

Evaluating the Discrete Element Method as a Tool for Predicting the Seasonal Evolution of the MIZ

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LONG-TERM GOALS

The goal of this work is to evaluate the utility of the discrete element method (DEM) in (a) advancing the understanding of the dynamic and thermodynamic processes governing the seasonal evolution of the marginal ice zone (MIZ) and (b) forecasting conditions in the MIZ in support of an anticipated increase in operational requirements.

OBJECTIVES

To achieve this goal we will address the following objectives:

- Initialize DEM using high-resolution satellite-borne imagery.
- Assimilate atmospheric and ocean models results to provide sea ice dynamics forcing, i.e. one-way coupling of the wind and ocean surface stresses that induce ice motion.
- Conduct a sensitivity study to understand the effects of the temporal and spatial variability of the surface stress fields to icepack evolution.
- Evaluate the DEM's effectiveness in simulating the seasonal evolution of the floe size distribution by comparing the DEM model results with imagery and other sea ice models, e.g. NRL's NAVGEM/HYCOM/CICE forecast system.

APPROACH

The discrete element method (DEM) is a numerical approach that describes a medium as a collection of small parcels of material, or elements, and the mechanical behavior as the result of the element-to-element interaction governed by prescribed contact laws or mechanical bond models. Sea ice is a spatially heterogeneous material that is riddled with discontinuities in the form of cracks and leads, therefore a modeling approach that can explicitly describe discontinuities and variation physical properties at fine scales is well suited to model sea ice dynamics at high spatial resolutions (sub kilometer scale). The DEM has been successfully applied to model sea ice processes such as pressure ridging (Hopkins 1998), aggregation due to wave-ice interaction (Hopkins & Shen 2001), and the mesoscale evolution of the floe size distribution (Hopkins & Thorndike 2006).

This modeling effort will leverage the work of Richter-Menge and Perovich (ONR Project, "The Seasonal Evolution of Sea Ice Floe Size Distribution") and Polashenski (ONR Project, "Remote

Sensing of Meter-Scale Sea Ice Properties”), where both projects are compiling a library of high-resolution remote sensing imagery and developing sea ice classification algorithms to examine the role of winter preconditioning of the ice on summer floe breakup and to identify meter-scale sea ice features, e.g. melt ponds. Specifically, we will use the imagery collected under these projects to (a) initialize the CRREL DEM and (b) evaluate the model’s ability to accurately simulate the seasonal evolution of the floe size distribution. A key resource will be the imagery acquired as part of the ONR MIZ and Sea State DRIs, via the MEDEA/National Security and Climate Change Research Program and the Center for Southeastern Tropical Advanced Remote Sensing (CSTARS).

Using the satellite-borne high-resolution imagery, we will define the initial spatial distribution of open water, ice cover and ice thickness in the DEM model’s simulation domain. For instance, we will apply several image processing techniques, e.g., minimum distance filtering, texture filtering, etc., to identify floes, ponds, and open water. Linear flaws will be assumed to be regions where the gradient of the surface roughness distribution is relatively high-valued, then incorporated into the DEM’s initial condition as weaker, i.e. thinner, ice bonds.

Weather and ocean circulation models from several sources will be used to force the DEM sea ice dynamics. These sources will include, but will not be limited to, the NCEP’s Global Forecast System (GFS), the US Navy’s Global Environmental Model (NAVGEM), and the community developed Weather Research and Forecasting Model (WRF). The CRREL DEM model will be run in an ensemble fashion where perturbations will be applied to the wind fields according to uncertainty estimates in either the simulated or measured values allowing the DEM model to generate probabilistic ice concentrations and trajectories.

To evaluate the CRREL sea ice DEM’s ability to simulate the observed evolution of the seasonal MIZ, we will compare the results from the model with a time series of the available satellite imagery. Image analysis from the existing Richter-Menge and Perovich, and Polashenski projects will provide a more detailed and quantitative comparison of the evolution of floe properties, to include floe size, area fraction and floe perimeter.

