Discrete Element Model for Sea Ice

The DEMSI Team

LANL, SNL, NPS

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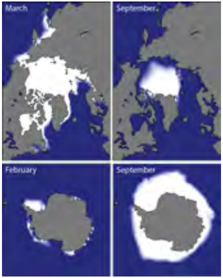
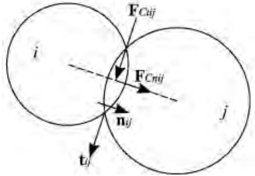
- **Develop a Discrete Element Method (DEM) sea ice model suitable for global climate modeling**

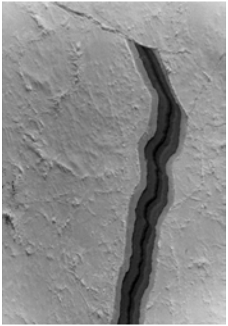
- Sea ice is the frozen surface of the ocean at high latitudes
  - $\sim 7\%$ Earth surface, $\sim 12\%$ of ocean surface
  - Highly reflective $\rightarrow$ major impact on global climate
  - Very thin shell (few m vs 10^3 km) $\rightarrow$ 2D dynamics problem
  - Motion from winds and currents is resisted by internal strength of ice



Discrete Element Method

- Regions of sea ice modeled as particles
- Previous models assumed continuous viscous-plastic material
- Allows complex physical contact laws, e.g. explicit fracturing
- Project goals:
  - Better representation of sea-ice dynamics: spatial/temporal scaling, dispersion, intermittency, heterogeneity, anisotropy
  - Better utilization of heterogeneous computer architectures





DEMSI

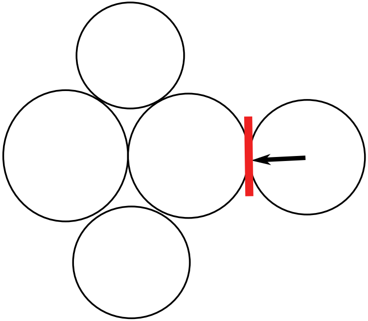
- Circular elements to start (speed)
- Each element represents a region of sea ice, and has its own ice thickness distribution (initial resolution $>$ floe size)
- *Dynamics*: **LAMMPS**
  - SNL particle based molecular dynamics code
  - Built in support for DEM methods including history dependent contact models
  - Computationally efficient with massive parallelization
- *Thermodynamics*: **CICE consortium Icepack library**
  - State-of-the-art sea-ice thermodynamics package
  - Vertical thermodynamics, salinity, shortwave radiation, snow, melt ponds, ice thickness distribution, BGC

Major Project Challenges

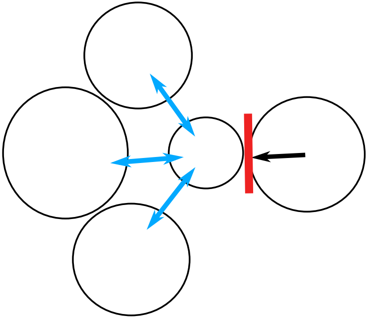
- Element contact model
- Coupling
- Element creation and destruction
- Performance

Element creation and destruction

- Convergence of sea ice results in the formation of a pressure ridge – Sea ice build up on Canadian Archipelago
  - Sea ice area is converted to sea ice thickness while mass is conserved
  - Model elements will decrease in area during simulation
  - Decreases time step, add artificial strain



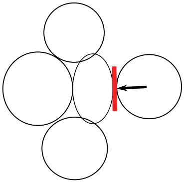
Convergence and ridge formation of two elements in pack



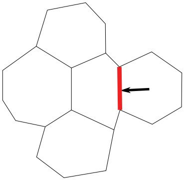
Shrinking of element adds strain to the pack

Element creation and destruction

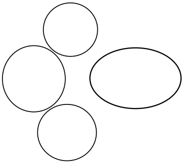
- Possible solutions – Ellipses, Polygons, Merging, Remapping, Transference



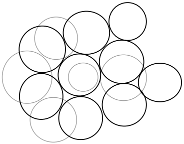
Use elliptical elements



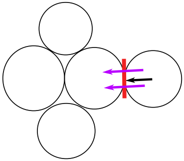
Use polygonal elements



Merge elements that get too small



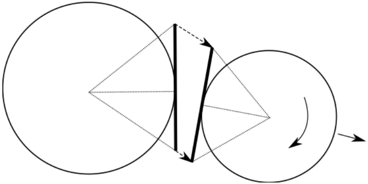
Periodically remap elements back to initial distribution

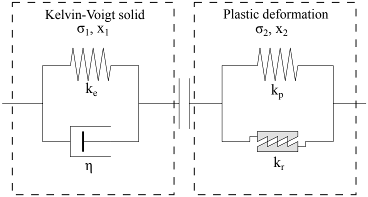


Keep elements same size and transfer mass between them

Contact Model

- The element contact model determines the forces between elements in close proximity
- Explicitly represent physical processes
  - Fracturing of bonded elements
  - Ridge formation during ridging
- Initially using contact model developed by Mark Hopkins
- Challenge: how do we determine appropriate contact model for regions of sea ice?





Contact Model Progress

- Initial Hopkins contact model has been implemented
- The history dependence and strength in tension needed special treatment in LAMMPS
- Model verified with the implementation of test cases to demonstrate and test each aspect of the model

Cantilever no fracture

Two particle fracture

Cantilever with fracture

Impact fracture

Further Contact Model Development

Ridge experiments

Simulations of individual ridges forming

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Floe level experiments

Simulations of individual floes

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Regional experiments

Simulations of Arctic regions e.g. Barrow, AK

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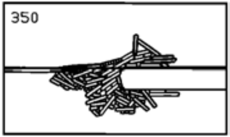
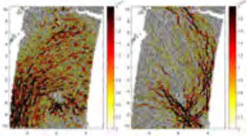
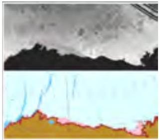
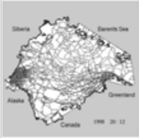
Arctic basin experiments

Simulations of Arctic basin



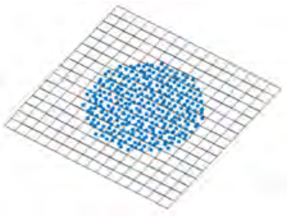


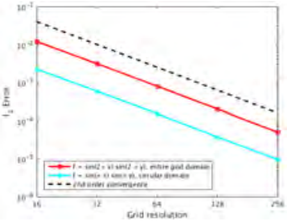




Coupling

- DEMSI requires an method for interpolation between Lagrangian particles and Eulerian grids
- Moving least squares method for interpolating particle data a fixed structured grid within DEMSI
- Second order convergence
- Will implement an optimization-based strategy to ensure property preservation





Performance

- Climate applications require good computational efficiency (long, high-res integrations)
- LAMMPS is a mature code $\rightarrow$ good parallel performance
- Initial timing studies suggest DEMSI will be competative
- Adding Kokkos support to LAMMPS DEM for heterogeneous architectures
- Will investigate effect of decreasing element stiffness to increase allowable time step

Potential SciDAC institute collaboration

- RAPIDS
  - PNetcdf - Parallel Netcdf IO
  - TAU performance system
  - Paraview visualization
- FASTMATH
  - Particle based methods?
  - Dynamic load balancing/partitioning?
- Open to other suggestions!