SAND2022-7831C

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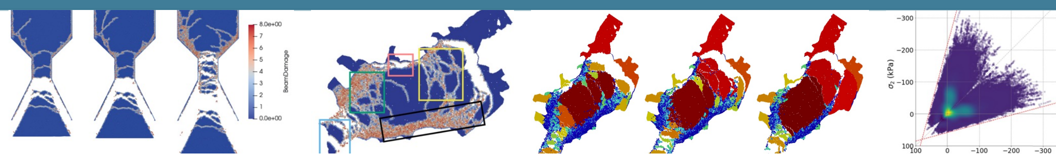
# Modeling High-Resolution Sea Ice Dynamics with a Bonded Discrete Element Method



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U.S. DEPARTMENT OF ENERGY NNSA

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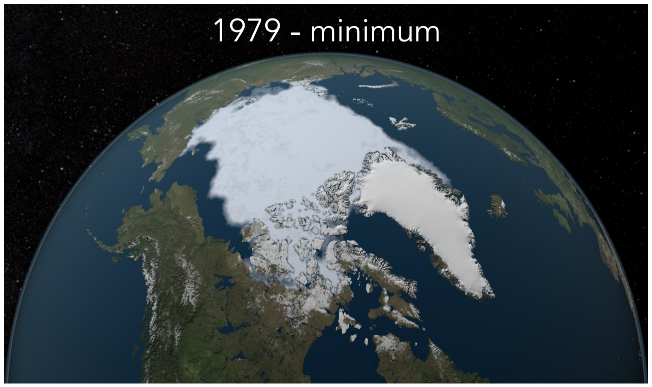
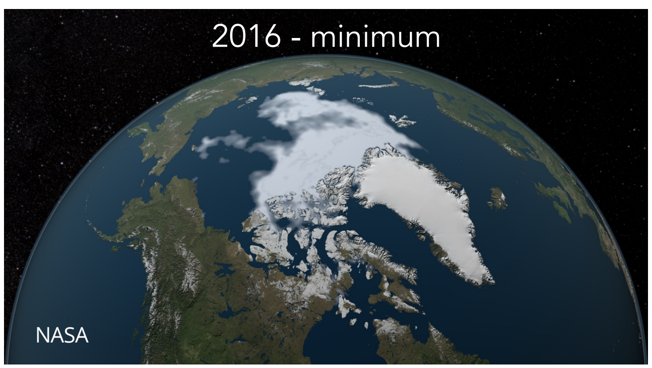
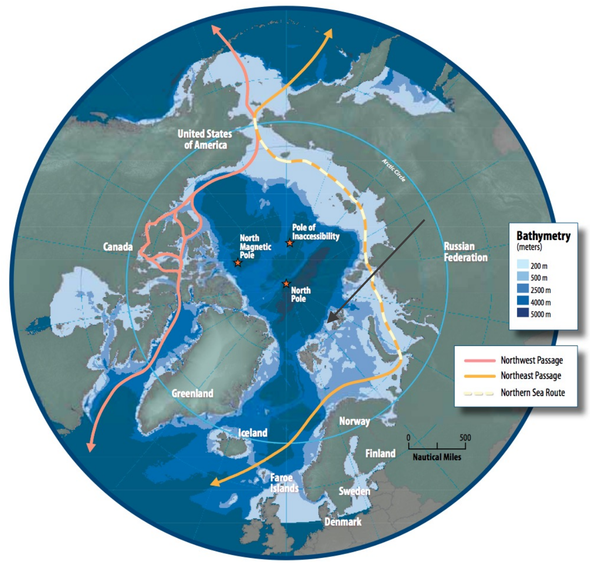
# The Arctic is Changing




- Navigating the new Arctic
  - Younger and thinner ice
  - Increased wave fetch with larger marginal ice zones
  - Increased vessel activity with new shipping routes opening
- New models and updated ice rheologies are needed to predict ice dynamics in the Arctic

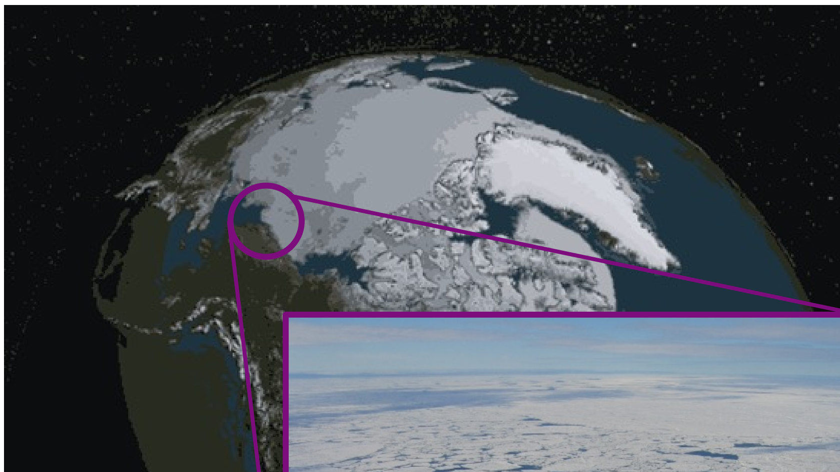
**Russian tanker sails through Arctic without icebreaker for first time**

**Climate change has thawed Arctic enough for $300m gas tanker to travel at record speed through northern sea route**

**Arctic nations square up as clamour for resources grows**

With the Danes rebuffing Russia, and Canada laying further claim to the Northwest Passage, rising access to north pole reserves risks flashpoints

