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Modeling Wave-Ice Interactions in the Marginal Ice Zone

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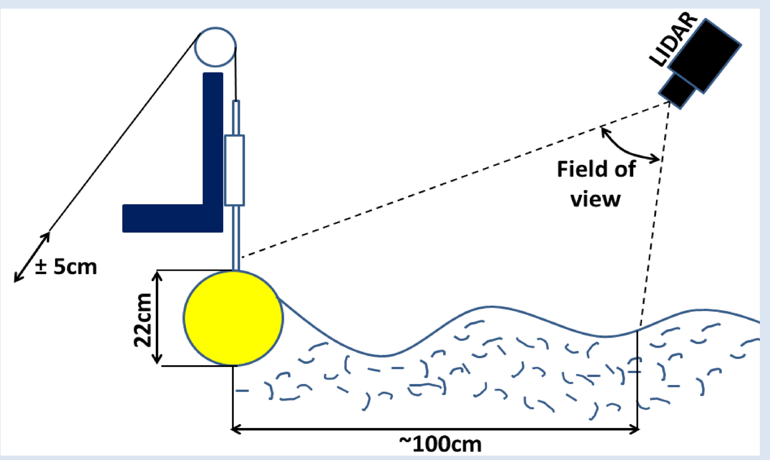
Summary: The small-scale (O(m)) interactions between waves and ice floes in the marginal ice zone (MIZ) are investigated with a coupled model system. Waves are simulated with the non-hydrostatic finite-volume model NHWAVE (Ma et al., 2012) and ice floes are represented as bonded collections of smaller particles with the system LIGGGHTS (Kloss et al., 2012), based on the discrete element method (DEM). The physics of fluid and ice are recreated as authentically as possible, to allow the coupled system to supplement and/or substitute for more costly and demanding field experiments. Here we describe development and validation of the coupled system, present preliminary results, and discuss an upcoming series of virtual experiments in which ice floe and wave characteristics will be varied to examine effects on energy dissipation, MIZ floe size distribution, and ice pack retreat rates.

Although Wadhams et al. (1986) suggest that only a small portion (roughly 10%) of wave energy entering the MIZ is reflected, dissipation mechanisms for the remaining energy have yet to be delineated or measured. The coupled system is designed to focus on specific small-scale properties and processes – such as floe size and shape, collision and fracturing events, and variations in wave climate – measuring their relative roles the transfer of energy and momentum from waves to ice.

