SAND2019-2525PE

Sea Ice Modeling and Arctic Change

Center for Computing Research

UNM Women in Computing

March 6, 2019

Kara Peterson

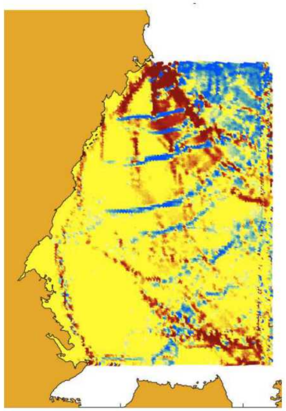
BACKGROUND

- B.S. Physics, NMSU
- M.S. Astrophysics CU Boulder
- Applied Research Associates

- Ph.D. Applied Math UNM
  - Advisor: Prof. Deborah Sulsky

UNM

Sea ice modeling with MPM

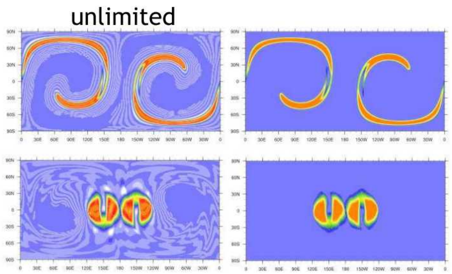


- Sandia National Labs

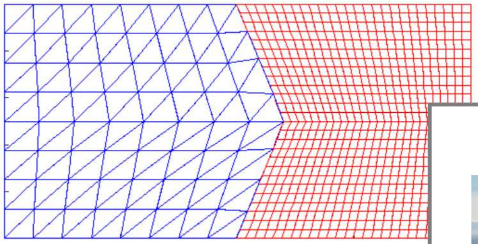
CCR
Center for Computing Research

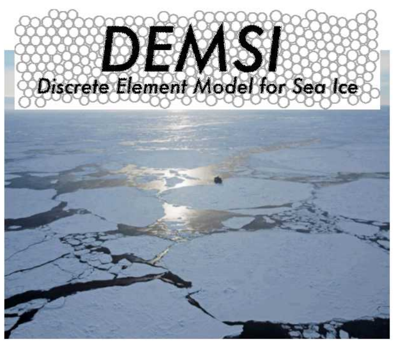
Developer for compatible discretization library

Optimization-based property preserving remap & transport



Lagrange-multiplier based coupling schemes for non-matching interfaces





OUTLINE

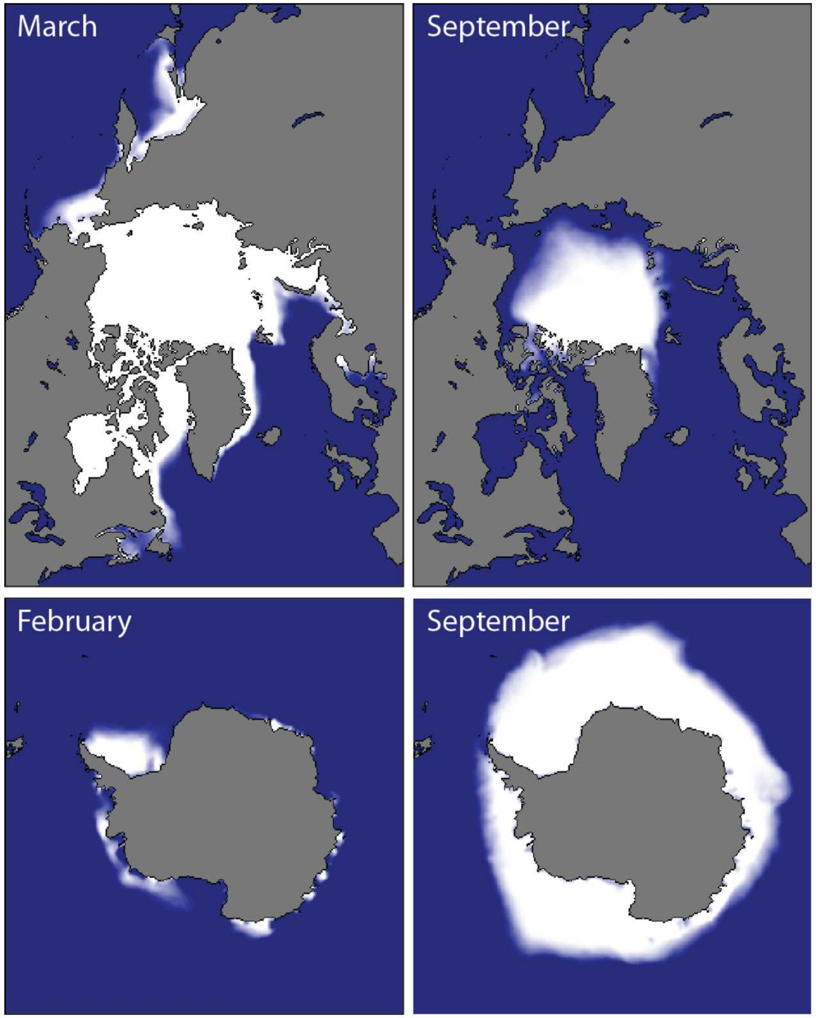
- Introduction to sea ice
  - Sea ice response to Arctic change
  - Sea ice model components

- Overview of sea ice modeling projects
  - MPM sea ice model
  - Sensitivity analysis, parameter estimation
  - Discrete element sea ice model
  - Tipping points, machine learning, and sea ice

SEA ICE

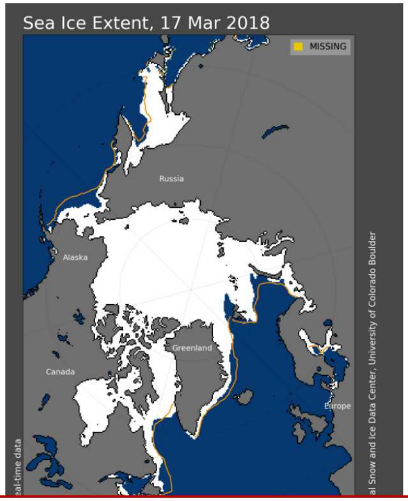
- Frozen surface of the ocean at high latitudes
- Covers ~7% of Earth surface and ~12% of ocean surface
- Important in global climate
  - Reflects solar radiation
  - Insulates ocean from atmosphere
  - Influences ocean circulation
- Accurate modeling of sea ice is important for both global climate and shorter-term forecasting for navigation

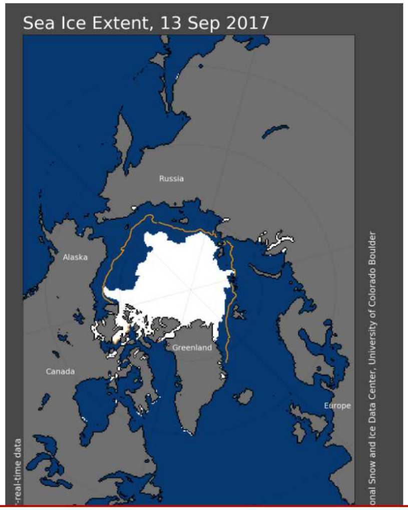
Climatology: 1981-2010 (nsidc.org)

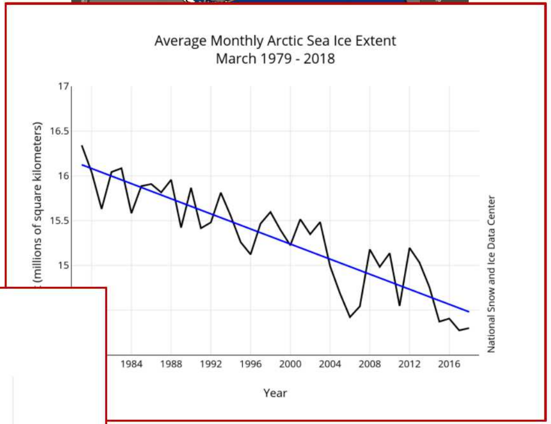


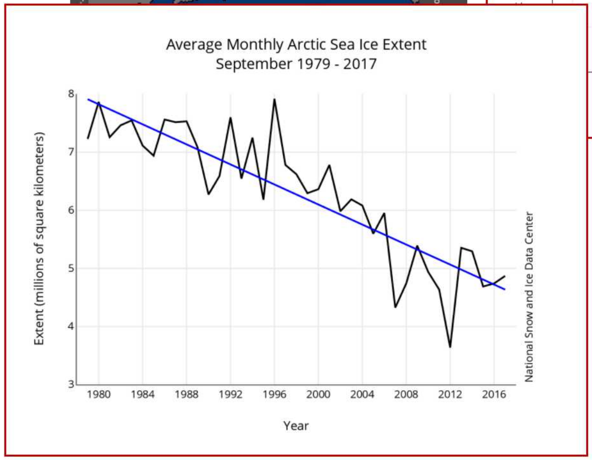
ARCTIC SEA ICE CHANGES

- Satellite passive microwave sea ice concentration data available since 1979
- Decline in extent is seen both in all seasons
- Fastest reductions in minimum sea ice extent





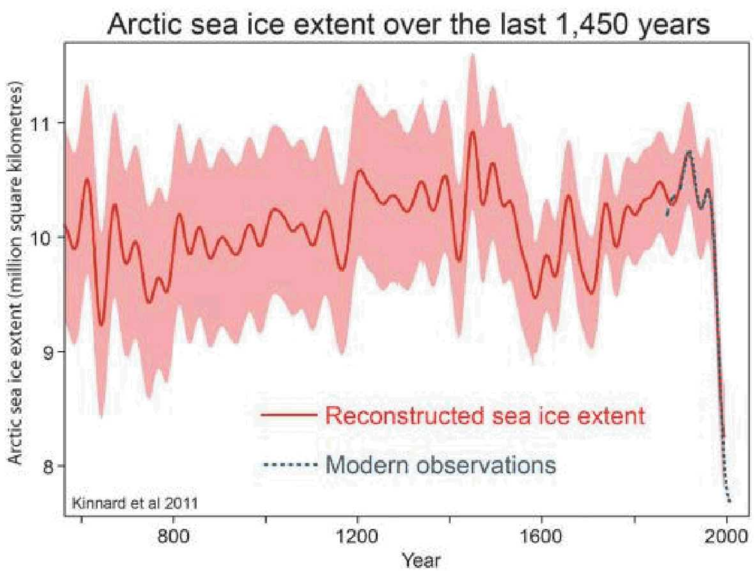


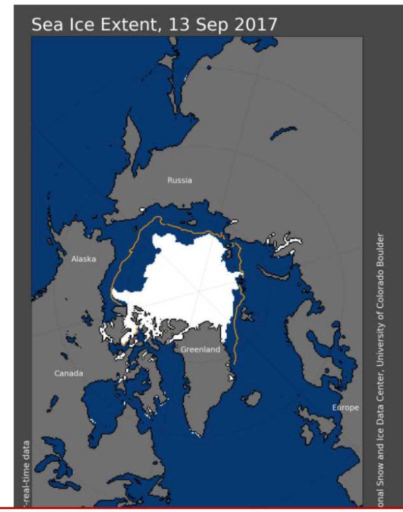


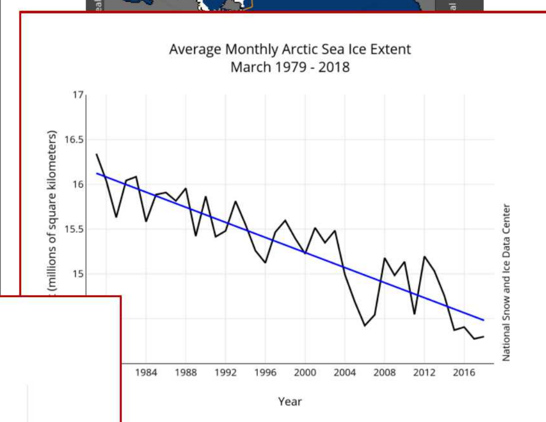
nsidc.org

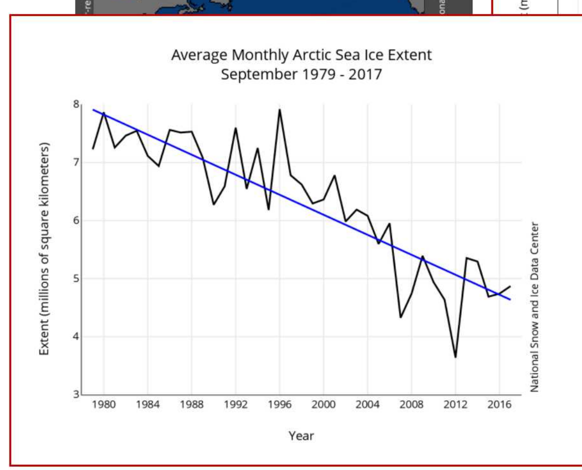
ARCTIC SEA ICE CHANGES

- Satellite passive microwave sea ice concentration data available since 1979
- Decline in extent is seen both in all seasons
- Fastest reductions in minimum sea ice extent
- Reconstructions from proxies, Kinnard *et. al* 2011