# Modeling Sea Ice Dynamics



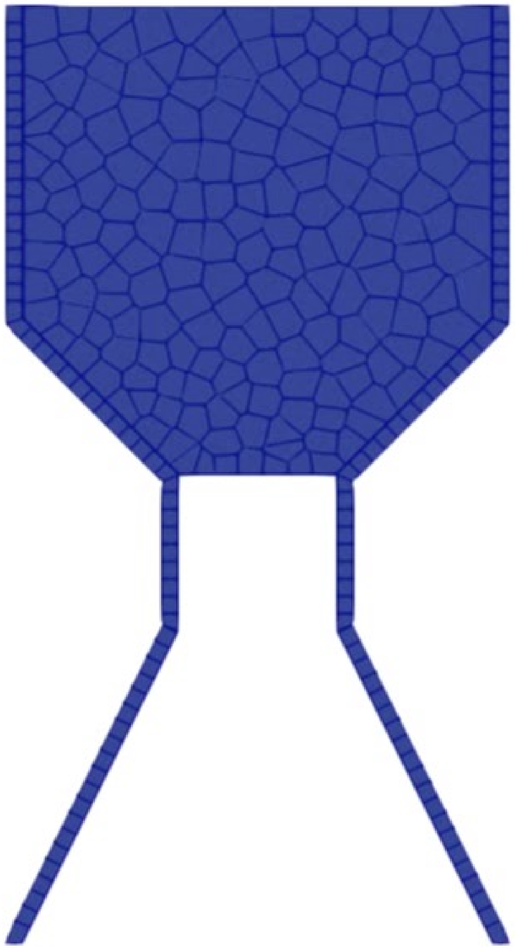
Evoluti

- Most often modeled at the Arctic basin scale
- Important component of Earth System Models (ESM)
  - Impacts planetary albedo
  - Coupled with ocean and atmospheric models
- Eulerian perspective
  - Ice behaves more like a viscous fluid
- Assumed to be a continuous material at all scales
  - Viscoplastic constitutive law
  - Based on observations made by the Arctic Ice Dynamics Joint Experiment (AIDJEX)
- Can we use these models to predict short term (days) and high resolution (100's m to km's) ice dynamics?
  - Near term sea ice forecasts for navigation
  - "High resolution" models are needed

[1] https://svs.gsfc.nasa.gov/11999

# ParticLS Simulation Framework

- CRREL-developed general purpose meshless method code
  - Discrete Element
  - Peridynamics (not discussed in this talk)
- Purpose built for modeling sea ice dynamics
- Spherical and non-spherical particle geometries
  - Particle geometries defined by level sets
- Rigid and bonded contact laws
- Code written in C++
- Threaded parallelization with OpenMP
- Open source (available on GitLab)

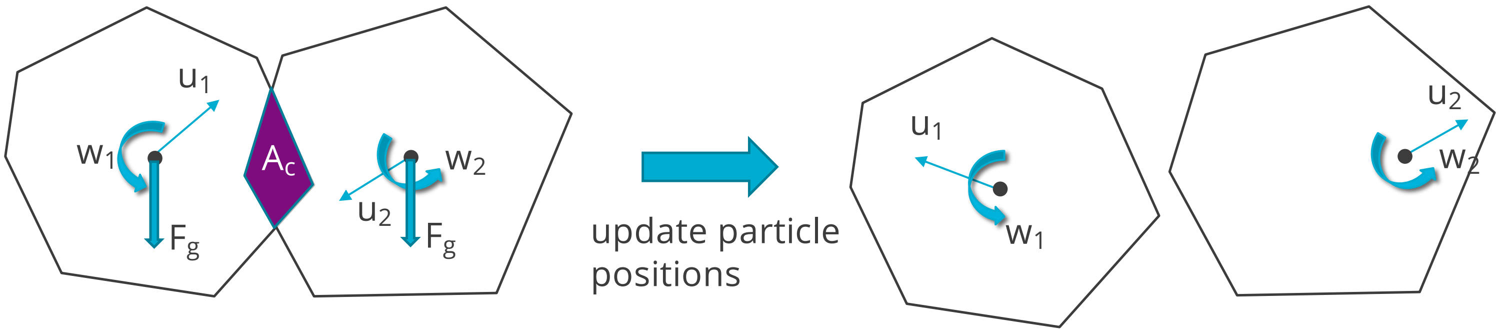


A. Davis et al. "ParticLS: Object-oriented software for discrete element methods (DEM) and peridynamics with applications to geophysics and ice physics" (accepted).

# The Discrete Element Method

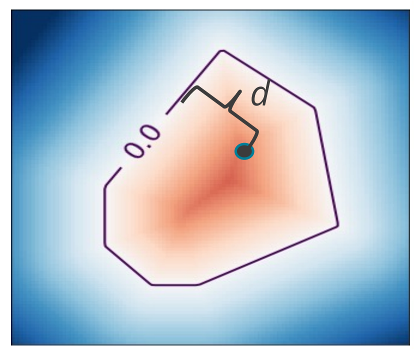
- Particle-based method (e.g. granular media modeling)
  - Individual particles treated as rigid
- Particle-Particle contact
  - Contact force: $F_c = KA_c$
- Rigid body dynamics
  - Translation: $m_p \frac{\partial u_p}{\partial t} = \sum F_c + F_e$
  - Rotation: $I_p \frac{\partial w_p}{\partial t} = \sum \tau_p$

Sea Ice (granular media)

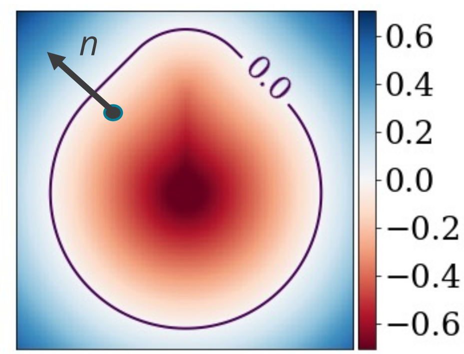


# Level-Set Based Particle Geometries

- Particle level set description (Kawamoto et al. 2016)
  - Surface ($\phi(x) = 0$), interior ($\phi(x) < 0$), exterior ($\phi(x) > 0$)
- Contact detection
  - Particles in contact if $\phi(x) < 0$
- Distance measures and contact normal
  - Penetration distance: $d = \phi(x)$
  - Contact normal: $\boldsymbol{n} = \frac{\nabla\phi(x)}{|\nabla\phi(x)|}$
- Contact force
  - Normal contact: $F = K_n \phi(x) \frac{\nabla\phi(x)}{|\nabla\phi(x)|}$