WORK COMPLETED

To date we have:

- Developed capability to initialize the DEM model ice geometry using the Multisensor Analyzed Sea Ice Extent (MASIE), sea ice concentration maps derived from SMMR and SMM/I-SSMIS passive microwave sensors, and ice thickness estimates derived from CICE model runs. We anticipate that assimilation of ice thickness estimates derived from CryoSAT measurements will be straightforward and will be part of the tasking for this year.
- Developed capability to assimilate high-resolution visible imagery that delineates ponded areas and performed numerical experiments to understand how weaknesses introduced by the formation of ponds affect bulk mechanics.
- Examination of several filtering techniques to classify Radarsat-2, TerraSAR-X, and Cosmo-SkyMed SAR images, in conjunction with the ONR-funded project, “Remote Sensing of Meter-Scale Sea Ice Properties” (PI – Polashenski). The backscatter intensity based segmentation creates several image classes that are subsequently manually grouped into aggregate ice and water superclasses. These segmented images will then used to initialize the DEM ice geometry.
- Continued coordination with an in-house weather forecasting team to provide WRF atmospheric forcing output for assimilation in the DEM model.

RESULTS

Image processing and classification:

This is not the primary goal or tasking for this project, however, image processing of sea ice SAR imagery is an ongoing area of research, so processed imagery of the Arctic is not always readily available. We are working with several PIs that are processing imagery as their primary focus (Richter-Menge {CRREL}, Polashenski {CRREL}, and Hwang {SAMS}) and will assimilate products that emerge from these projects as they become available. Our efforts in this area is mainly to expedite model development effort, which is the primary focus of this project and we report the image processing results as another perspective into this challenging problem.

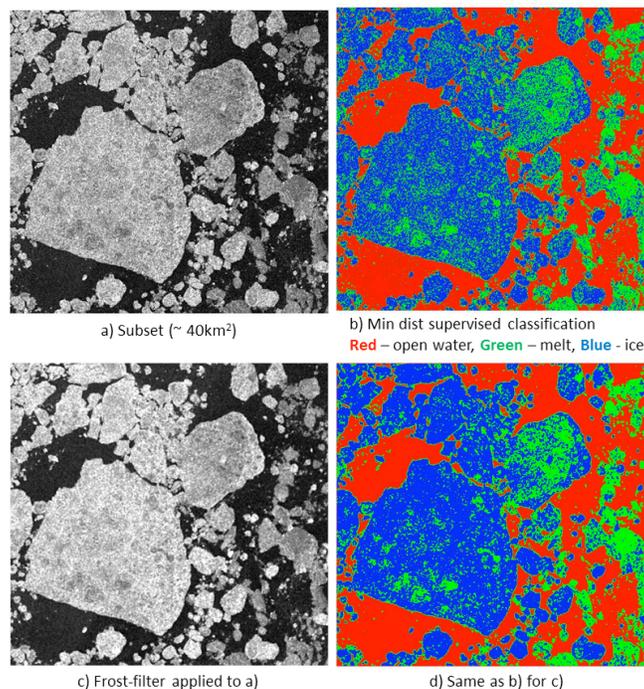
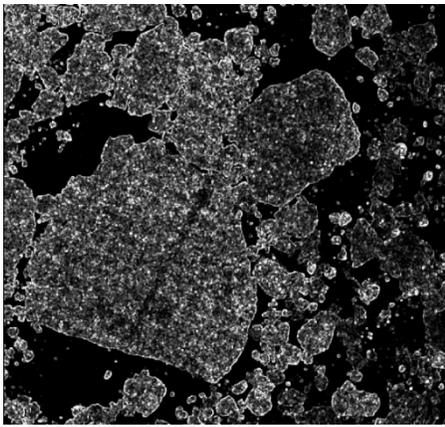
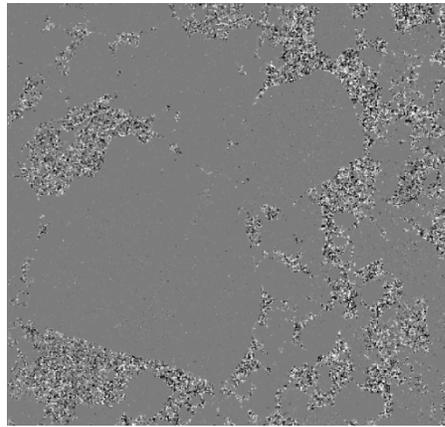


Figure 1. Segmentation of TerraSar-X image using a supervised minimum distance classifier. For this example subset image, this type of segmentation appears to work well to classify areas of bare ice, ponds, and open water. This approach requires user input for classifier training and is an intensity based method that is prone to error when the class-specific pixel intensity distributions overlap.