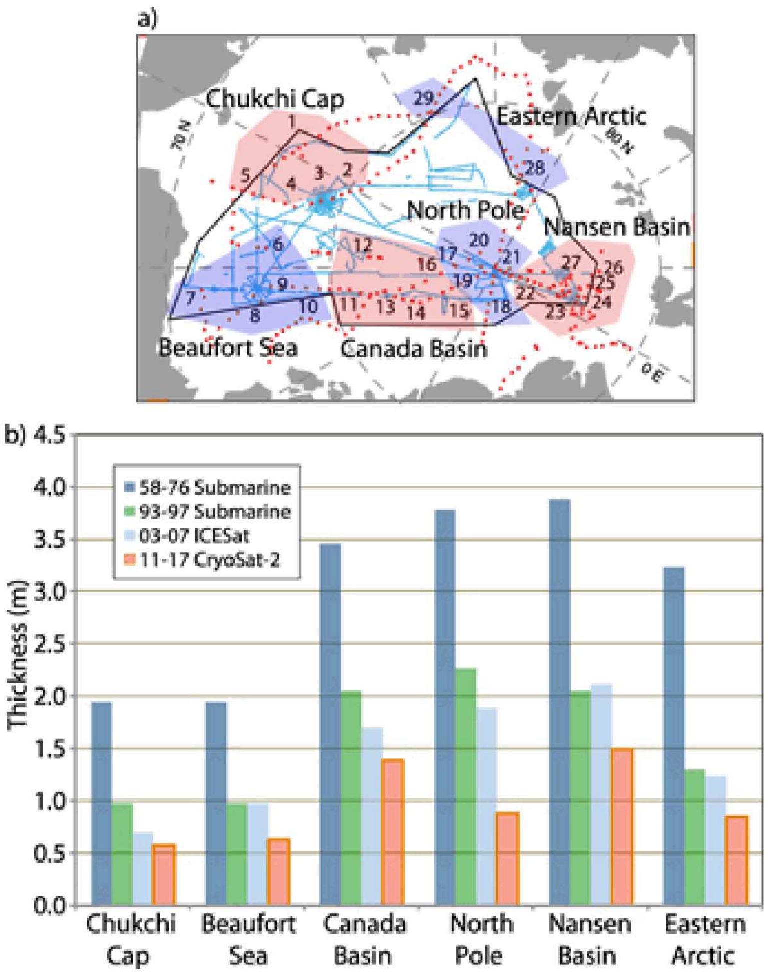




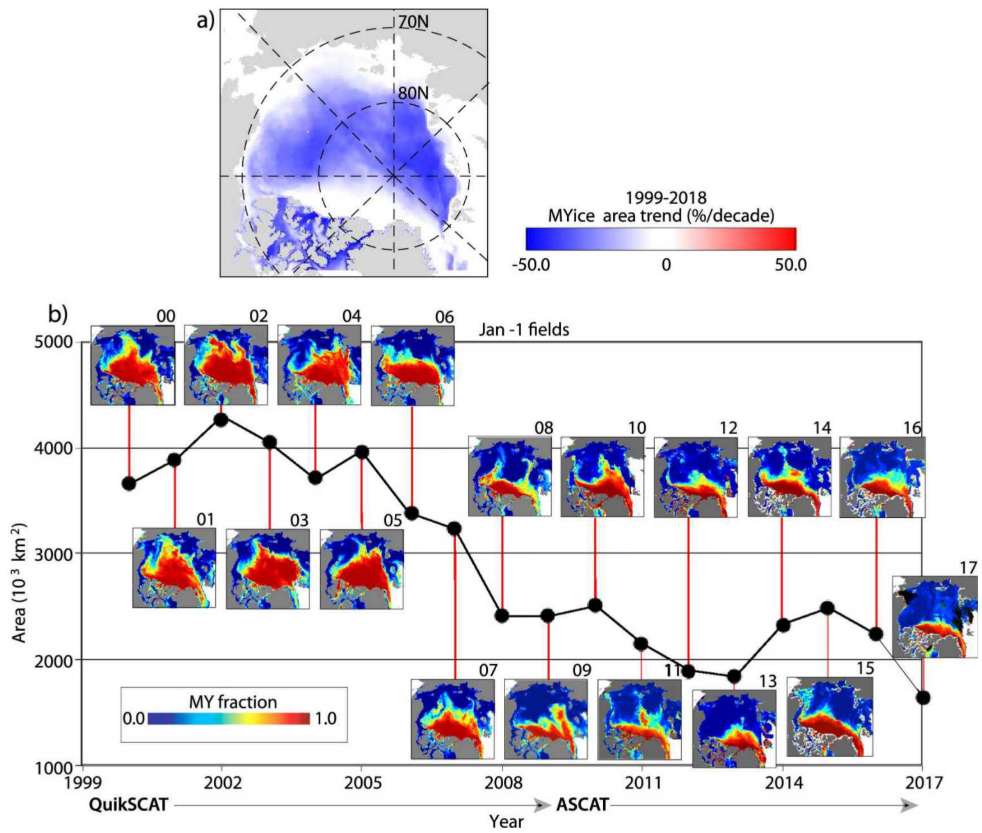
nsidc.org

ARCTIC SEA ICE CHANGES

Thickness



Ice Age

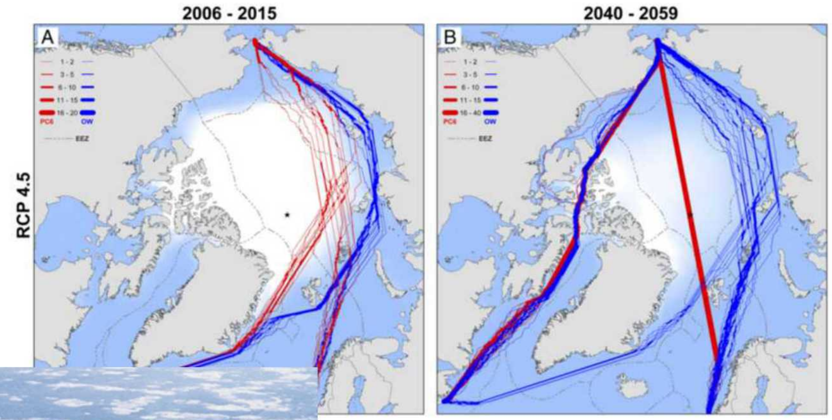


Kwok (2018) *Environmental Research Letters*

IMPACTS OF SEA ICE LOSS

Direct Arctic impacts

- Increased maritime activity in Arctic
- Geopolitical conflict concerns
- Increased wave activity and coastal erosion
- Habitat changes

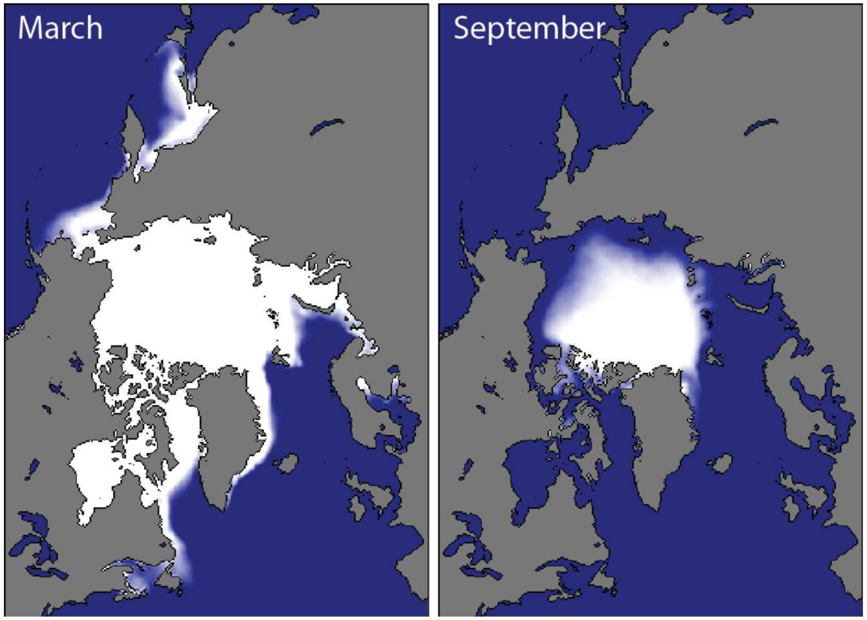


Smith and Stephenson (2013) *PNAS*

Downstream impacts

- Impacts to mid-latitude weather, potential increases in winter storms and drought (Francis and Skific 2015, Cvijanovic et al. 2018, Cohen et al. 2018)
- Disruption of Atlantic ocean circulation (Sévellec et al 2017)

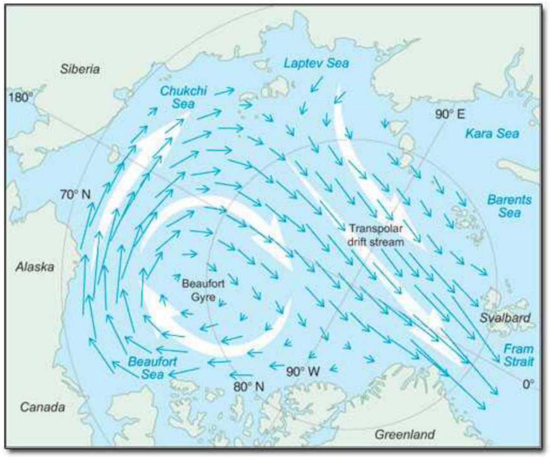
SEA ICE MODELING



Important physical processes:

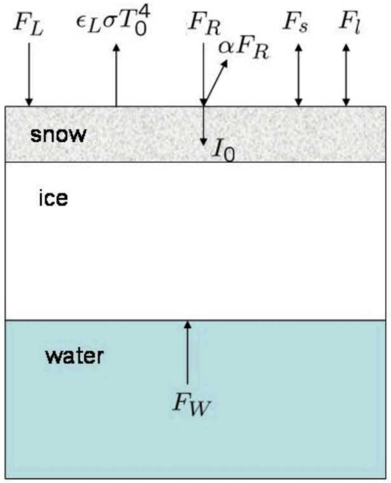
- Mechanical deformation due to surface winds and ocean currents
- Changes in thickness including lead and ridge formation
- Annual cycle of growth and melt due to radiative forcing

SEA ICE MODEL COMPONENTS



Dynamics

- 2-D momentum equation solve for velocity
- Typically continuum using viscous-plastic rheology (Hibler 1979)
- Alternatives: anisotropic constitutive models, discrete element method (non-continuum)



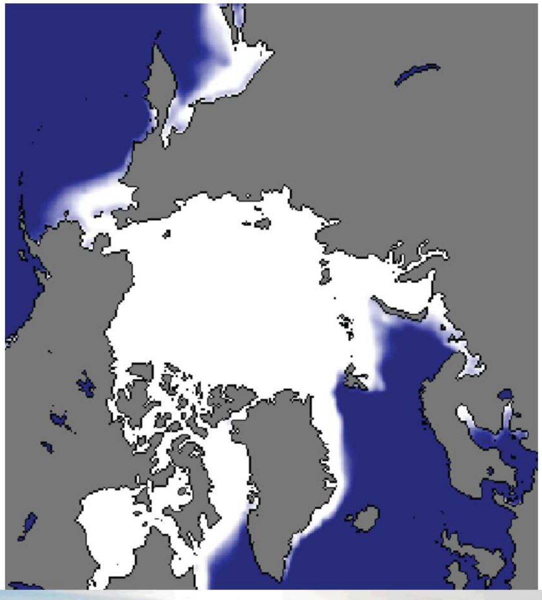
Thermodynamics

- Energy equation solved in column determines temperature and thickness
- Balance of longwave and shortwave fluxes determines top layer temperature and melt/growth of ice

Ridging

- Convergent velocity leads to ridging
- Conserves volume and redistributes ice

MODEL LIMITATIONS



Dynamics

- At high resolutions (10 km) isotropic continuum models not good approximation of dynamics
- As temperatures are increasing, sea ice may be better represented as a discrete set of floes rather than as a continuous ice cover

Numerical Methods

- Artificial diffusion in transport can lead to errors in thickness and smearing of ice edge
- Eulerian methods are less efficient for multiple tracers

Performance

- Not designed to run on next generation architectures

Other

- Missing physical processes, e.g. wave ice interactions

MATERIAL-POINT METHOD SEA ICE MODEL

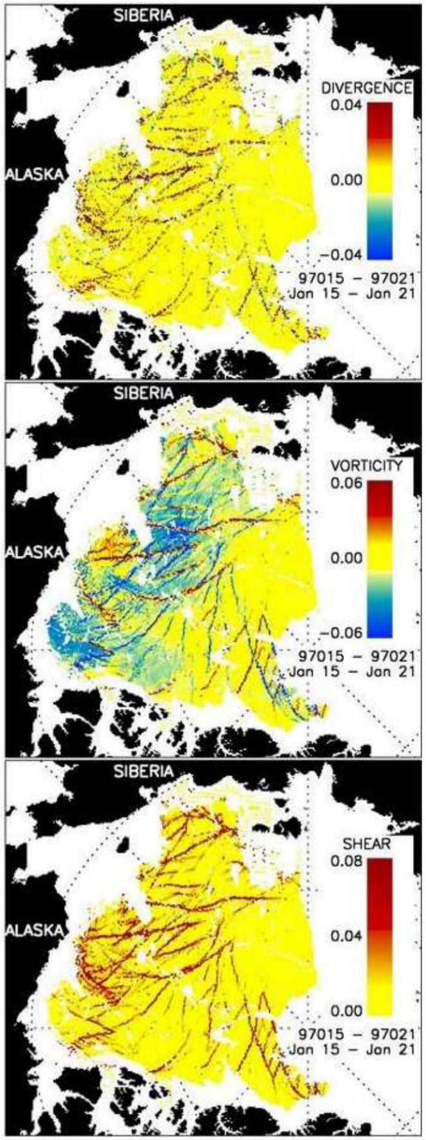
Objective: Develop new sea ice model using MPM as the discretization method with an anisotropic rheology.