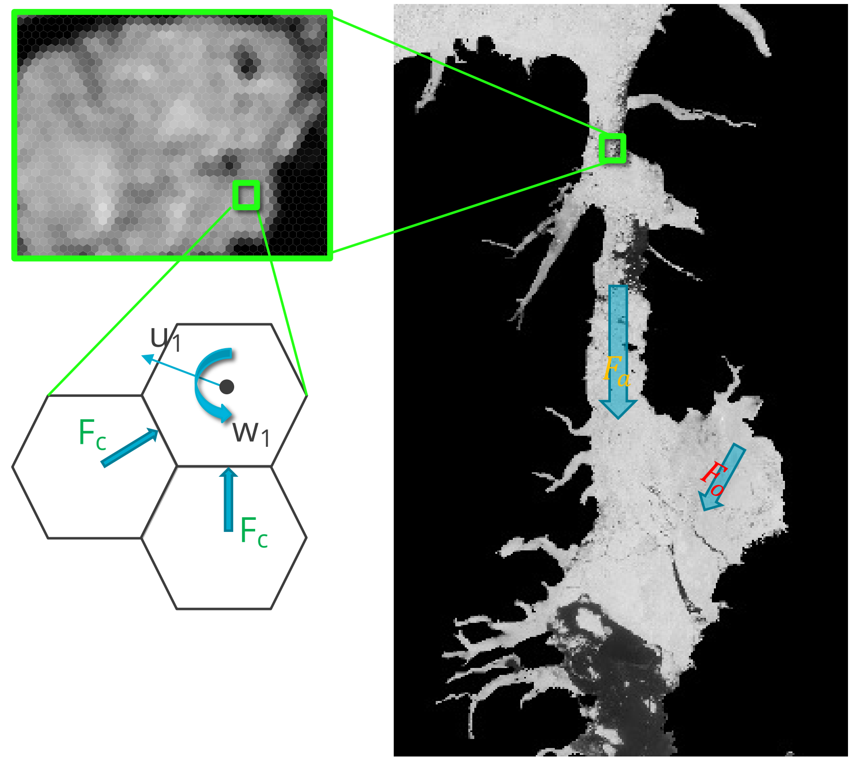
Polygon SDF with contact distance



“Pear” SDF with contact normal

# Application of DEM to Sea Ice Dynamics

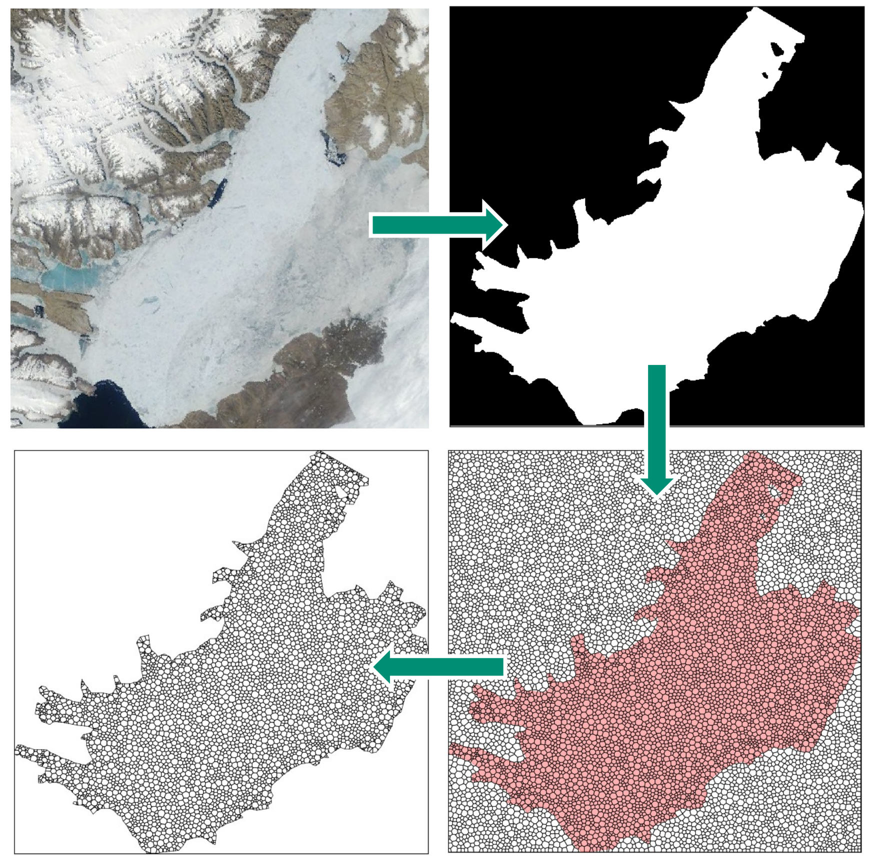
- Lagrangian formulation
  - Easily track sea ice positions and where cracks are
- Sea ice modeled as a collection of rigid particles (initialized from imagery)
- Able to capture finer scale aspects of sea ice dynamics related to it's discrete nature
  - Pressure ridging
  - Ice divergence/fragmentation
  - Floe rotation
- External forcing (drag-based)
  - Wind: $F_a$
  - Ocean current: $F_o$
- Sea Ice Dynamics
  - $m_p \frac{\partial u_p}{\partial t} = \sum F_c + F_a + F_o$




Nares strait 12, July 2015

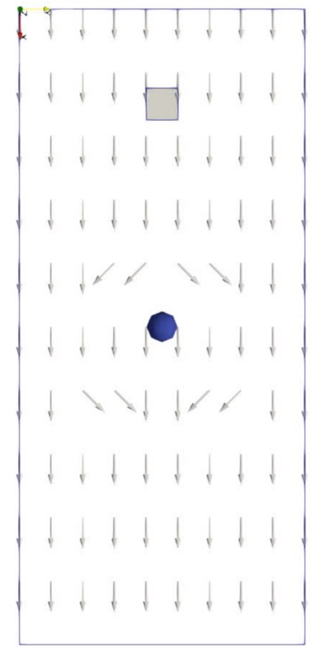
# Sea Ice Particle Initialization

- Acquire remote sensing image of domain
  - Typically use visible images, but could use SAR
  - Example sources: MODIS, PlanetScope, Landsat-8
- Threshold image to create binary image
  - Mask land using GIS software
  - Result is a binary image (ice pixels = 1, else = 0)
- Discretize ice extent
  - Allows the specification of particle size distributions
- Clip discretized polygons
  - Discretization creates polygons inside and outside domain – polygons are clipped by ice extent