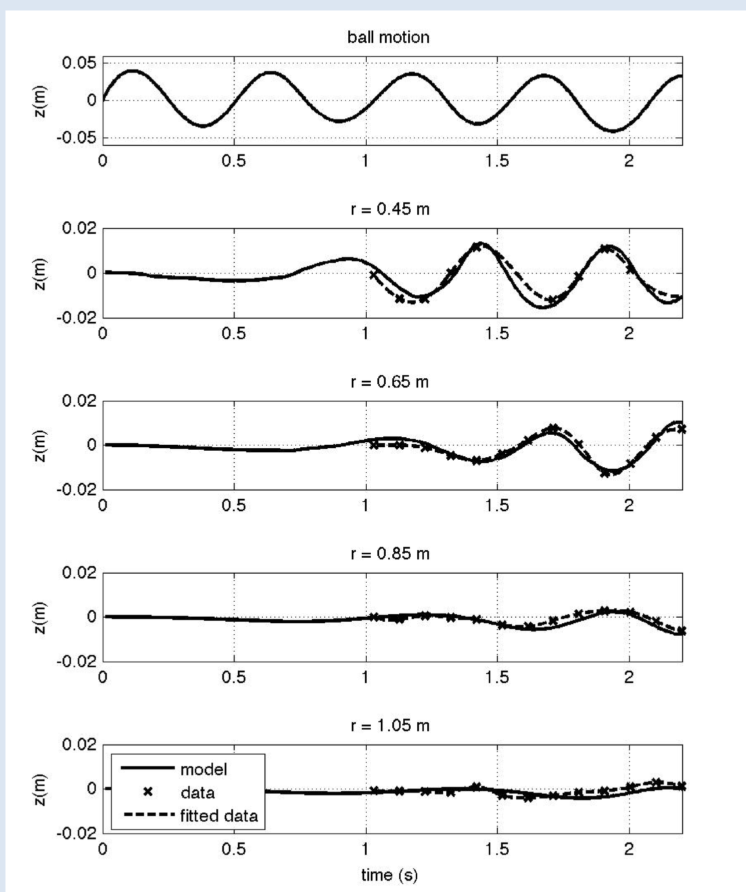
Validation: Waves



Lab Experiment Setup

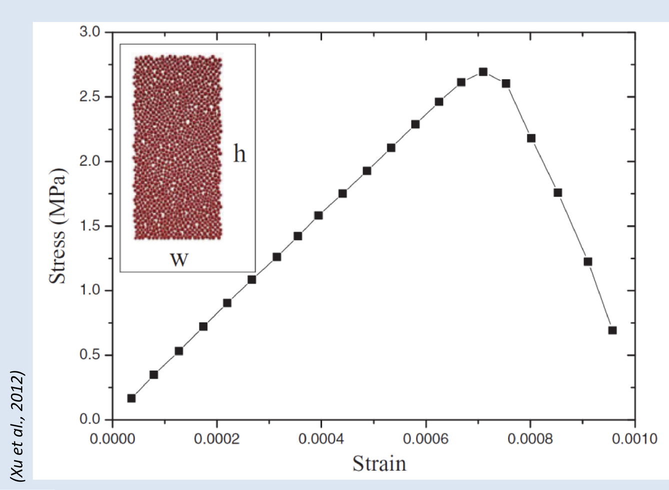
Wave model output is validated by comparison with a lab experiment. A sphere is vertically oscillated in a cylindrical water tank, and its motion is tracked by LIDAR (at left).

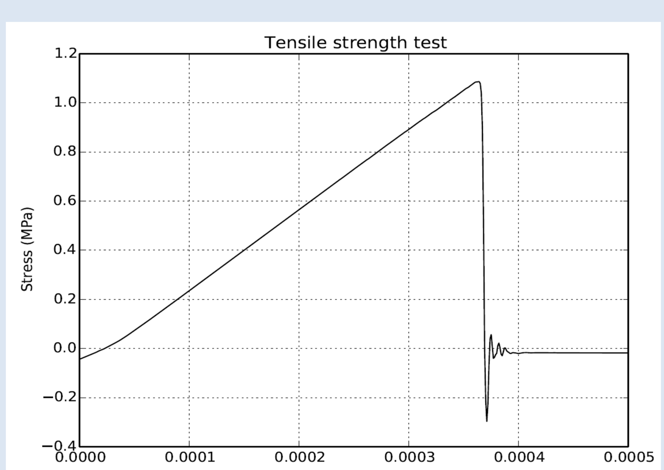
This setup is duplicated in NHWAVE, and time series of measured/computed water surface elevation are compared at multiple locations (right). Model performance is reasonable, although neglect of shear and LIDAR averaging likely play a role in overall error.



Validation: DEM Ice

Ice model bonding parameters are initially validated by comparison with 2D modeling results from Xu et al. (2012). A tensile stress (max: 2.7kPa) is applied to a block of bonded elements with k_n=60GPa/m. The Xu et al. stress-strain curve shape (below left) is reasonably reproduced by our simulation (below right). Additional validation/calibration of the DEM ice model will be obtained by comparison to results from a range of experiments (Timco & O'Brien, 1994).