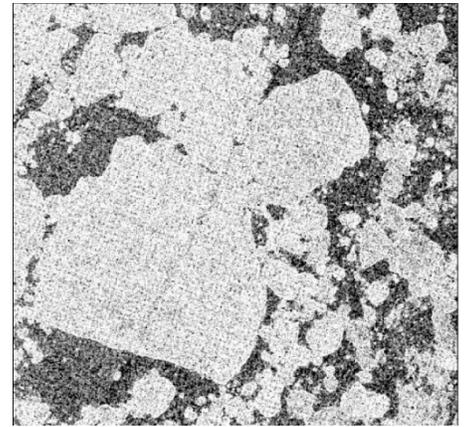
We applied several filtering techniques to a sample TerraSAR-X Multi-look Ground Range Detected image. This SAR product that reprojects the images from slant to ground range using the WGS84 ellipsoid and multi looks the pixels to reduce speckle and output an image with square pixels. Figure 1 illustrates the classification results using a supervised minimum distance classifier. As part of the supervision, the analyst selects pixels from each class, and then the image is segmented accordingly. For this particular image, the classifier works relatively well with some improvement when the image is preprocessed with a Frost filter to further reduce speckle. Our goal for this side effort was to develop an automatic image processing workflow for these images, so although the results were promising, the need for analyst input was not satisfactory. In addition, this method is



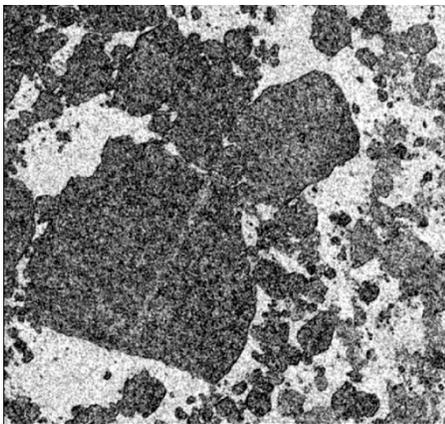
(a) Occurrence: Variance



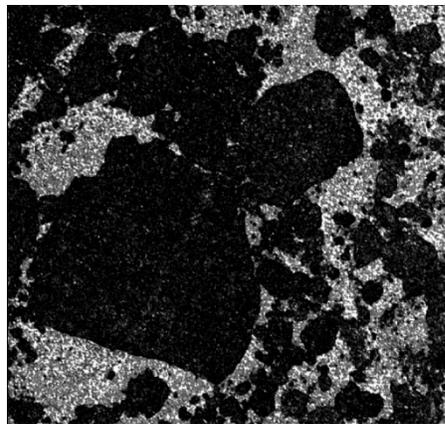
(b) Occurrence: Skewness



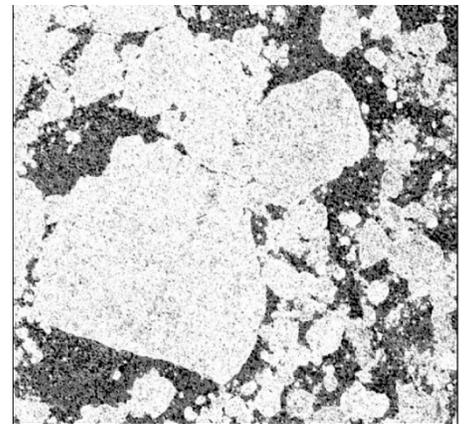
(c) Occurrence: Entropy



(d) Co-occurrence: Homogeneity



(e) Co-occurrence: 2nd moment



(f) Co-occurrence: Entropy

Figure 2. Occurrence and co-occurrence filters applied to SAR imagery. The ice and water tended to separate out relatively well when applying texture filters to the SAR images, especially when the measures included directionality, e.g. in (f) where the directional entropy is calculated.