# Momentum Transfer – Atmosphere and Ocean

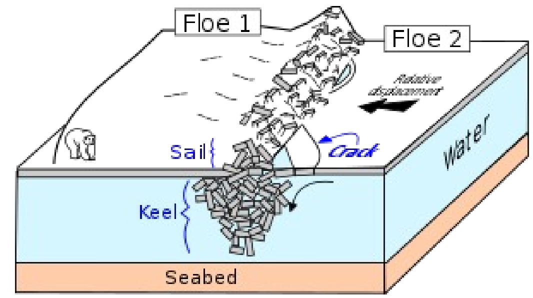
- Ocean and atmosphere drive the sea ice dynamics
  - Most often atmospheric winds are the largest driver
- Fixed background mesh stores the ocean and atmospheric velocity vector fields (time-varying)
- Atmospheric wind forcing on particles
  - $\overrightarrow{F_a} = \rho_a C_a A |\overrightarrow{v_a}| \overrightarrow{v_a}$
- Ocean current drag on particles
  - $\overrightarrow{F_f} = \rho_f C_f A \left|\overrightarrow{v_f} - \overrightarrow{v_{ice}}\right| \left(\overrightarrow{v_f} - \overrightarrow{v_{ice}}\right)$
- Simple drag-based model is approximating very complicated physics



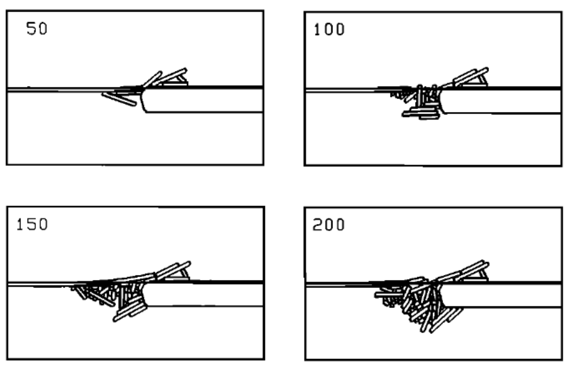
Square particle moving through vector field around stationary object

# Pressure Ridging as a DEM Contact Law

- Pressure ridging contact law developed by Hopkins (CRREL)
- Based on small scale explicit DEM simulations of pressure ridging

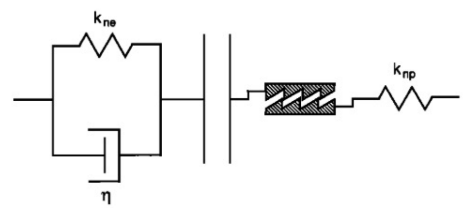



Pressure ridging process




DEM ridging simulations, Hopkins 1994

Homogenize




Viscoelastic: $F_n = K_{ne} A_e + \eta \dot{A}_e$

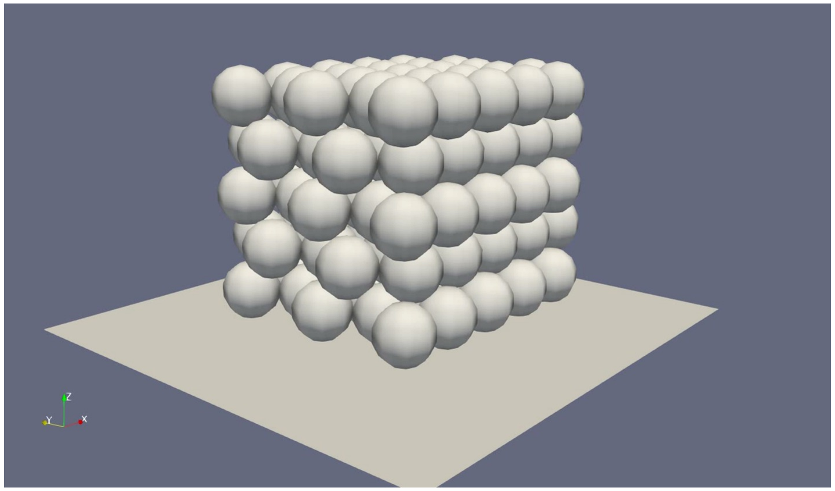
Viscoelastic-plastic: $\dot{A} + \left(\frac{K_{ne}}{\eta}\right) A = \left(\frac{1}{K_{np}}\right) \dot{F}_n + \left(\frac{1}{\eta}\right)\left[1 + \left(\frac{K_{ne}}{K_{np}}\right)\right] F_n - \left(\frac{K_{ne} K_r W}{\eta K_{np}}\right)$

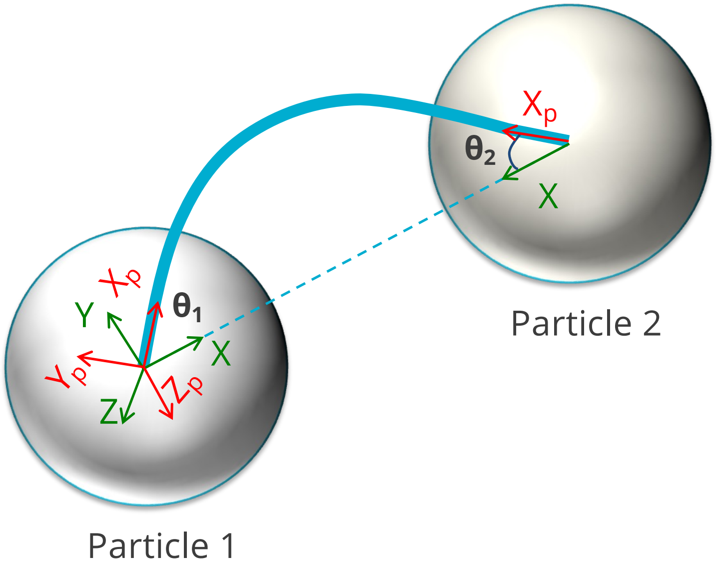
# Continuous Material Behavior with the DEM

- Want to be able to model floes that can deform and contact other floes
  - Kinetics: wind and ocean stresses can stretch and compress sea ice floes
  - Fracture: enough stress in a floe leads to fracture
- Approximate floes with many particles
  - How do these particles interact?