Motivation:

- Better represent sea ice dynamics, including lead formation
- Enable more accurate advection with sharper ice edge

Collaborators: Deborah Sulsky, Howard Schreyer (UNM), Ed Love (SNL), Giang Nguyen (U. of Adelaide), Han Tran (German Vietnamese University), Lynn Munday (SNL)

Satellite Deformation Data

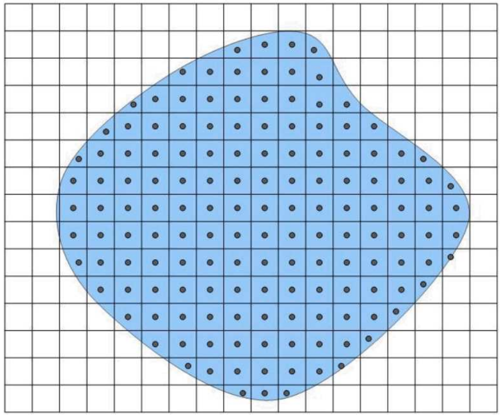


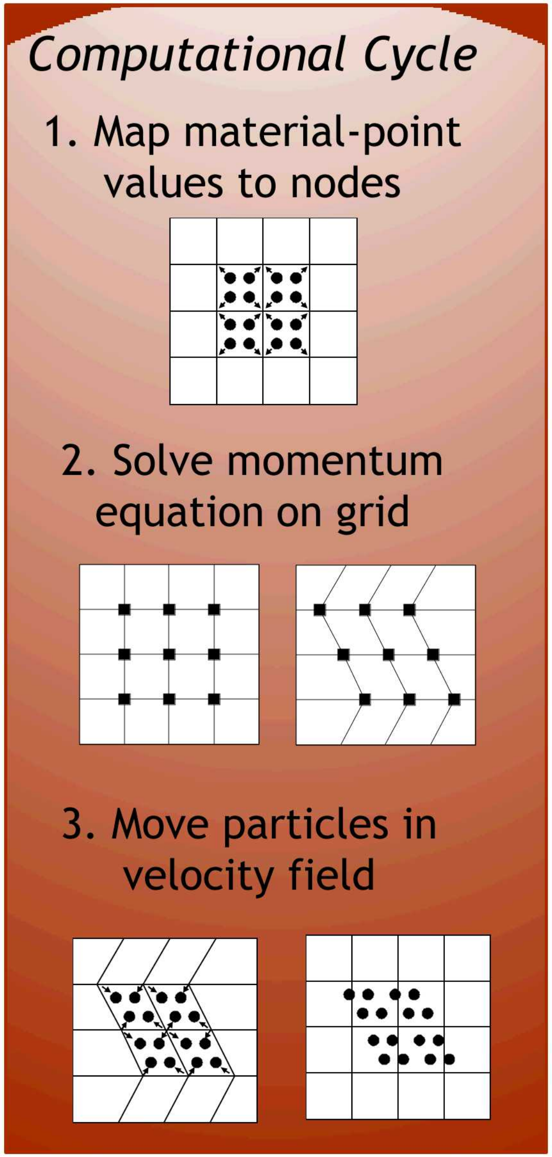
MATERIAL-POINT METHOD (MPM)

- Domain divided into material points and background grid
- Lagrangian material points carry mass, momentum, and internal variables

Advantages

- Mass conservation automatic
- Advection handled naturally with Lagrangian points
- Large deformations without mesh tangling

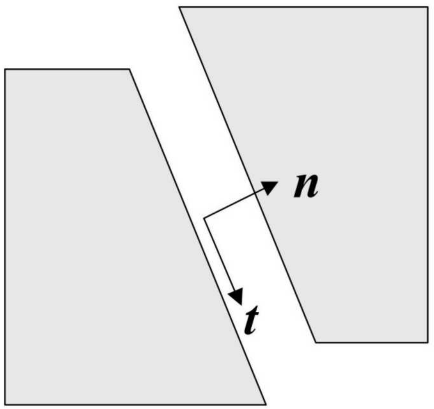




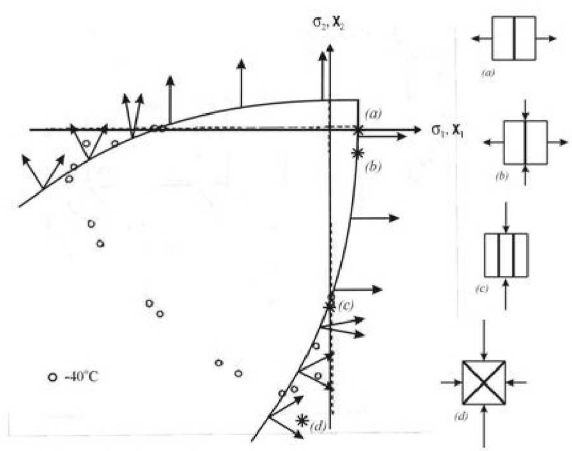
Sulsky, Chen, Schreyer, *CMAME* 1994
Sulsky et al., JGR, 2007

ELASTIC DECOHESIVE RHEOLOGY (EDC)

- Leads modeled as displacement discontinuities $[\![\mathbf{u}]\!]$
- Intact ice modeled as elastic
- Predicts initiation and orientation of leads
- Once failure begins behavior is anisotropic



$$[\![\mathbf{u}]\!] = u_n \mathbf{n} + u_t \mathbf{t}$$

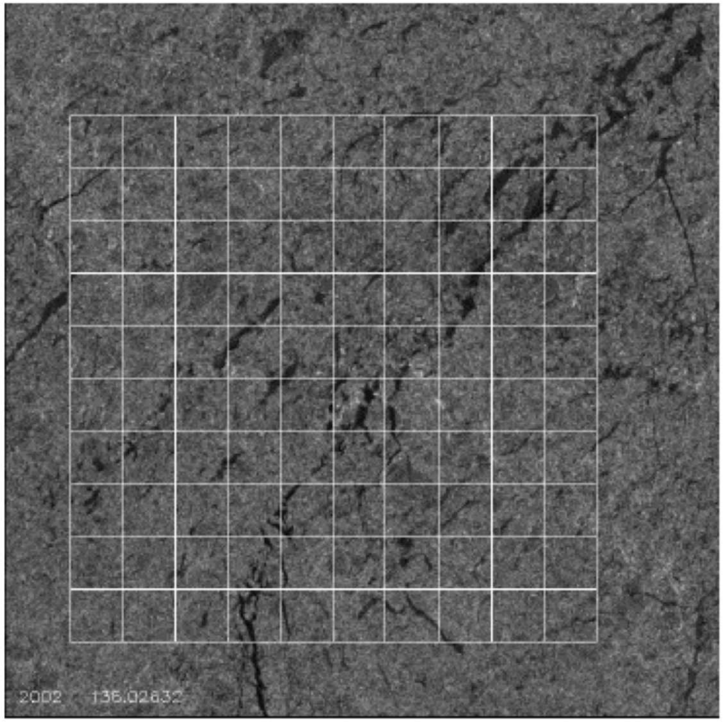


Schulson (2001) *Engng. Frac. Mech.*

Schreyer et al. (2006) *JGR*

RADARSAT GEOPHYSICAL PROCESSOR SYSTEM (RGPS)

- Developed by Polar Remote Sensing Group at JPL
- Extracts sea ice motion data from SAR imagery using area and feature based tracking
- Points tracked can be interpreted as nodes of a grid
- Grid quantities such as divergence, shear, and vorticity can be derived



Kwok (1998) in *Analysis of SAR Data of the Polar Oceans*

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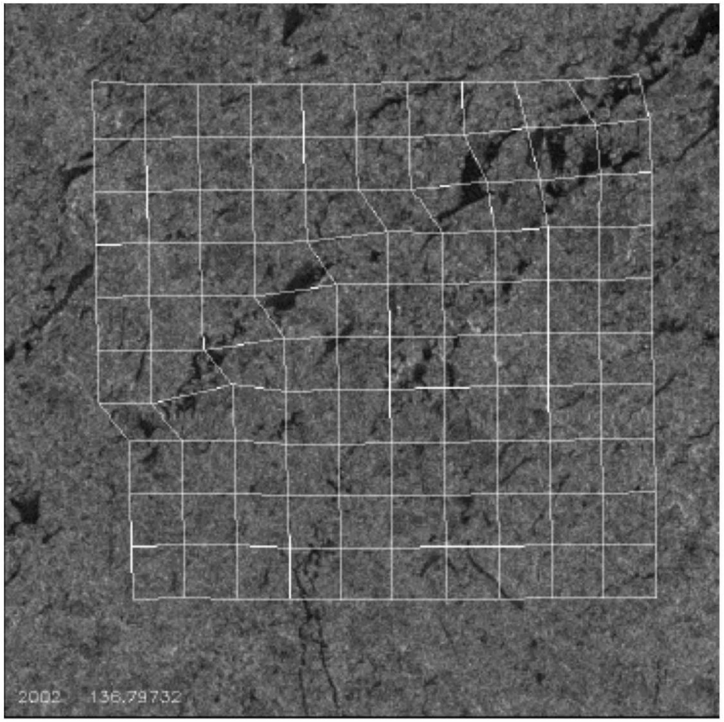


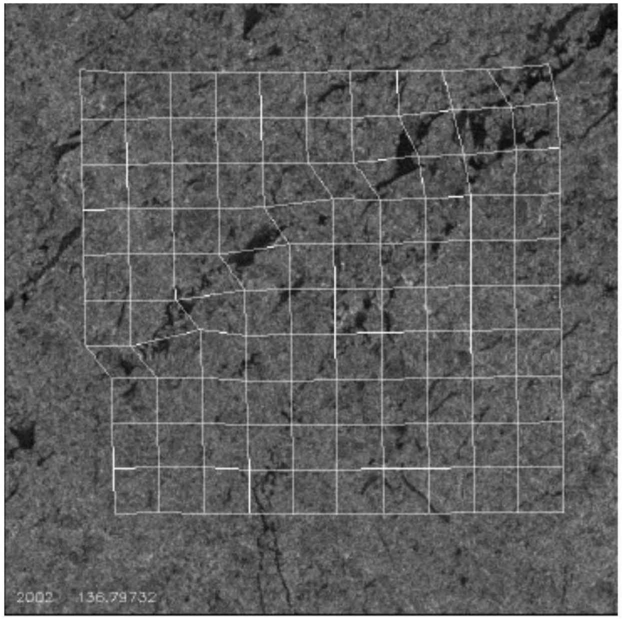
Kwok (1998) in *Analysis of SAR Data of the Polar Oceans*

