a function of wave period in the 6–15 s range (b) Distance to isotropy plotted over the same range of wave periods.

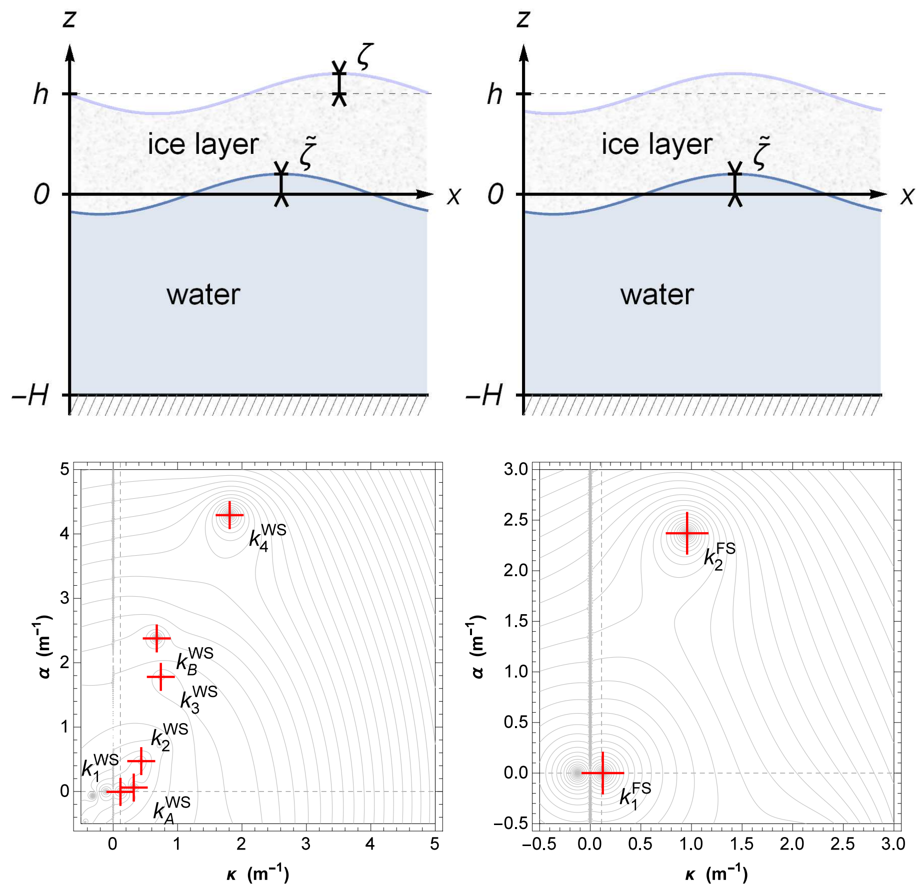

Figure 6: The upper two plots show the two continuum models being compared; a viscoelastic layer (Wang and Shen, 2010) (left) and a (parsimonious) Euler-Bernoulli viscoelastic beam (Mosig et al., 2015a). The lower two plots show the roots in the first quadrant of the complex plane for the two continuum models. While both models give very similar results for the primary propagating wave, designated k_1^{WS} and k_1^{FS} respectively, field measurements of dispersion and attenuation can readily be inverted (algebraically) to get the material constants for the beam but this is not so for the viscoelastic layer because of the large number and nearness of roots.