# Continuous Material Behavior with the DEM

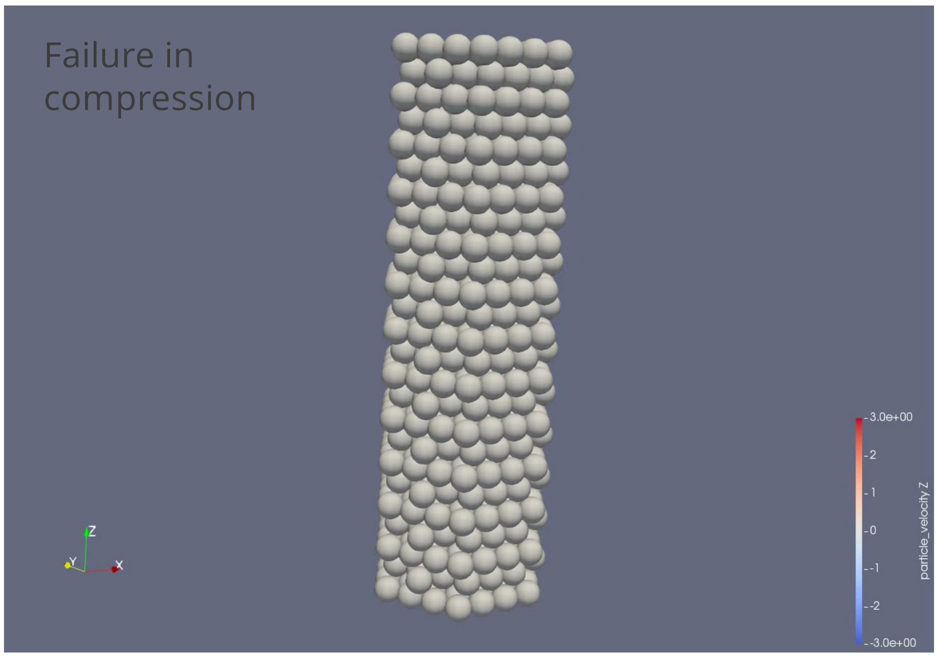
- Cohesive Beam Model
  - Response defined by solution of Euler-Bernoulli beam (stretching, bending, torsion)
  - Similar to lattice-spring model with rotation

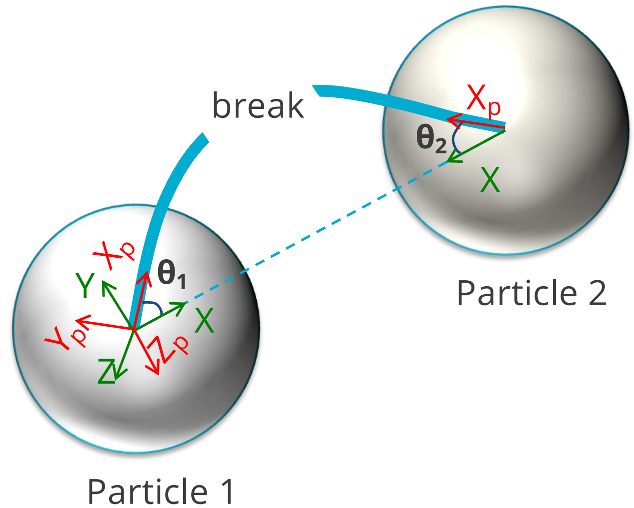





Cohesive Beam Model

# Local Fracturing of Cohesive Particles



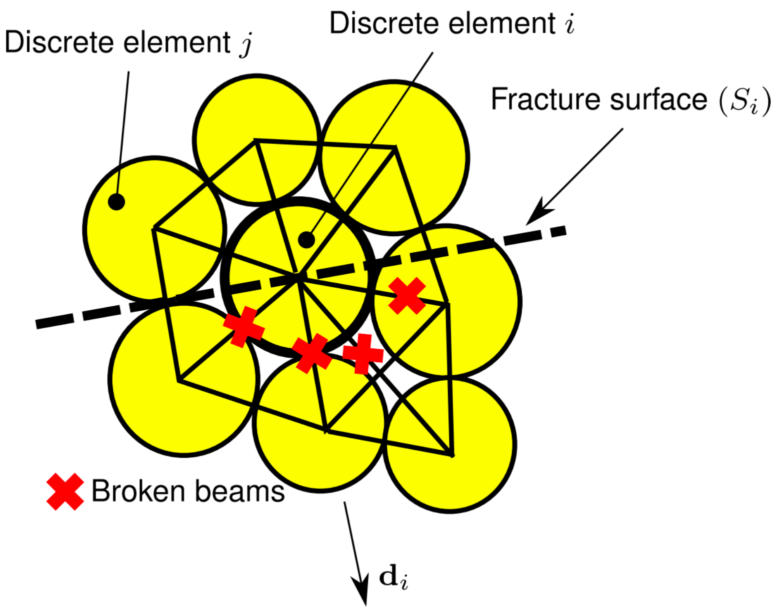

Local bond-based failure

Strain-based: $$\left(\frac{\varepsilon_x}{\varepsilon_f}\right)^2 + \frac{\max\left(|\theta_1|, |\theta_2|\right)}{\theta_f} \geq 1$$