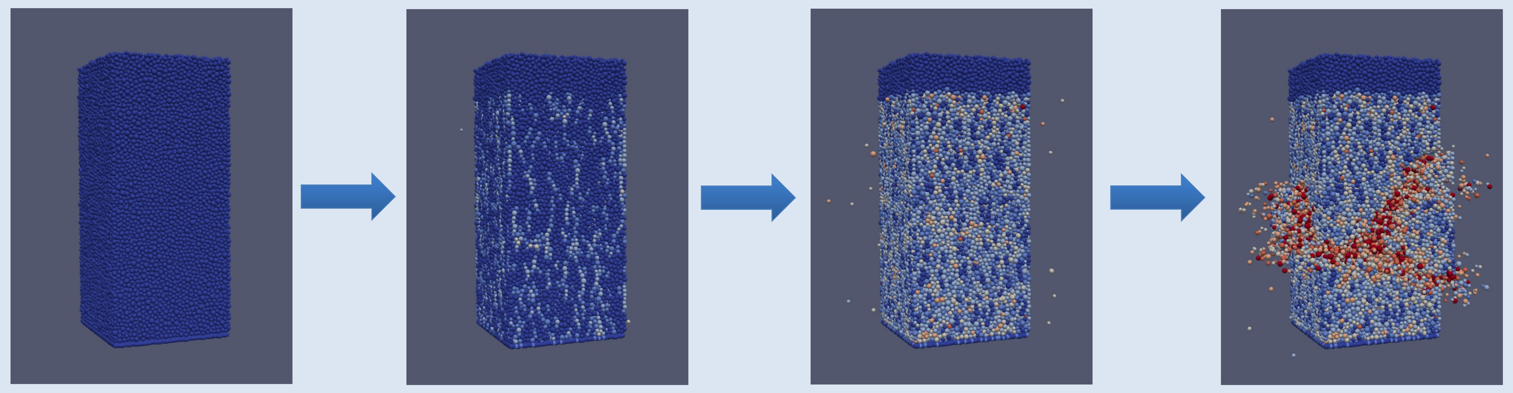




Preliminary Simulations

Ice Compression Test (uncoupled)

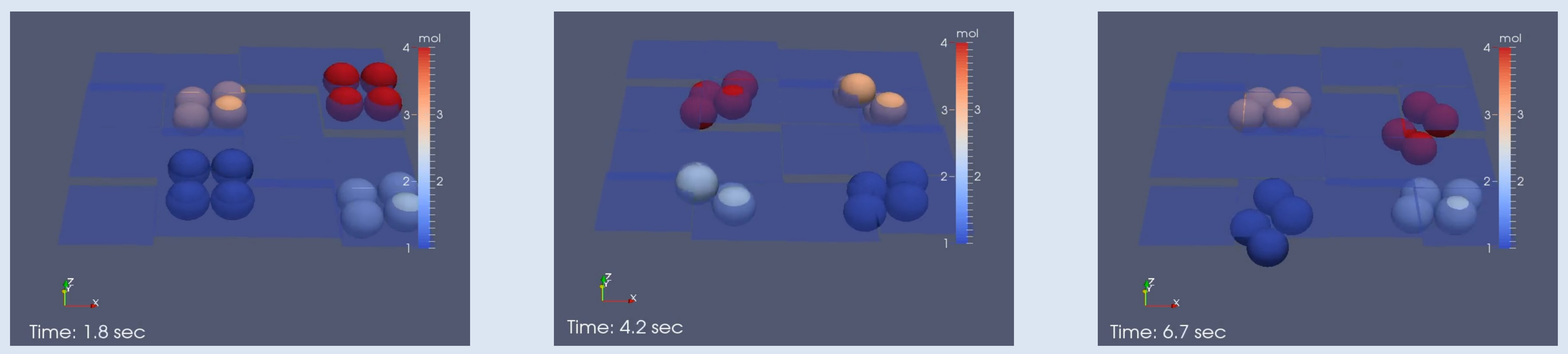
Panels below show simulation results from a uniaxial compressive strength test using a 31 m^3 block of ice, composed of 53,838 particles with a distribution of diameters, D = 0.1 ± 0.025 m. For the test shown, the block of ice was compressed at a strain rate of 10^{-3} s^{-1} using a critical bond stress of 0.001 E, where E is the Young's modulus. The large bond forces required a small numerical time step, $\Delta t = 10^{-6}$ s. The particles are colored by the number of broken bonds, from 0 (blue) to 6 (red).