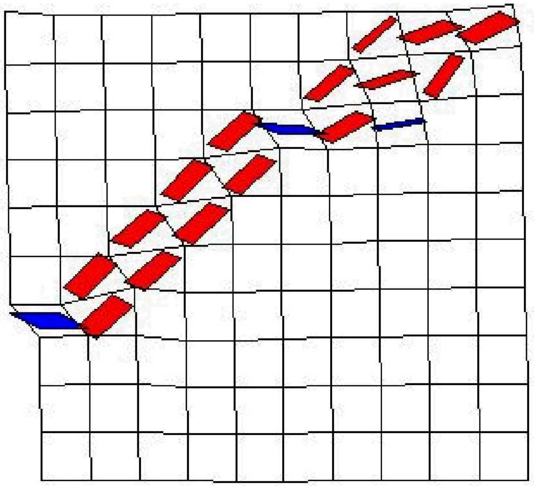
DECOHESIVE KINEMATICS USING RGPS

- Want a procedure to extract information on cracks or leads from RGPS data
- Assume all deformation in cell due to discontinuity

$$\varepsilon = \frac{1}{L}\left(\llbracket \mathbf{u} \rrbracket \otimes \mathbf{n}\right)^{s}$$

- Given strain or deformation gradient from RGPS cell data, calculate best fit jump and normal

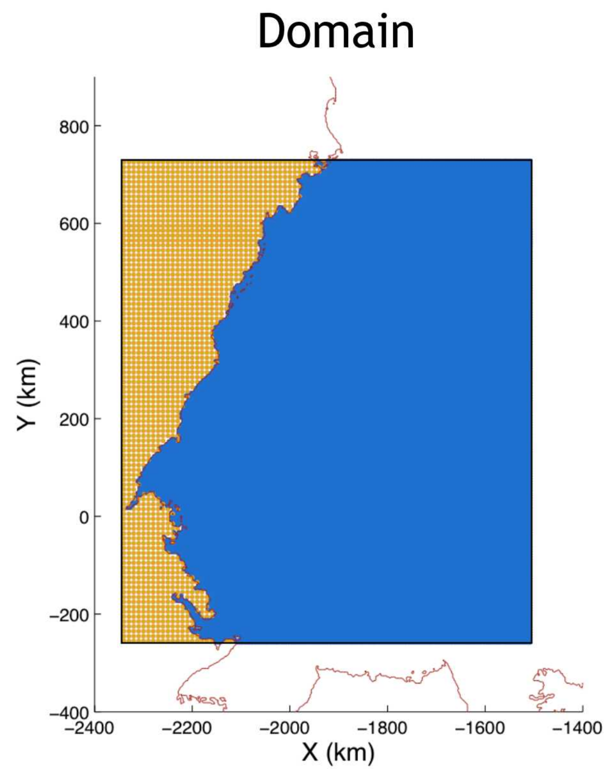


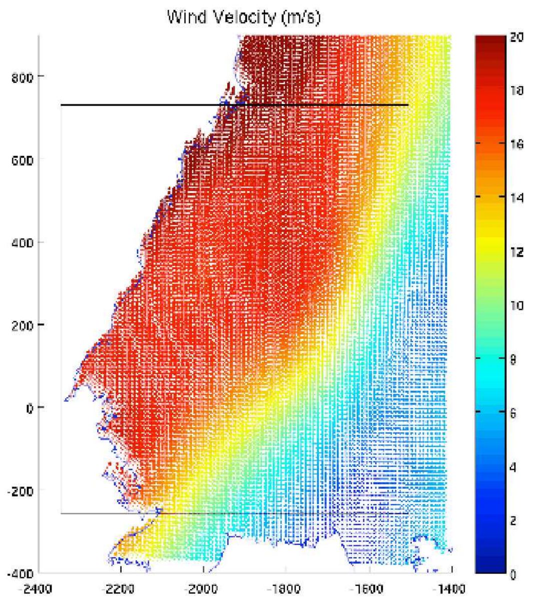


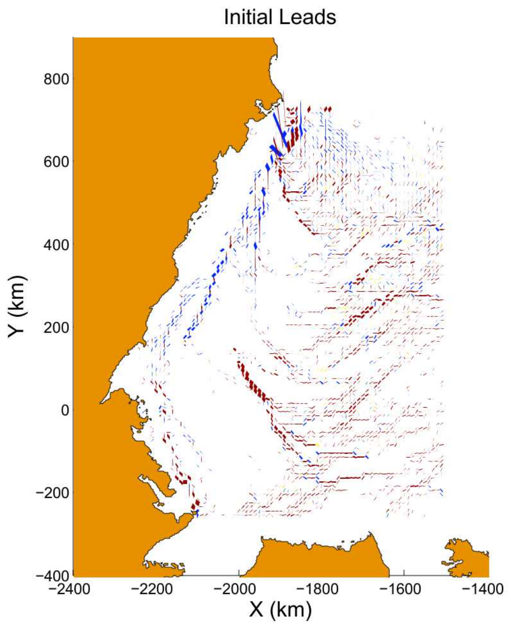
Peterson, Sulsky (2011) in *Remote Sensing of the Changing Oceans*

BEAUFORT SEA CALCULATION

- Simulate 15 days in Feb/Mar 2004
- 10 km resolution
- Compare with RGPS satellite data provided by R. Kwok, JPL
- Initialize with cracks from data







BEAUFORT SEA NET DEFORMATION RESULTS

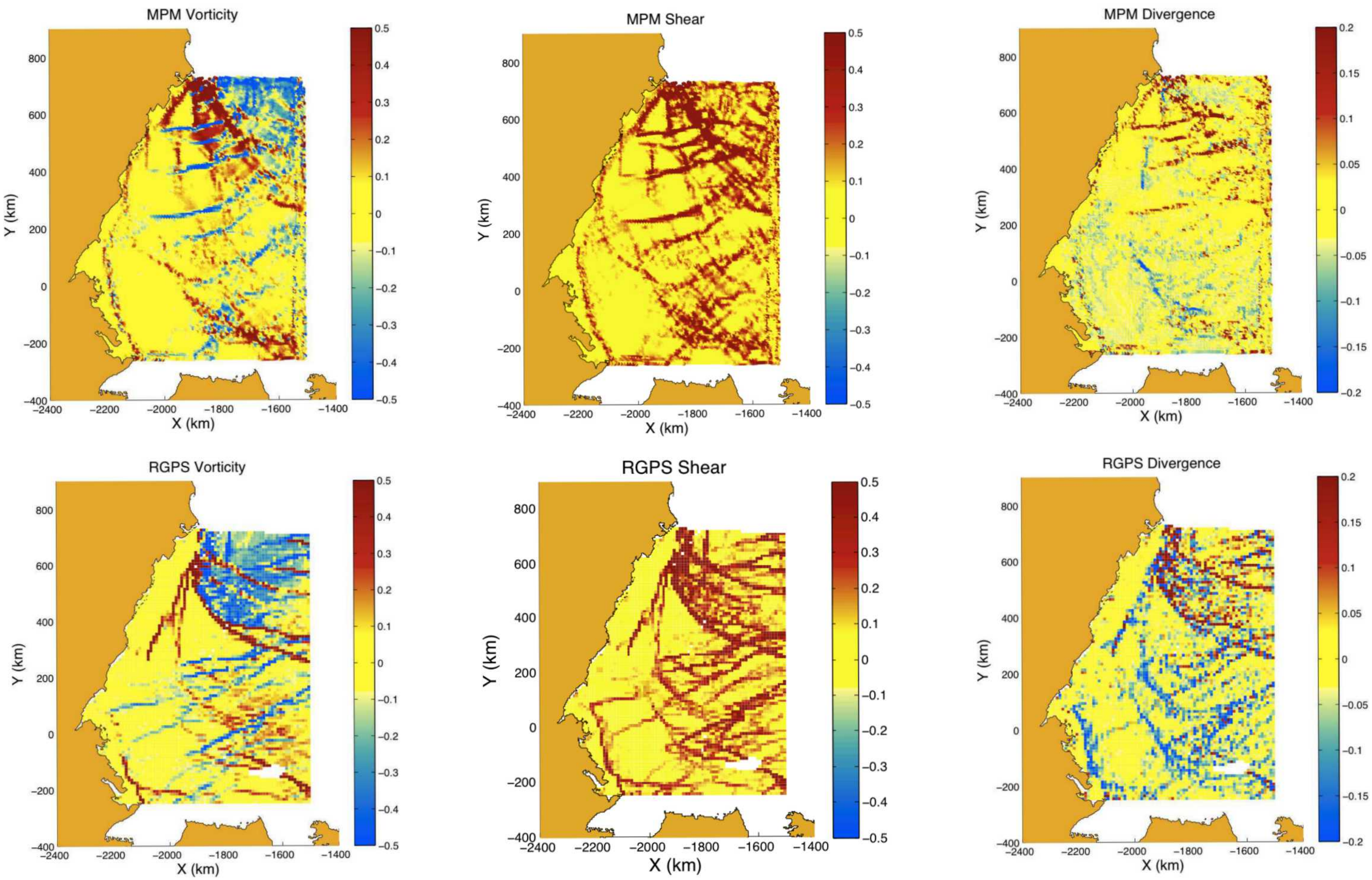
Vorticity

Shear

Divergence

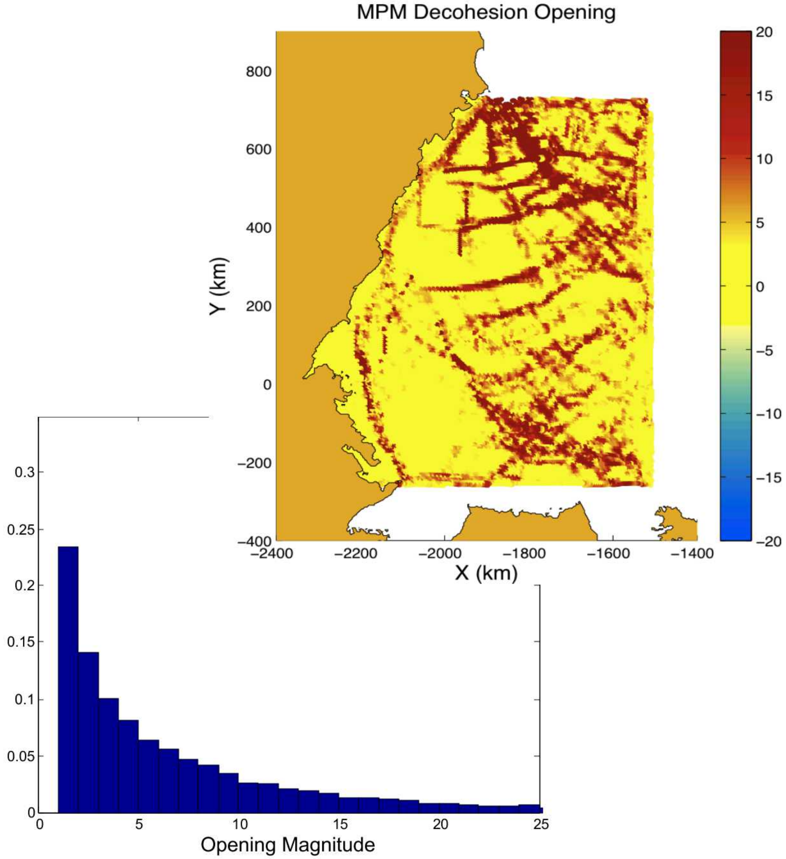
MPM

RGPS

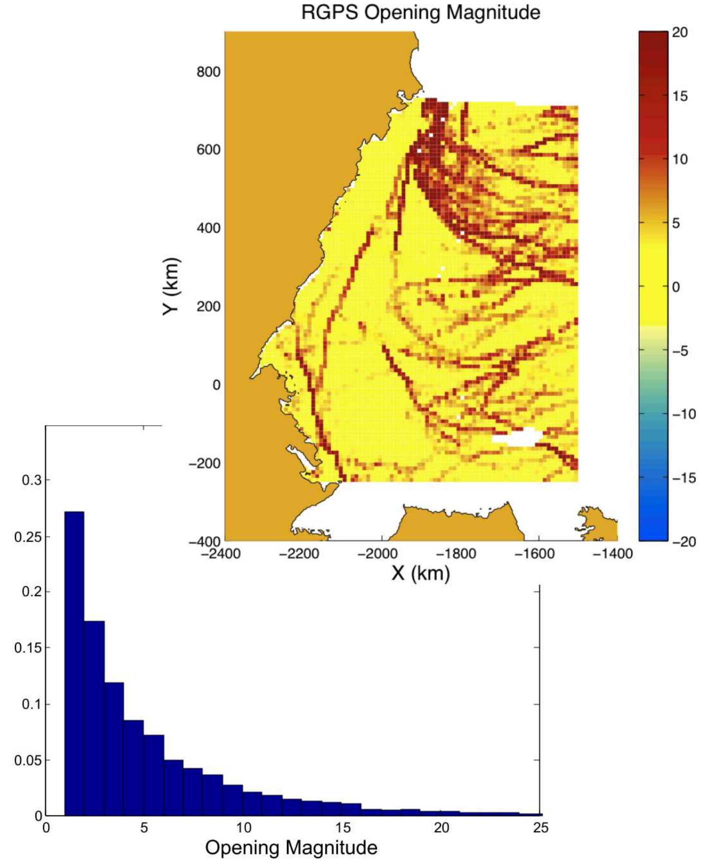


BEAUFORT SEA CRACK OPENING MAGNITUDE

MPM



RGPS



Sulsky, Peterson (2012), *Physica D*

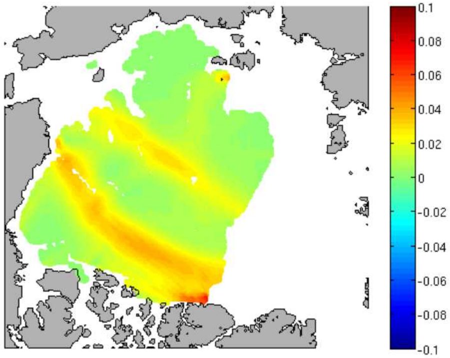
MODEL SENSITIVITIES & COMPARISON WITH CICE

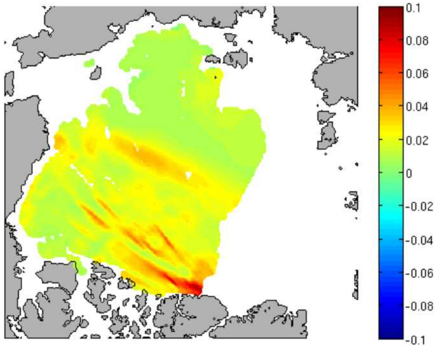
Objective: Arctic basin scale simulations comparisons