Stress-based: $$E\varepsilon_x + \frac{My}{I} \geq \sigma_c$$

# Nonlocal Stress and Failure

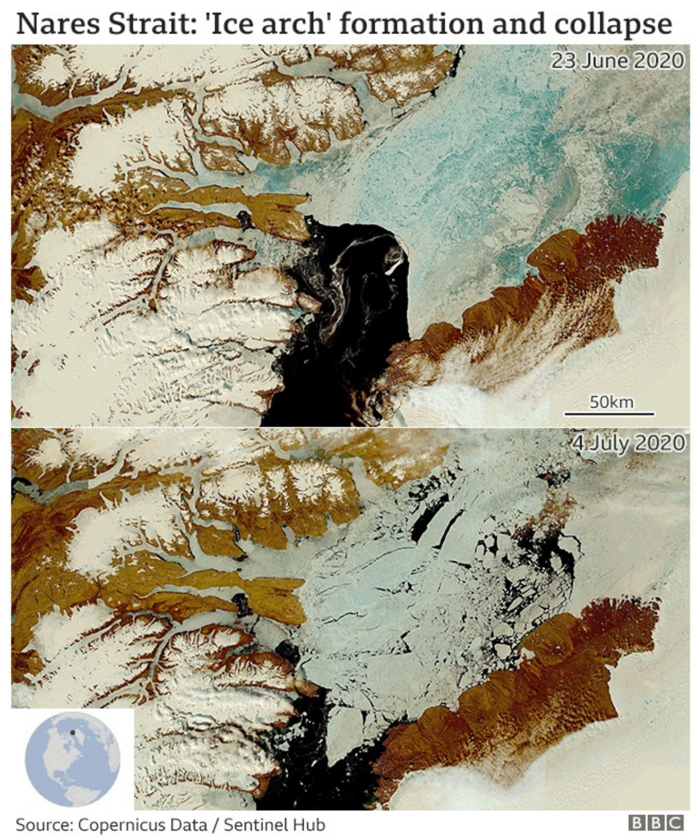
- Cauchy stress tensor calculated from nearest neighbors
  - $\sigma_i = \frac{1}{\Omega_i}\left(\frac{1}{2}\sum_j r_{ij}\otimes f_{ij} + f_{ij}\otimes r_{ij}\right)$
- State of failure defined by failure surface
- Failure surface defined by normal aligned with largest eigenvalue of stress tensor
  - Bonds are cut if cleaved by failure plane




Nonlocal Stress and Failure from Andre et al. 2017

# Ice Transport through the Nares Strait

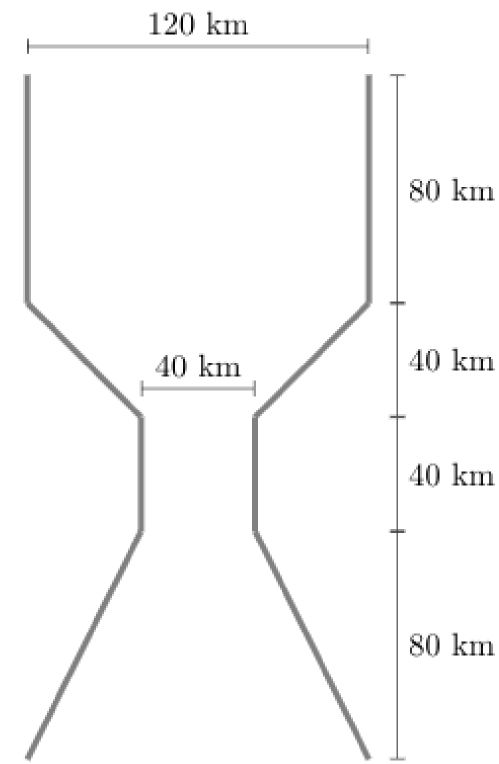
- Controls multi year ice transport out of the Arctic
- Arches develop and slow down ice transport
- Arches weakening due to climate change
- Increased ice transport can lead to a reduction of multiyear ice in the Arctic.


https://www.bbc.com/news/science-environment-55594585

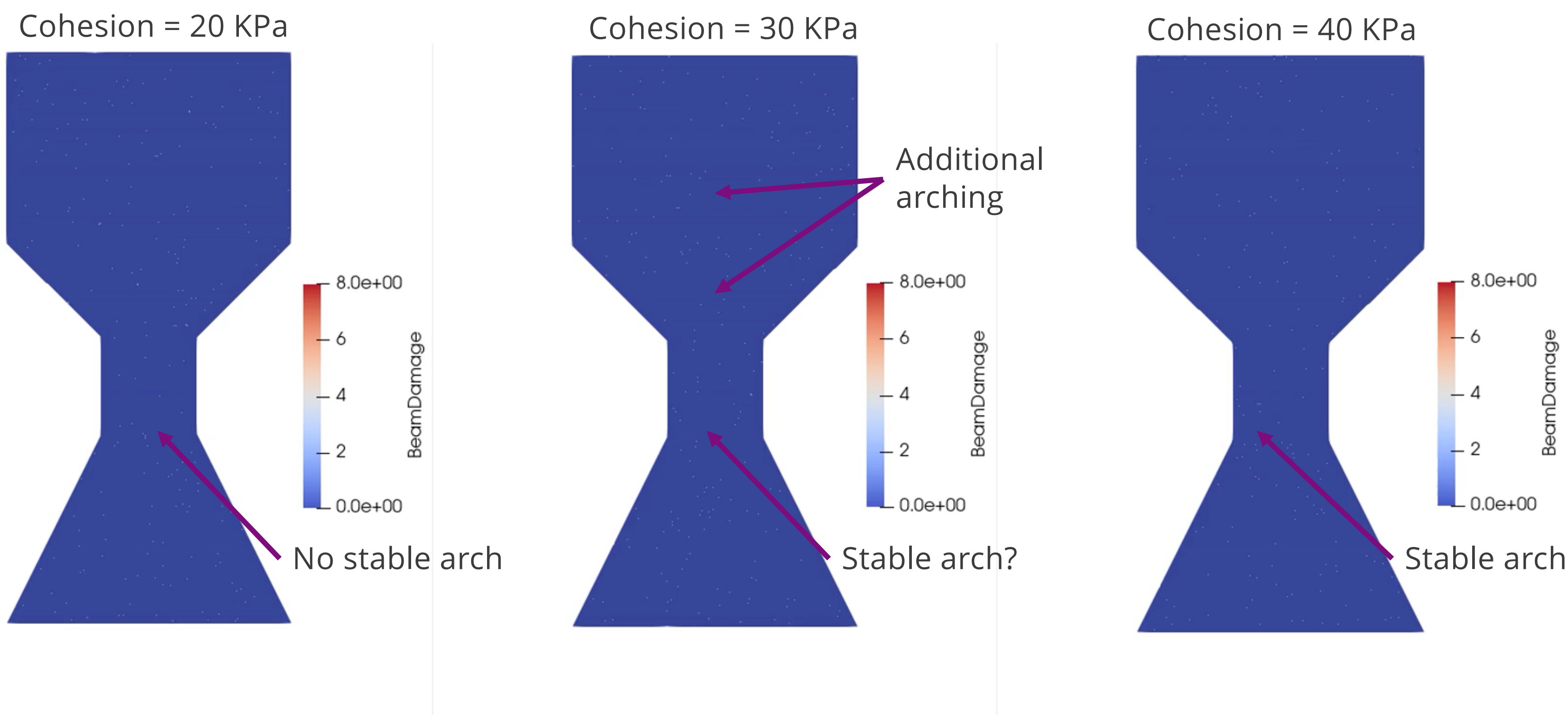
# Idealized Channel Simulation

- Geometry from Dansereau et al. 2017 (approximate regional scale of the Nares Strait)
  - Approximately 8000 particles with average particle radius of 1 km
- Sea Ice Properties:
  - Ice thickness is 1 m
  - Sea ice pressure ridging contact model
  - Mohr-Coulomb failure model
  - Vary material strength through cohesion term
- External Forcing:
  - Down-channel wind
    - Increases from 0 m/s to 22 m/s over 24 hours and then is constant for 24 hours
    - Approximates storm passing through region
  - Stagnant ocean
    - Only provides drag load resisting ice motion