essentially an intensity thresholding method that determines the boundary between classes, e.g., the ice-ocean interface, with the assumption that the separation between the mean intensity of each class is large with respect to the variance of the respective intensity distribution of each class. This assumption is not generally the case especially for spring conditions when the first-year ice is relatively smooth making the determination ice versus water ambiguous. We have applied occurrence (isotropic) and co-occurrence (oriented) filters to the image (as illustrated in Figure 2) to demonstrate how texture information (both isotropic and oriented) could enhance the classification of SAR images. This is in the preliminary stages, but the results using the co-occurrence values show promise, which indicate that there is significant contrast between the directionality of the roughness features of sea ice and the water surface.

DEM sea ice model:

The Arctic sea ice cover, especially at fine spatial length scales, is heterogeneous and is riddled with a network of mechanical discontinuities in the form of cracks, linear flaws, and areas of open water. In addition, heterogeneities in the mechanical properties manifest where meltwater collects into ponds.

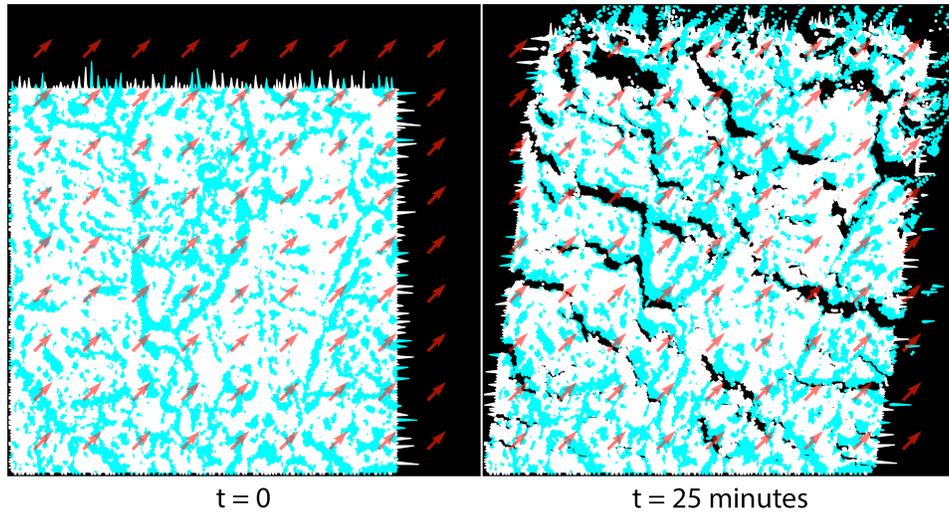


Figure 3. The simulated break up of ponded ice. The DEM ice configuration was initialized from high resolution visible imagery from August 2014. The bare ice is colored white and the ponded ice is cyan. The bottom of the domain is fixed and the ice is subjected to a stress indicated by the red arrows. The lines of fractures tend to be perpendicular to the principal stress direction indicating that failure happens primarily in tension and initiates at the pond boundaries.

Due to the lower albedo of the ponded regions, the underlying ice tends to be warmer and more porous, therefore is weaker than the surrounding ice. We conducted numerical experiments to examine the effect that this type of heterogeneity has on the breakup dynamics, namely the floe size distribution.

For these numerical experiments, the ice configuration for the DEM model was initialized using high-resolution visible imagery sourced from the USGS Global Fiducials Library. The image was acquire on August 11, 2014, so the ice in the image was heavily ponded. We selected a representative subregion with an area of 25 square kilometers; the DEM model had a spatial resolution of 2 meters. The tensile and compressive strength of the ice was determined as a function of porosity according to Timco & Weeks (2010). The differences in porosity can be seen visually in Figure 3 as the regions white and cyan regions indicating stronger (low porosity) and weaker (high porosity), respectively.