Motivation:

- Better represent sea ice dynamics, including lead formation
- Gain understanding of uncertain parameters in dynamic and thermodynamic sea ice models
- Compare with widely used model, CICE (https://github.com/CICE-Consortium/CICE/wiki)

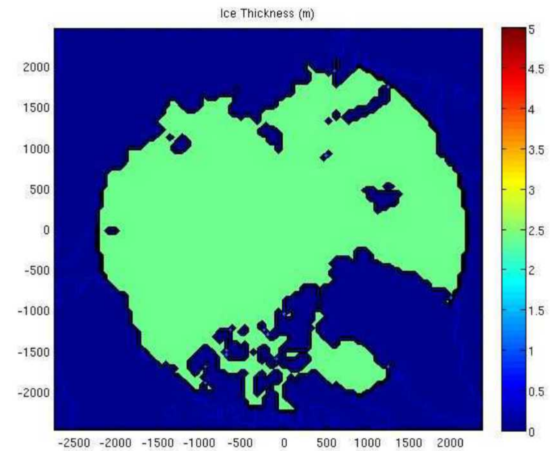
Collaborators: Pavel Bochev, Biliana Paskaleva (SNL), Deborah Sulsky, Howard Schreyer (UNM), Elizabeth Hunke (LANL)





PAN-ARCTIC SIMULATIONS WITH PARAMETER SENSITIVITIES

- One year run starting from uniform ice conditions
- Prescribed ocean and atmospheric forcing
- 10 parameters, 6 response functions
- Use DAKOTA (Design Analysis Kit for Optimization and Terascale Applications)
- MPM Sea ice with EDC rheology
- CICE with isotropic EVP rheology
- 50 Latin hypercube samples



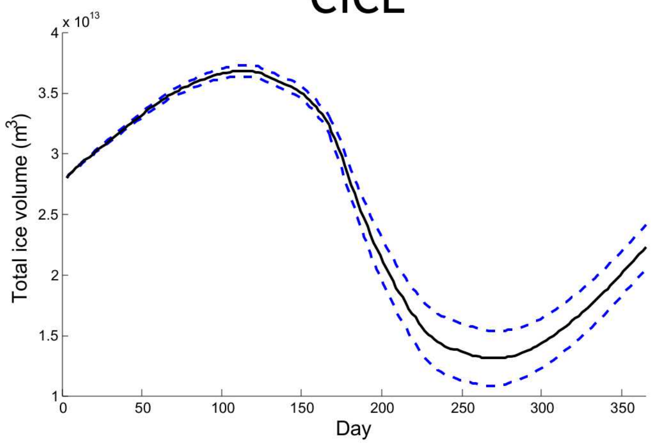
Response Functions

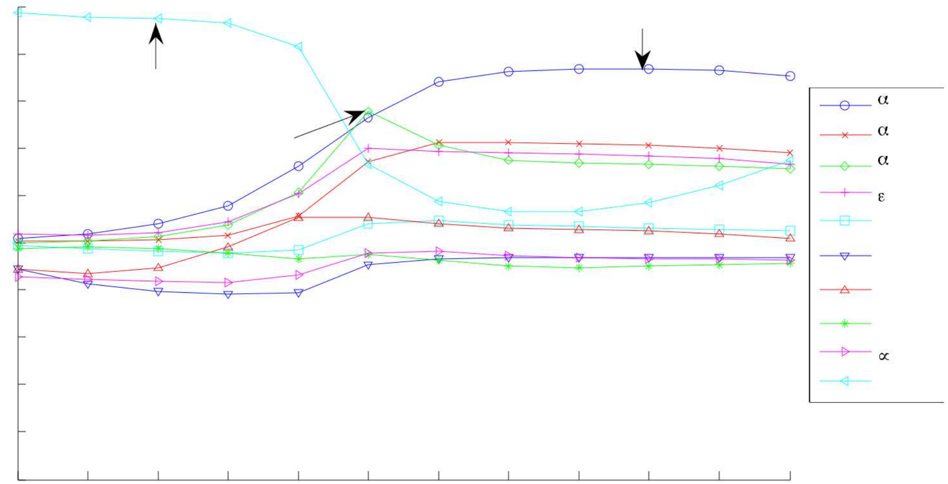
- Total ice area (km^2)
- Total ice extent (km^2)
- Total ice volume (m^3)
- RMS ice speed (m/s)

K. Peterson, P. Bochev, B. Paskaleva (2010) SAND 2010-6218.

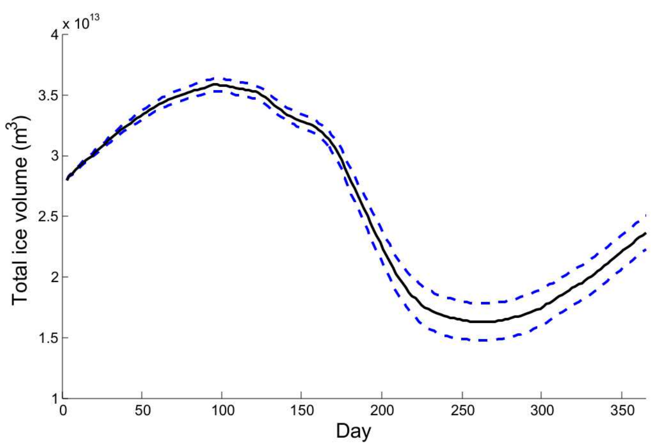
SENSITIVITY ANALYSIS SEA ICE VOLUME

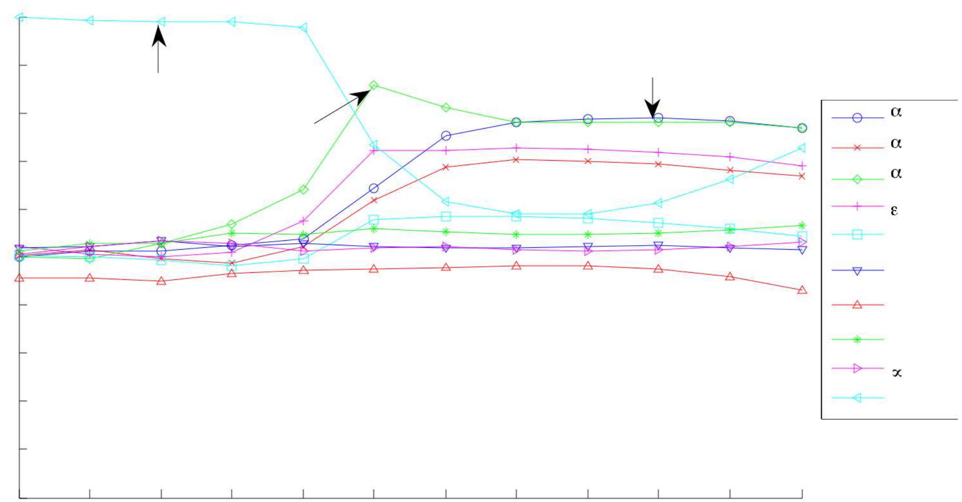
CICE





MPM





SENSITIVITY ANALYSIS FOR RHEOLOGY PARAMETERS

- Initial implementation of EDC in CICE
- Monte Carlo analysis using Latin Hypercube sampling
- 50 samples of Jan/Feb 1997 run of CICE with EDC
- Vary seven parameters, consider seven response functions
- Linear regression model to evaluate sensitivity of response functions to parameters
- Standardized regression coefficients between -1 and 1, provide measure of variable importance

Standardized Regression Coefficients

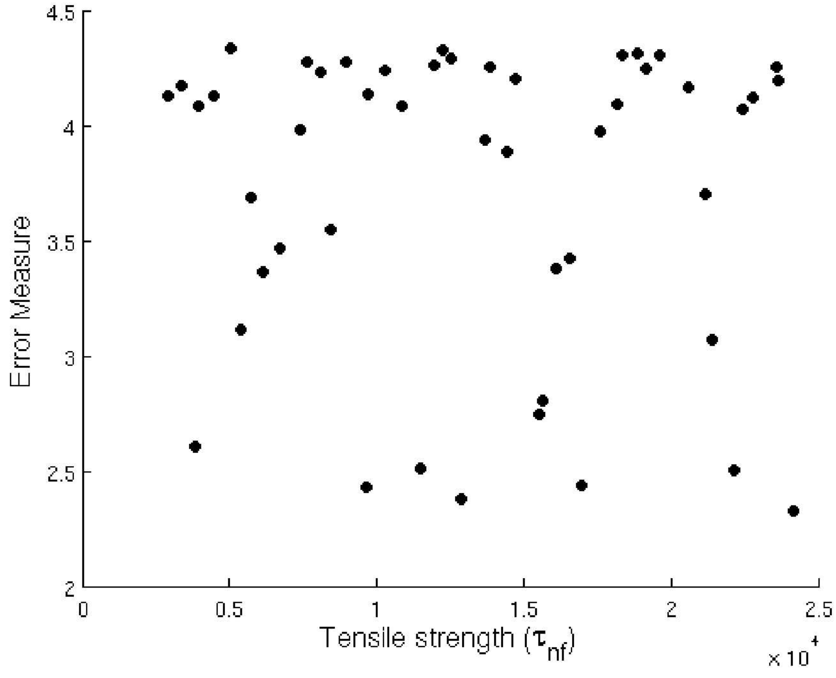
Parameter	Extent	Volume	RMS Speed	Velocity Error	Divergence Correlation	Vorticity Correlation	Shear Correlation
E	0.0678	0.0652	**-0.331**	**-0.403**	**-0.394**	-0.0994	**-0.319**
[illegible]	-0.0775	0.0706	-0.0393	0.00642	-0.136	-0.0132	-0.263
[illegible] n f	**-0.883**	**-0.931**	**-0.563**	-0.102	0.192	**-0.301**	0.0267
[illegible] t f	0.194	0.00283	**-0.601**	**0.411**	**-0.378**	**-0.833**	0.204
f_c^0	0.104	-0.0598	0.00651	0.0591	-0.0958	-0.0388	0.0399
sm	-0.0648	0.129	-0.140	0.0463	-0.00968	-0.137	-0.174
u_0 Factor	-0.104	**-0.377**	-0.197	-0.267	-0.0861	-0.115	-0.131

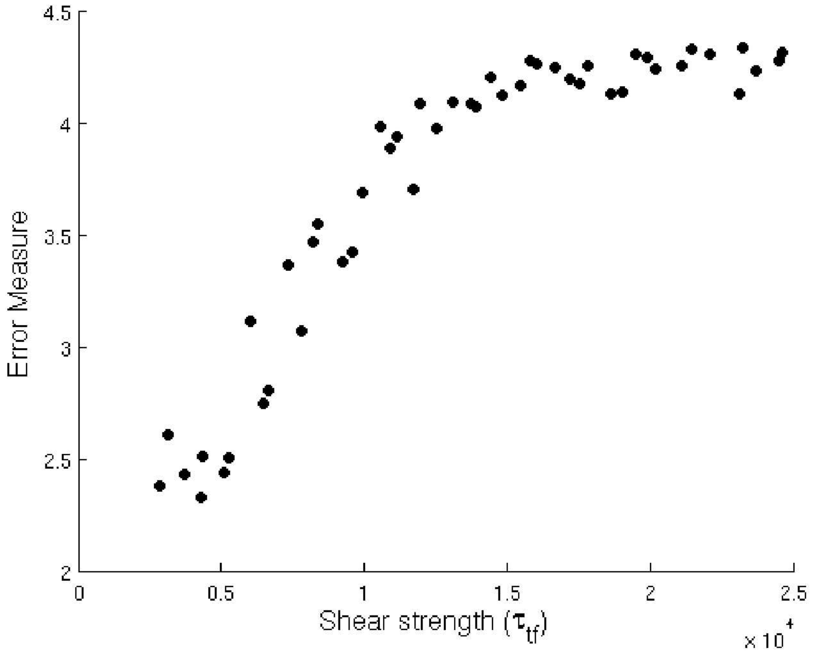
K. Peterson, P. Bochev (2013) SAND 2013-5484.