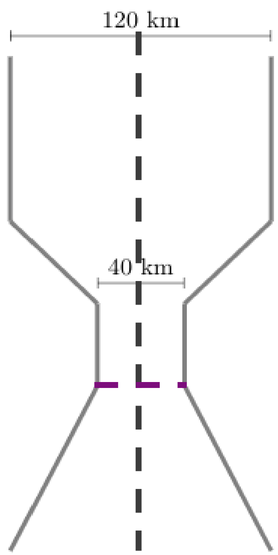


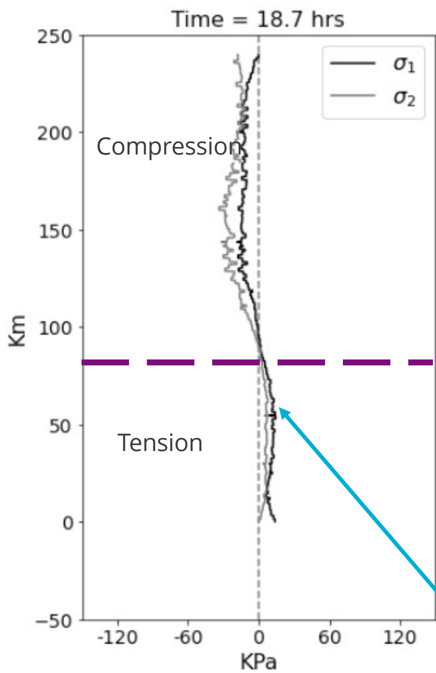
Idealized channel geometry

# Material Strength and Arch Formation

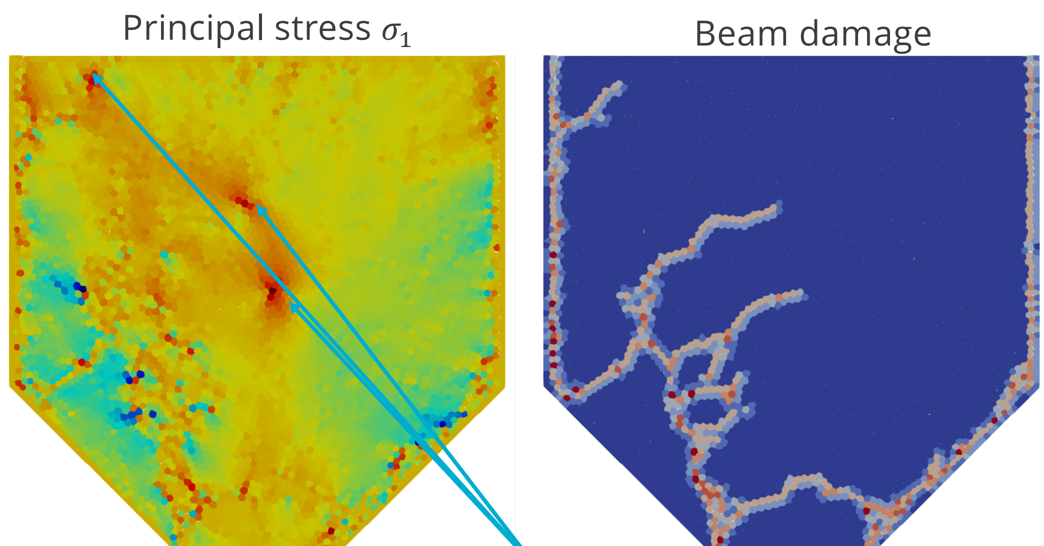


# Tensile Failure and Arch Formation




Principal stress prior to arch failure

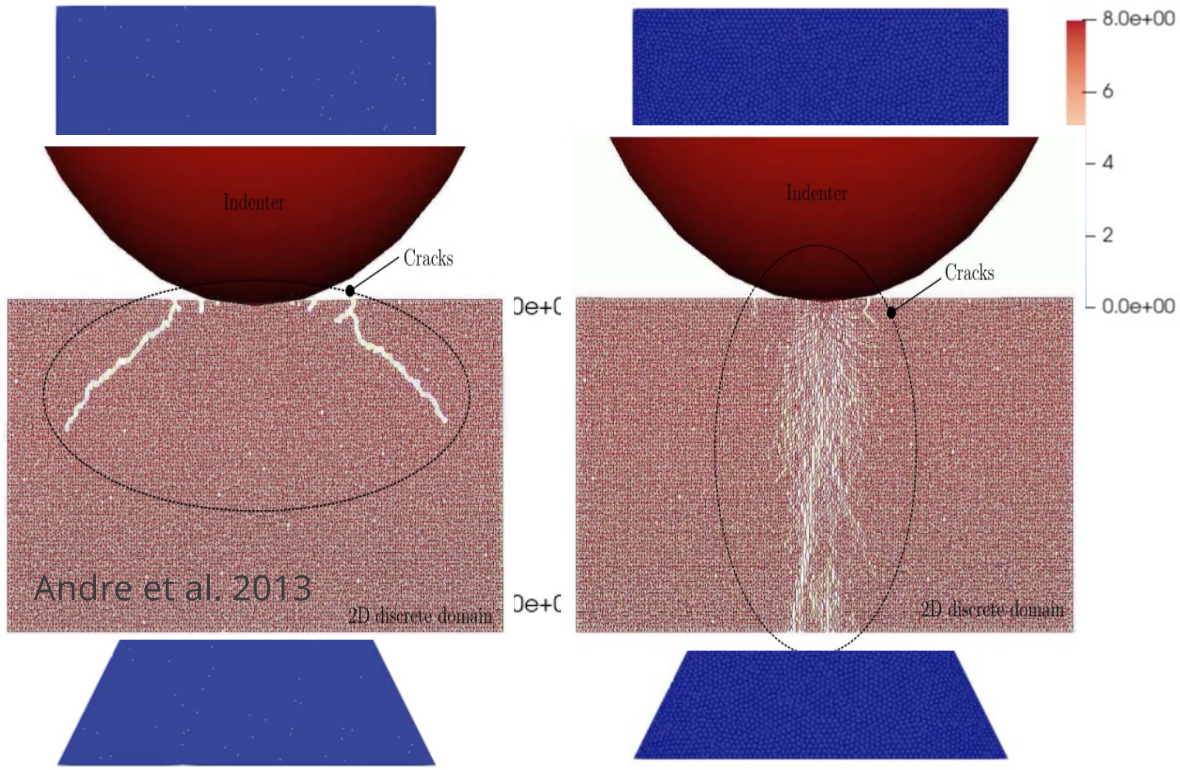



Large tensile stress seen at crack front

Tensile stress drives arch formation

# Nonlocal Stress and Sea Ice Break-up

- Equivalent ideal channel simulations
  - Mohr-Coulomb cohesion of 30 kPa
- Local stress-based failure model cannot produce a stable arch
- Similar behavior seen in other applications
- Can be avoided with softening in local bond model, i.e., cohesive model