(a) t = 0.0 sec (b) t = 1.0 sec (c) t = 1.8 sec (d) t = 2.0 sec

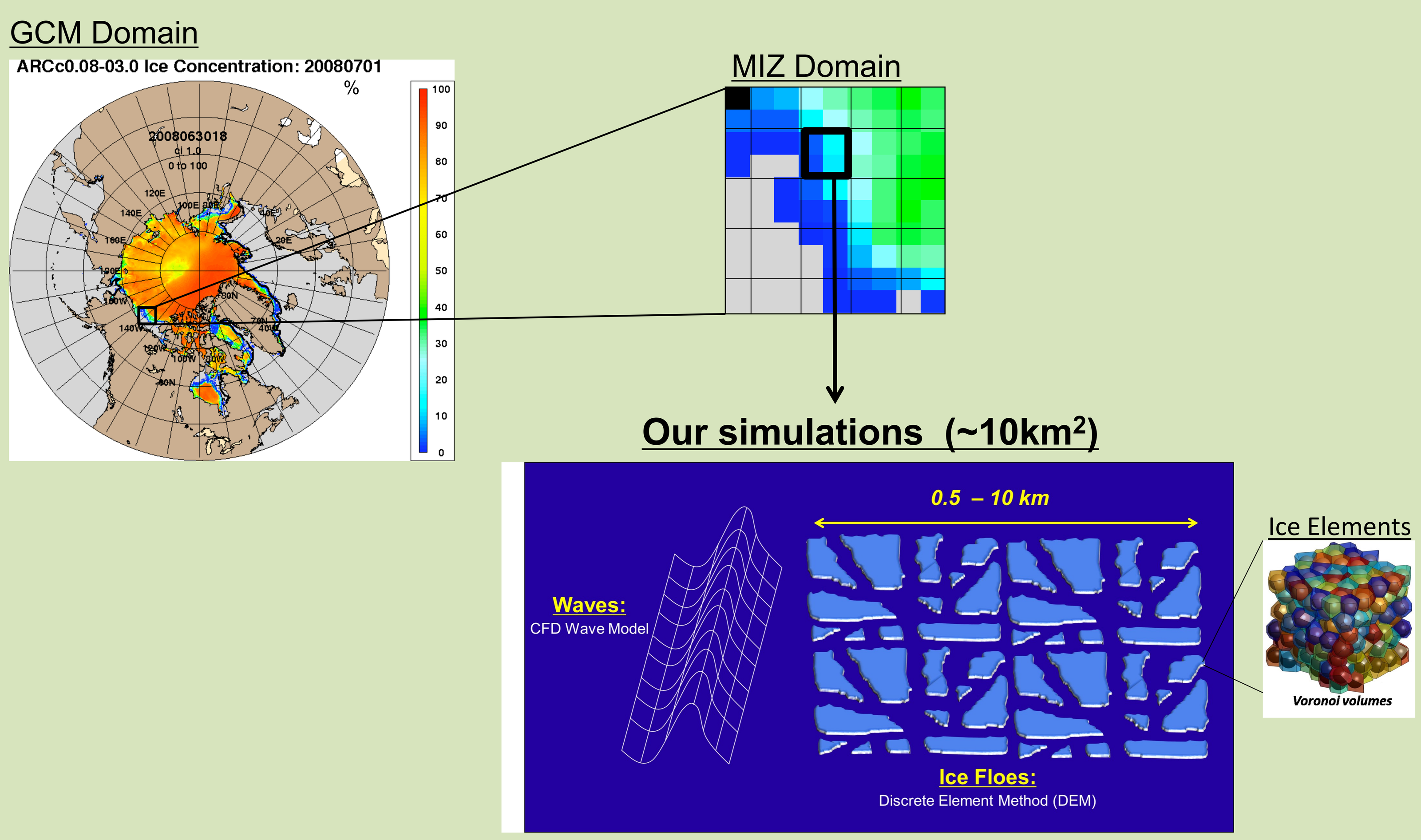
Waves and "Ice Cubes" (coupled)

Coupling software is tested in preliminary simulations with a simplified wave-current model coupled to the LIGGGHTS system to track the motion of groups of four bonded particles. Sample frames from a ten-second test run are shown below. The particle groups translate in response to the current and pitch and roll in response to the wave motion.