ANALYSIS OF MOST INFLUENTIAL PARAMETERS

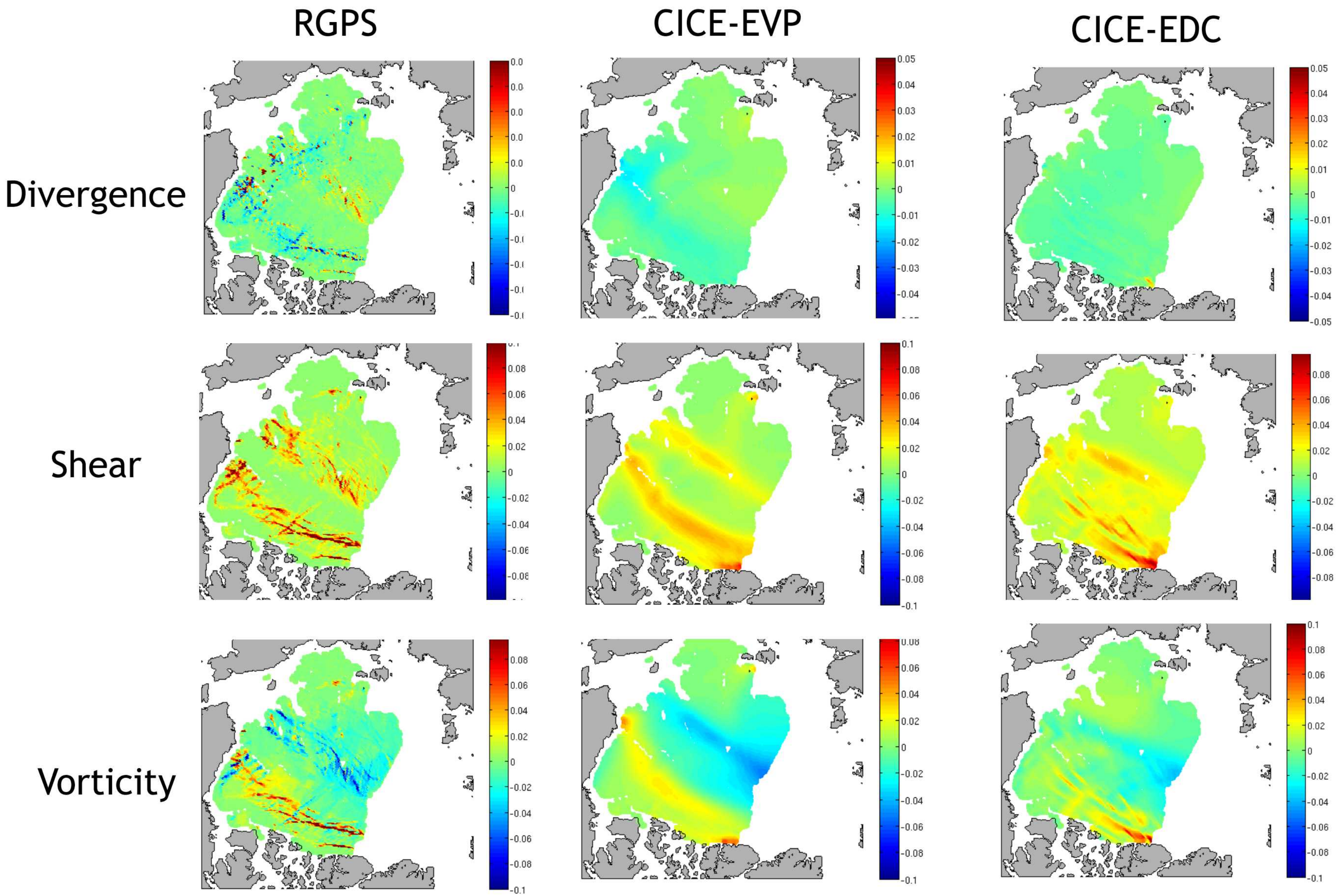
- 50 samples of Jan/Feb 2004 run of CICE with EDC
- Vary two parameters
- Using the following cost function, evaluate best fit parameters for EDC

$$J = v_{error} + (1 - D_{d,correl})^2 + (1 - D_{s,correl})^2 + (1 - D_{v,correl})^2$$



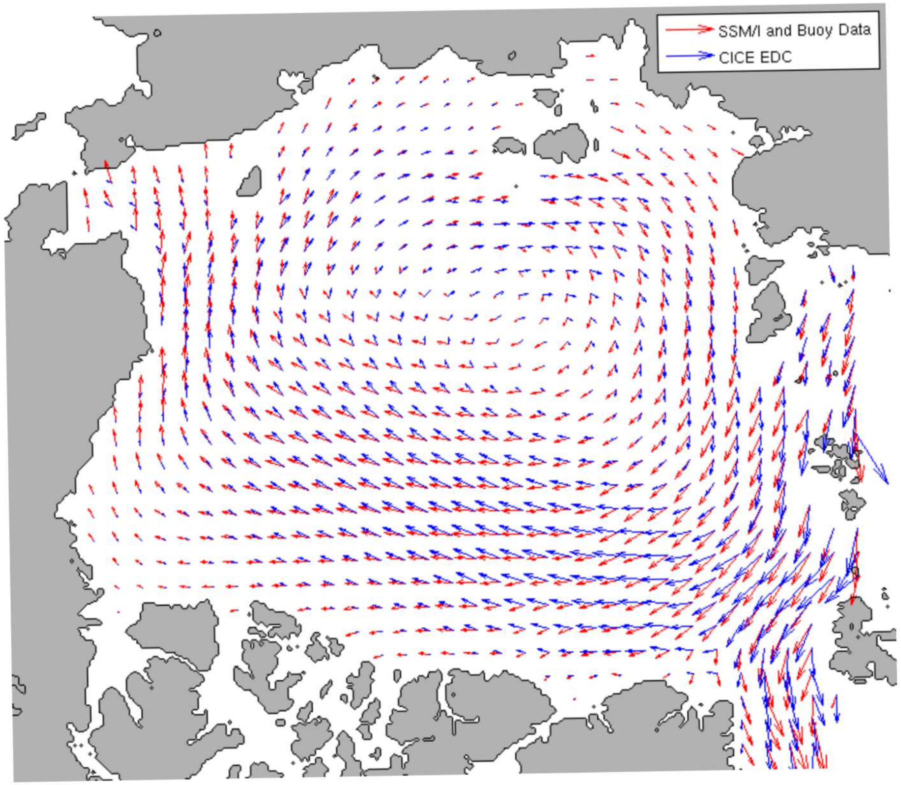


DEFORMATION COMPARISONS – FEBRUARY 17-19 2004

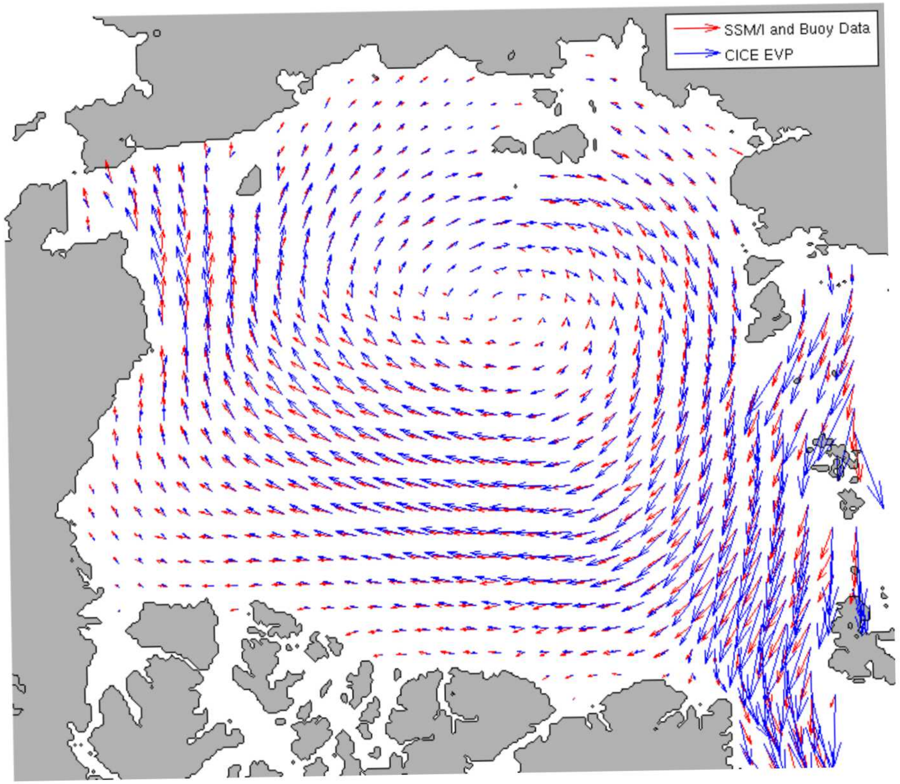


VELOCITY COMPARISON

EDC February 2004



EVP February 2004

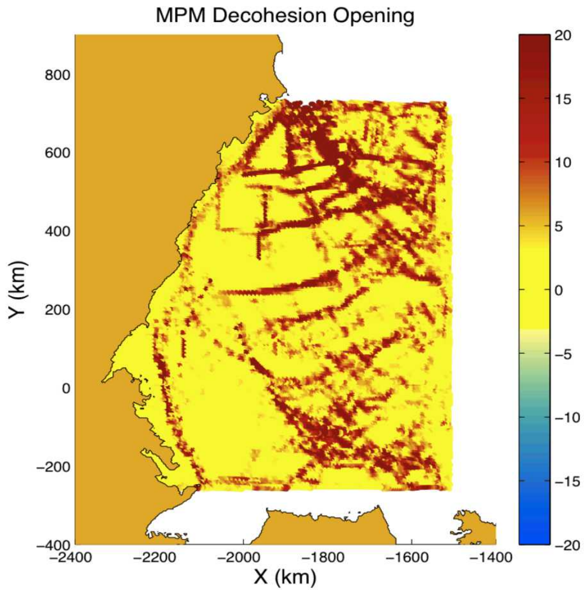


Comparison with optimally interpolated two-day ice motion derived from passive microwave instruments and buoy data
http://rkwok.jpl.nasa.gov/icemotion/index.html

SUMMARY

MPM with EDC very promising

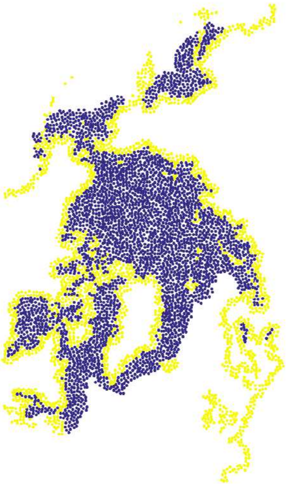
- At high resolutions, model captures linear deformation features well
- Development continuing at UNM
  - Coupling with MIT ocean model
  - Extensions to EDC model: Han, Sulsky, Schreyer (2015) *Numerical and Analytical Methods in Geomechanics*



- Opportunities
  - Improvements crack closure and freezing models
  - Relate open water fraction from ice thickness distribution to cracks more directly
  - More comparisons with data and parameter optimization

DISCRETE ELEMENT MODEL FOR SEA ICE

Los Alamos NATIONAL LABORATORY EST. 1943



Objective: Develop new Lagrangian particle sea ice model for use in coupled climate simulations

Motivation:
- Better represent sea ice dynamics at high resolution
- Incorporate programming model suitable for next generation architectures