Assuming that cumulative number distribution follows a power law with the form:

$$N(D) = \beta D^{-\alpha}$$

where the floe diameter, power law exponent and power law scale parameter are denoted by D , α , and β , respectively.

illustrates evolution of the cumulative number distribution as the ice domain is forced with a surface stress that applies shear and tension in the sample geometry. Shortly after the forcing is turned on, the distribution initially has an exponent value near 1.5 and quickly and steadily decreases as more of the intact ice is broken up into floes at the larger end of the distribution. As one would expect, the total number of floes steadily increases in tandem as indicated by the trend in the scale parameter, β . Tasking for the next fiscal year will be a more in depth suite of numerical experiments to examine how the different patterns of heterogeneity affect the evolution of the floe size distribution and the rheological parameters of a computational domain sized to be similar to climate model grid resolutions.

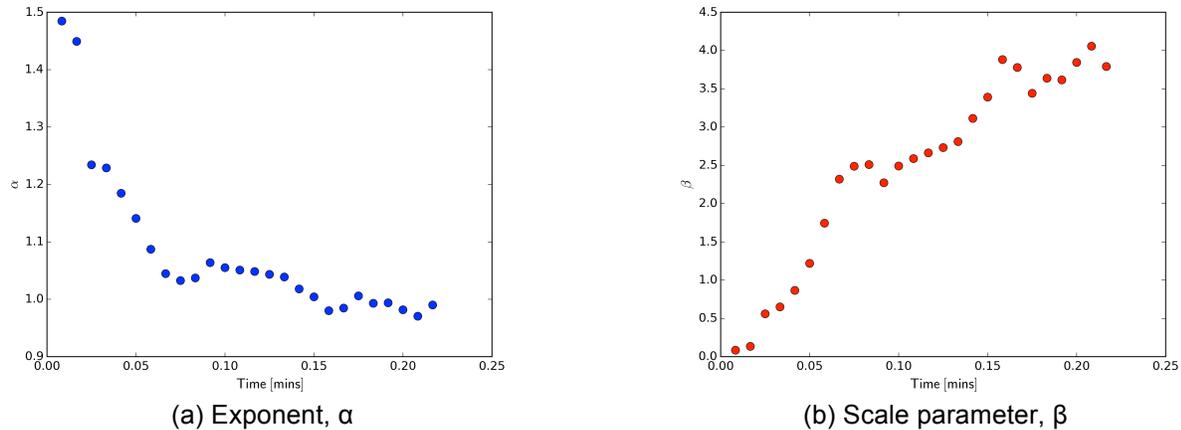


Figure 4. Cumulative number distribution evolution. These plots illustrate how the cumulative number distribution evolves as the ice cover transforms from an intact sheet to collection of smaller floes.

IMPACT/APPLICATIONS

The profound changes that occur in the appearance and morphology of the Arctic sea ice cover over an annual cycle are the result of thermodynamic and dynamic processes. Due to the high degree of variability in the composition of the ice cover, these processes can vary on a floe-to-floe basis. Further, the relative significance of the thermodynamic versus dynamic processes varies during the course of the transitional season and as a function of distance from the ice edge. It makes intuitive sense, then, that a model designed to capture these details at the floe scale would be an effective tool for investigating the governing processes and forecasting ice conditions. We are interested in testing this hypothesis by evaluating the abilities of the existing CRREL sea ice DEM to simulate the evolution of the ice cover as observed during the ONR MIZ and Sea State field projects.

RELATED PROJECTS

- CRREL: Richter-Menge and Perovich: “The Seasonal Evolution of Sea Ice Floe Size Distribution”, Funded by the Office of Naval Research.
Polashenski: “Remote Sensing of Meter-Scale Sea Ice Properties”, Funded by the Office of Naval Research.
We will be using satellite imagery collected as part of these projects to provide information about the initial configuration and condition of the ice cover for the DEM model.

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PUBLICATIONS

Arntsen, A.E., Song, A.J., Perovich, D.K., and J.A. Richter-Menge (2015), Observations of the summer breakup of an Arctic sea ice cover, *Geophys. Res. Lett.*, 42 [published, refereed]