Perspective: Model Scales

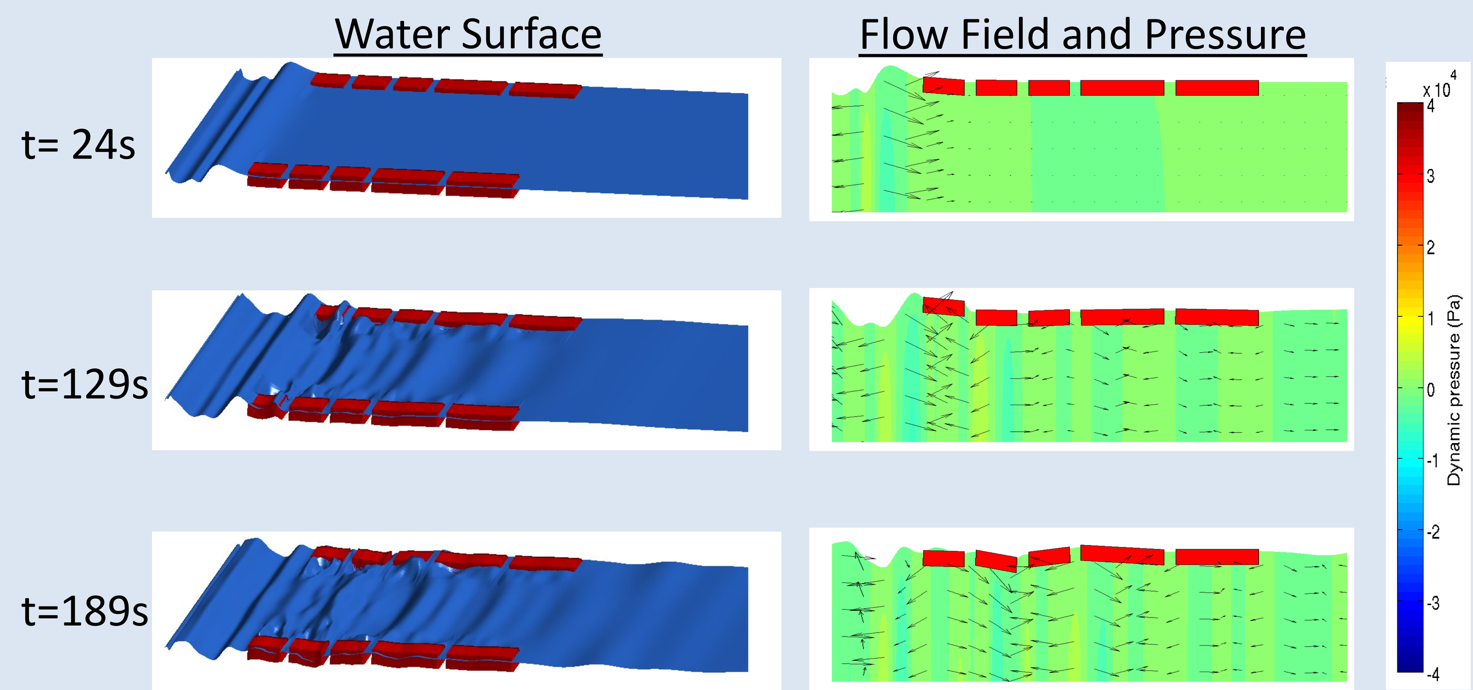
Domain size is limited to a maximum of 10 km^2; i.e., roughly one grid cell of a large-scale general circulation model (GCM) such as Arctic Cap (ACNFS).



Partially Coupled Tests

A. Wave-to-DEM Test: The following figures show four small (12m x 2.5m x 0.5m) ice floes, each composed of roughly 10k DEM elements, subjected to waves generated by an oscillating point source in NHWAVE. Water surface elevation and velocities are passed to the DEM, but DEM ice data are not used by the wave model. Floes both diverge and collide in response to the waves (NB: vertical dimension is exaggerated).

B. Wave Mask Test: The following figures show results of a test in which ten rectangular, 1m-thick ice floe "masks" of varying lengths (200-400m), with a large gap between them, are subjected to randomized wave oscillations. Each floe is artificially created within wave model only; DEM is not used. Water surface, pressure, and flow field data are tracked at each time step of the simulation. Wave energy is greatly reduced by interaction with the floes and shifts toward lower frequencies, as expected.



Planned Virtual Experiments

The virtual experiments will combine the DEM particle tracking (**A** above) with the wave model fluid cell data by translating particle data into wave model "masks" (**B** above). For each experiment, energy dissipation in the ice floes will be tracked by LIGGGHTS, including floe deformations and fracturing, collisions/scraping, and surface drag. Energy losses by the waves, as well as reflection, refraction, and diffraction effects, will be recorded throughout the model domain by NHWAVE.

1. Floe surface area: Vary the percentage of water surface covered by ice floes from 10–90%.
2. Floe dimensions: Length and width of floes varied from 10—1500m. Floe thickness varied from 0.5—2.0m.
3. Wave properties: Wavelength L_m=40—1400m, Wave period T_m=5—30sec, Height H_m=1—10m.
4. Floe material strength: Weak → Strong first-year ice; varied stress response

Questions to be examined:

- How is energy dissipated by ice floe collisions, fracturing, and drag, and how significant is the wave attenuation associated with each process?
- Do specific wave/floe length scale ratios cause greater wave attenuation?
- How does ice material strength affect the rate of wave energy loss?

The coupled system will ultimately be used to test and improve upon wave-ice parameterizations for large-scale climate models.

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