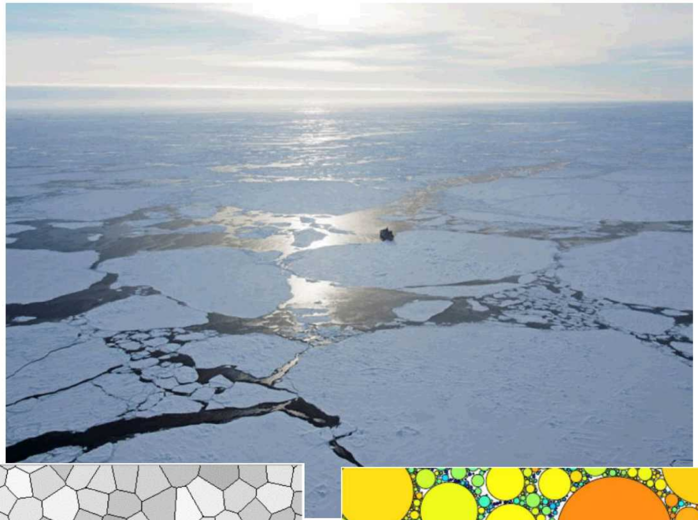
Collaborators: Adrian Turner, PI, Andrew Roberts, Min Wang (LANL); Dan Bolintineanu, Dan Ibanez, Paul Kuberry, Kara Peterson (SNL); Travis Davis (NPS)

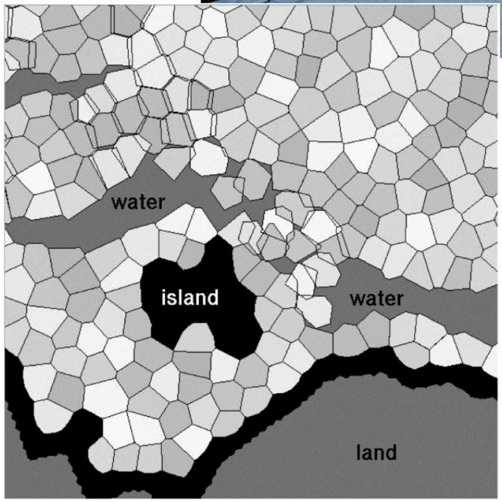
SciDAC Scientific Discovery through Advanced Computing

DEMSI Discrete Element Model for Sea Ice

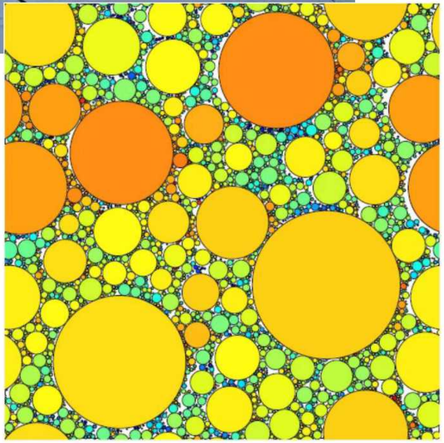
DISCRETE ELEMENT METHOD

- DEM for sea ice dynamics enables capture of
  - Anisotropic, heterogenous nature of sea ice deformation
  - Explicit fracture and break-up of pack
- Previous DEM sea ice modeling efforts focused on regional scale, short-term simulations
- Our objective is to develop a computationally efficient global climate scale sea ice model using DEM





Hopkins and Thorndike (2006)



Herman (2012)

DEMSI

Dynamics: LAMMPS (https://lammps.sandia.gov)

- Particle based molecular dynamics code
- Includes support for DEM and history dependent contact models
- Computationally efficient with massive parallelization

Thermodynamics: CICE consortium Icepack library (https://github.com/CICE-Consortium/Icepack)

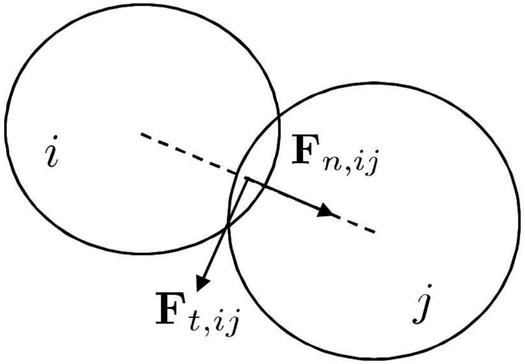
- State-of-the-art sea-ice thermodynamics package
- Vertical thermodynamics, salinity, shortwave radiation, snow, melt ponds, ice thickness distribution, biogeochemistry

DEMSI: Combines power of LAMMPS and Icepack

- Circular elements to start for efficiency
- Each element represents a region of sea ice, and has its own ice thickness distribution

PRINCIPLE CHALLENGES

1. **Contact model:** How should elements interact to represent sea ice physics?
   - Bonded elements – viscous-elastic glue, Mohr-Coulomb fracture law
   - Unbonded elements – no strength in tension
   - Adapt Hopkins (2003), Wilchinsky et al. (2010)

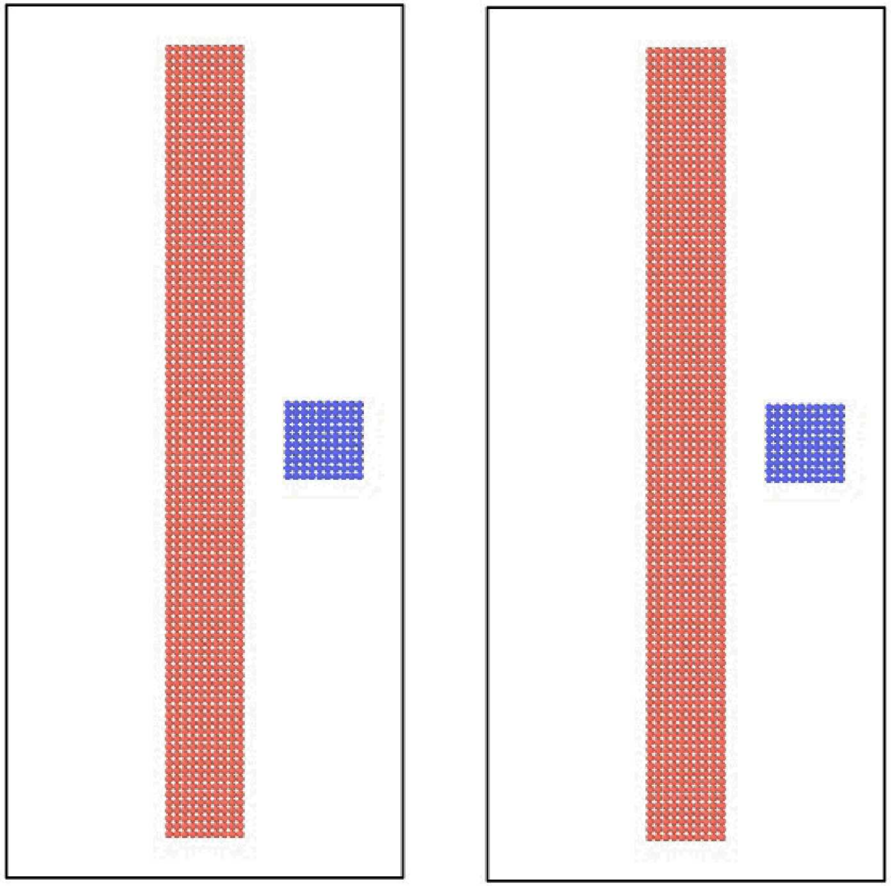


2. **Element distortion:** How to manage element creation, destruction, and distortion?
   - Periodically remap elements
   - Merge elements that get too small

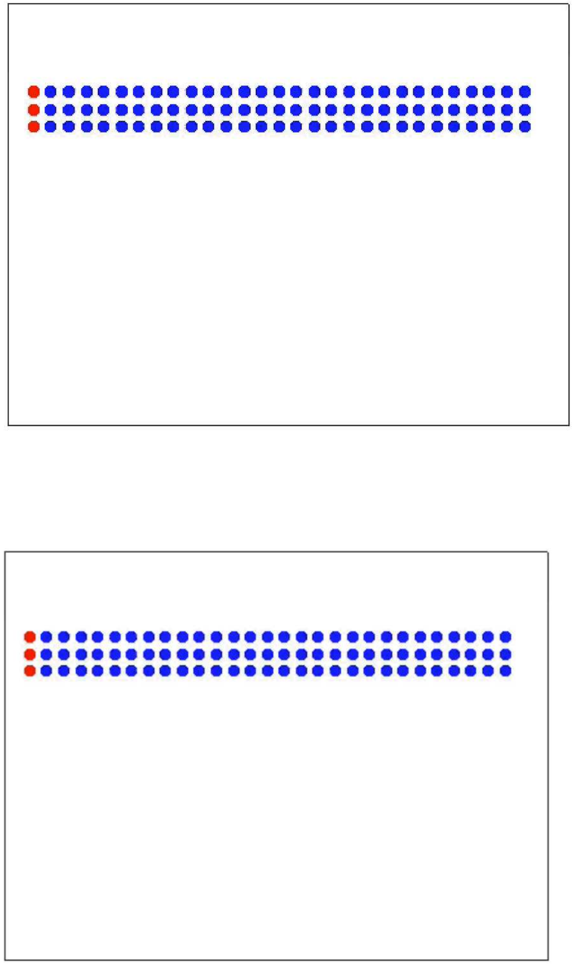
3. **Coupling:** How to couple particles to Eulerian mesh conservatively?
   - Moving least squares interpolation with optimization-based property preservation
4. **Computational performance:** How to make the model fast enough for global climate applications?
   - LAMMPS already highly-scalable for MPI
   - Incorporate Kokkos programming model for GPU, etc.

CONTACT MODEL TESTING

Impact

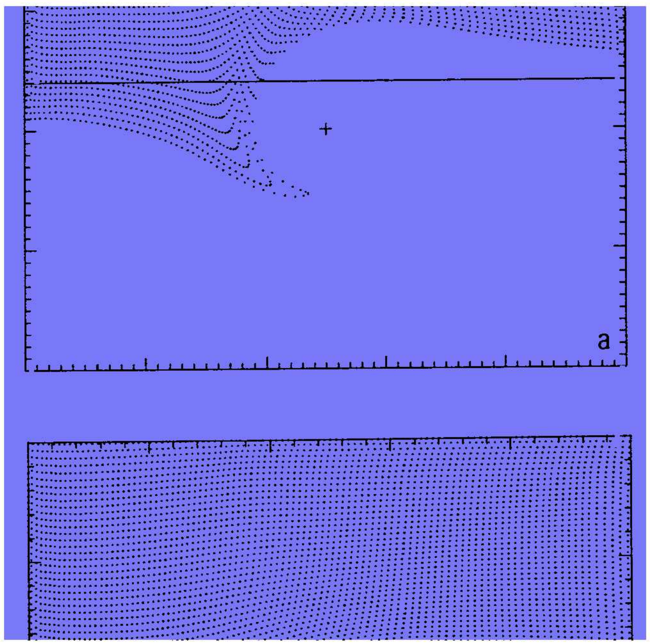


Cantilever



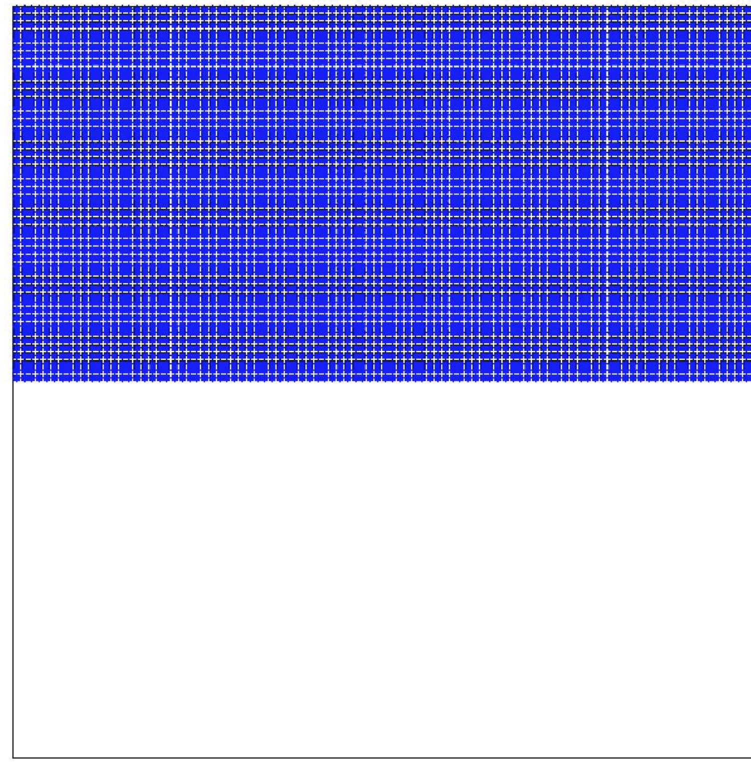
CONTACT MODEL TESTING

- Flato (1993) test case
  - 500 x 500 km domain
  - Constant in time swirling atmospheric wind field
  - Linear drag for atmospheric and ocean forcing



PIC solution after 5 days

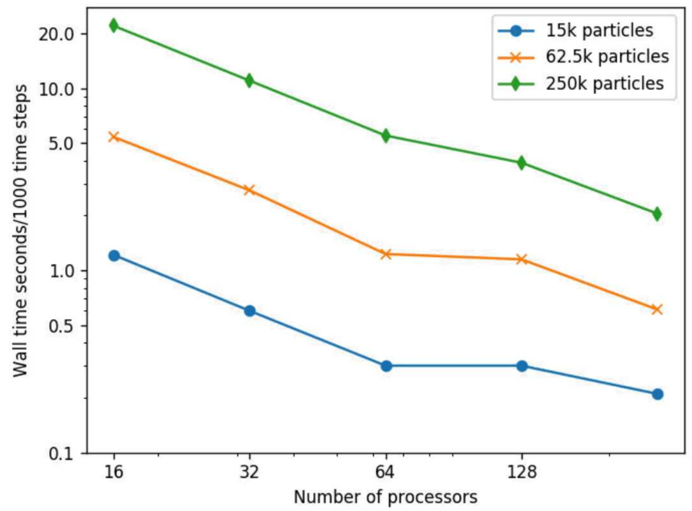
DEMSI solution through 5 days



PERFORMANCE

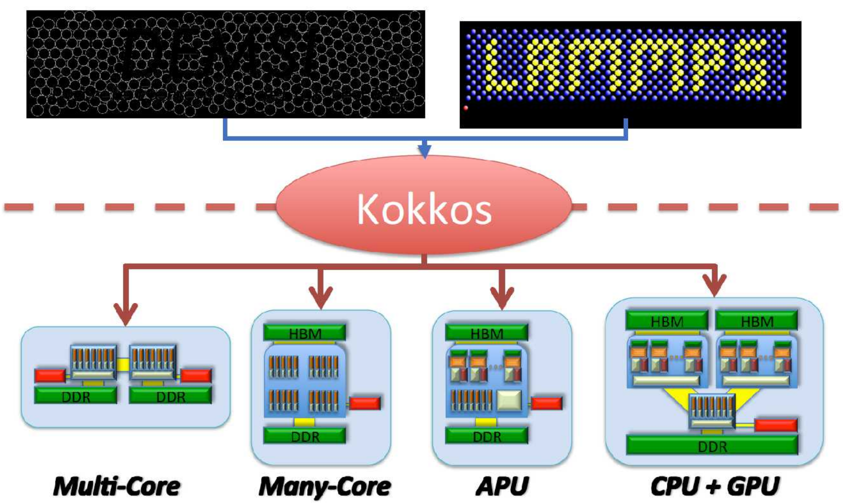
- Global climate simulations are computationally expensive
- Future codes will need to run on DOE next generation computers with heterogeneous architectures
- DEMSI using Kokkos programming model for acceleration

MPI-only Performance



Kokkos

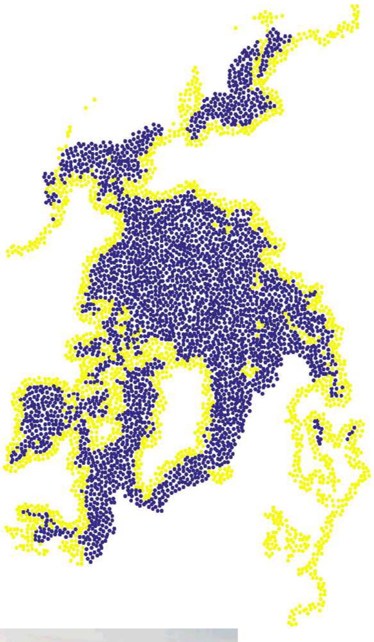
- C++ library
- Shared-memory programming model
- Enables writing algorithms once for many architectures
- Uses multi-dimensional arrays with architecture-dependent layouts

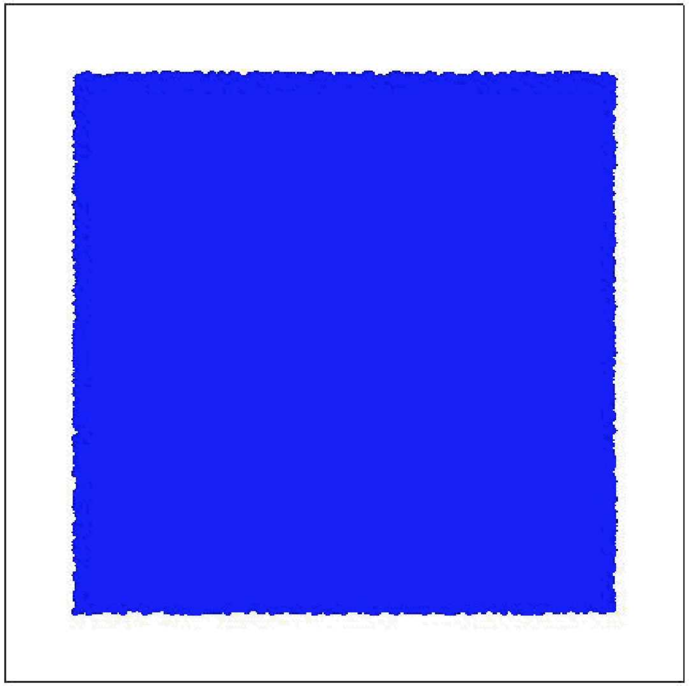


https://github.com/kokkos

NEXT STEPS

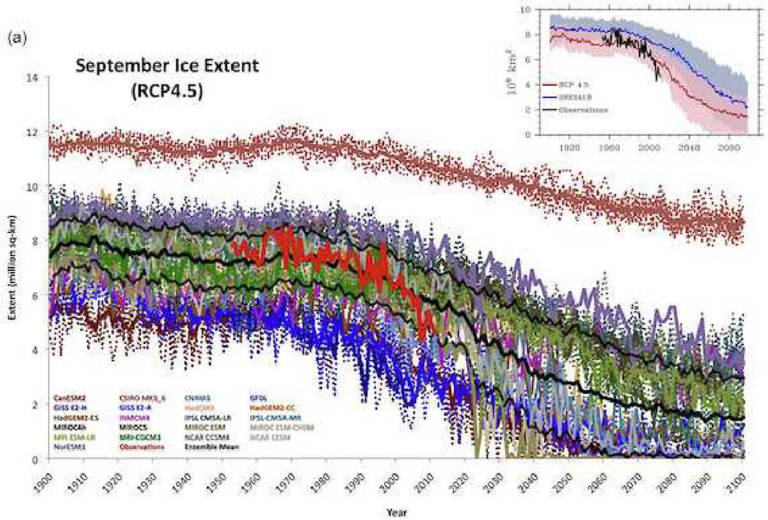
- Continue to improve sea ice contact model
- Regional and basin-scale testing
- Test options for element creation, destruction, and deformation
- Performance testing on GPUs





ARCTIC TIPPING POINTS

Objective: Gain understanding of the important feedbacks between Arctic physical and biological components and stability of the Arctic system.



Stroeve et al., (2012) *GRL*

Motivation:

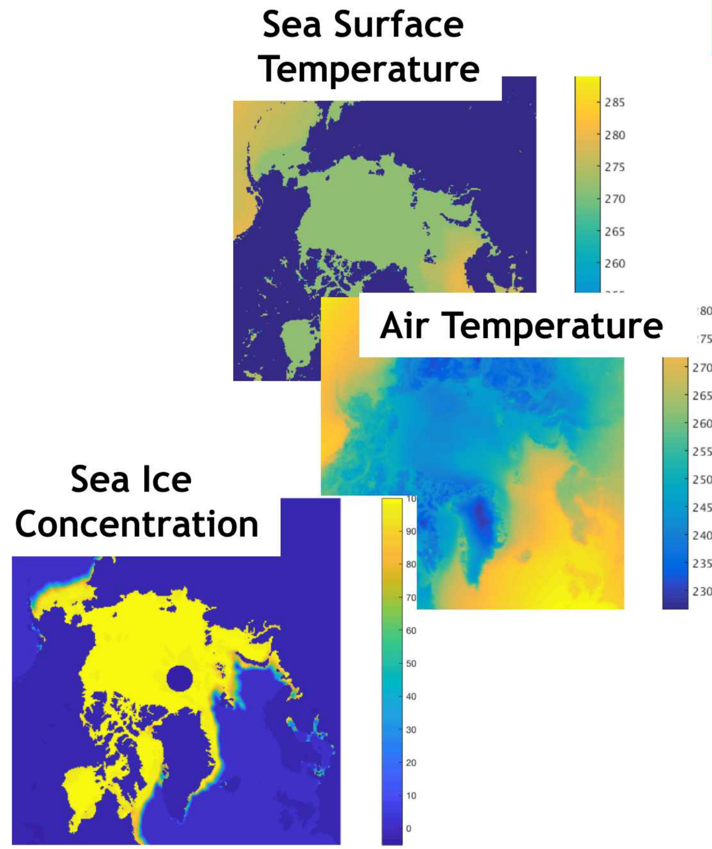
- Quantify system feedbacks that lead to sea ice loss using coupled Earth system models (E3SM) and data driven (machine learning-based) models.

E3SM
Energy Exascale
Earth System Model

Collaborators: Ray Bambha, Diana Bull, Jennifer Frederick, Jasper Hardesty, Anastasia Ilgen, John Jakeman, Amy Powell, Matt Peterson, Erika Roesler, Cosmin Safta, David Stracuzzi, Irina Tezaur, Mike Parks (SNL)

DATA DRIVEN MODEL

- Develop data-driven, predictive models for sea ice concentration in the summer season
- Using historical data from 1979-present for ice, ocean and atmosphere quantities
- Investigate whether predictive models provide new insights into coupled simulation

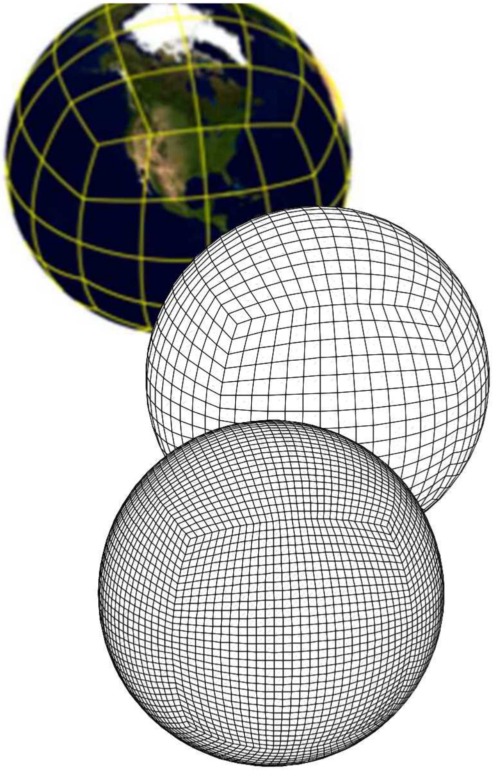


- Sea ice concentration https://nsidc.org/data/G02202/versions/2, Meier, *et al.* (2013)
- Reanalysis data (air temp, surface pressure, wind, downward longwave) https://www.esrl.niaa.gov/psd/data/gridded/data.ncep.reanalysis2.html, Kanamitsu, *et al.*, (2002)
- Sea surface temperature ftp/ncdc.noaa.gov/pub/data/cmb/ersst/v4, Huang, *et al.* (2014).

COUPLED MODELING

- Employ the DOE Energy Exascale Earth System Model (E3SM) to investigate system feedbacks that may lead to tipping events.
- Enrich high-fidelity simulations (~1 degree global) with an ensemble of ultra-low and medium resolution simulations to tractably capture uncertainty.
- Investigate stability of Arctic sea ice in ensemble members.

Ultra-Low Resolution Atmosphere Mesh



E3SM
Energy Exascale Earth System Model

CONCLUSIONS

- Arctic is changing rapidly
- Accurate and computationally efficient sea ice models are important for future predictions of the global Earth system
- Much work remains in understanding
  - Sea ice dynamics
  - Interactions with ocean and atmosphere
- Improvements in material models, numerical methods, and computational performance can have a large impact on sea ice predictions