Nonlocal failure model

Local failure model

# Nares Strait Simulation

- Geometry from MODIS imagery
  - Approximately 7000 particles with average particle radius of 1.2 km
- Sea Ice Properties:
  - Ice thickness is 1 m
  - Sea ice pressure ridging contact
  - Mohr-Coulomb failure model
  - Vary material strength through cohesion term
- External Forcing:
  - Down-channel wind
    - Increases from 0 m/s to 22 m/s over 24 hours and then is constant for 24 hours
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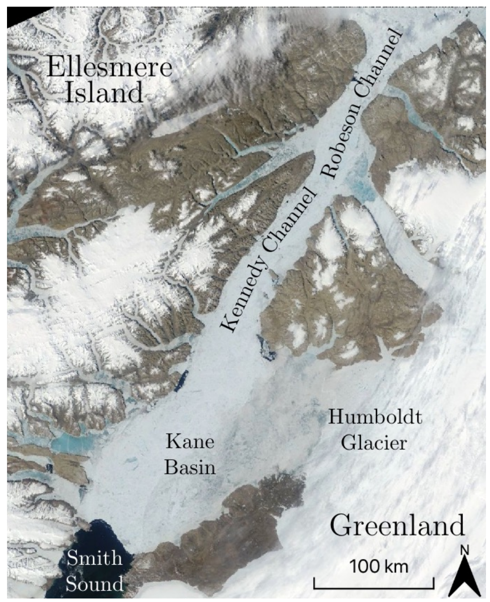
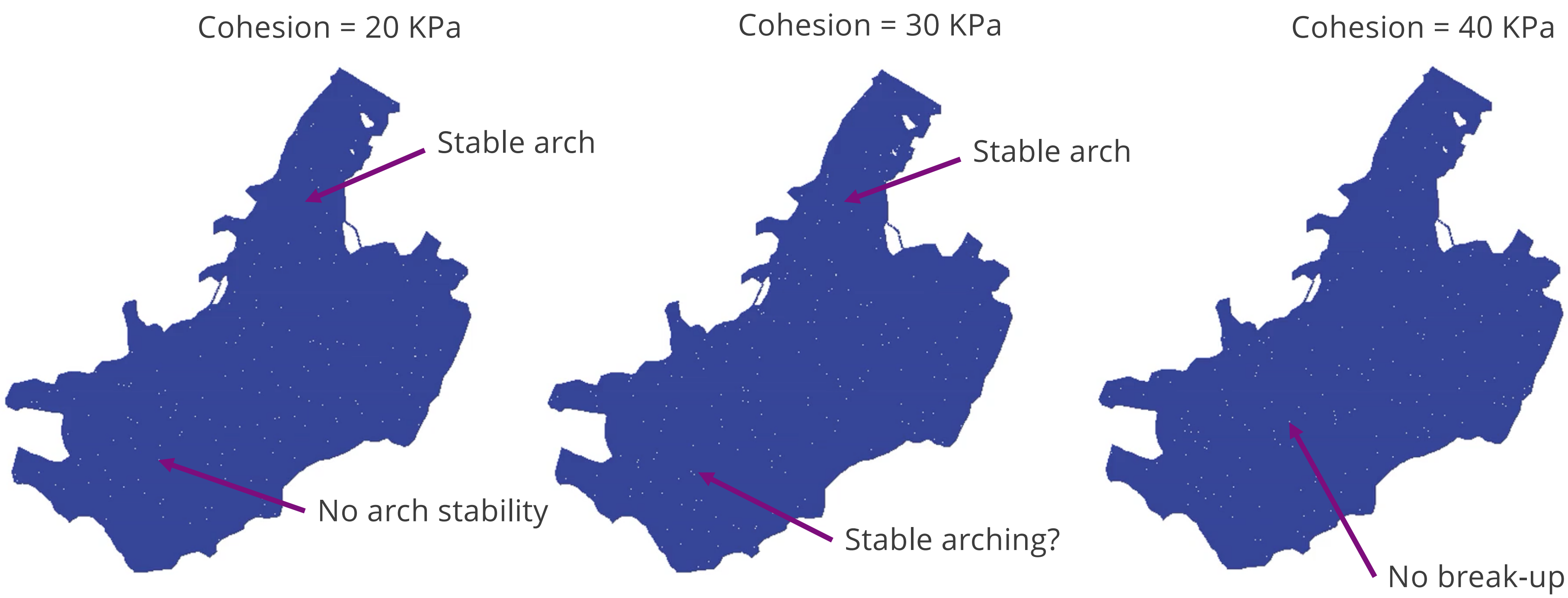



Channel and Kane Basin Region

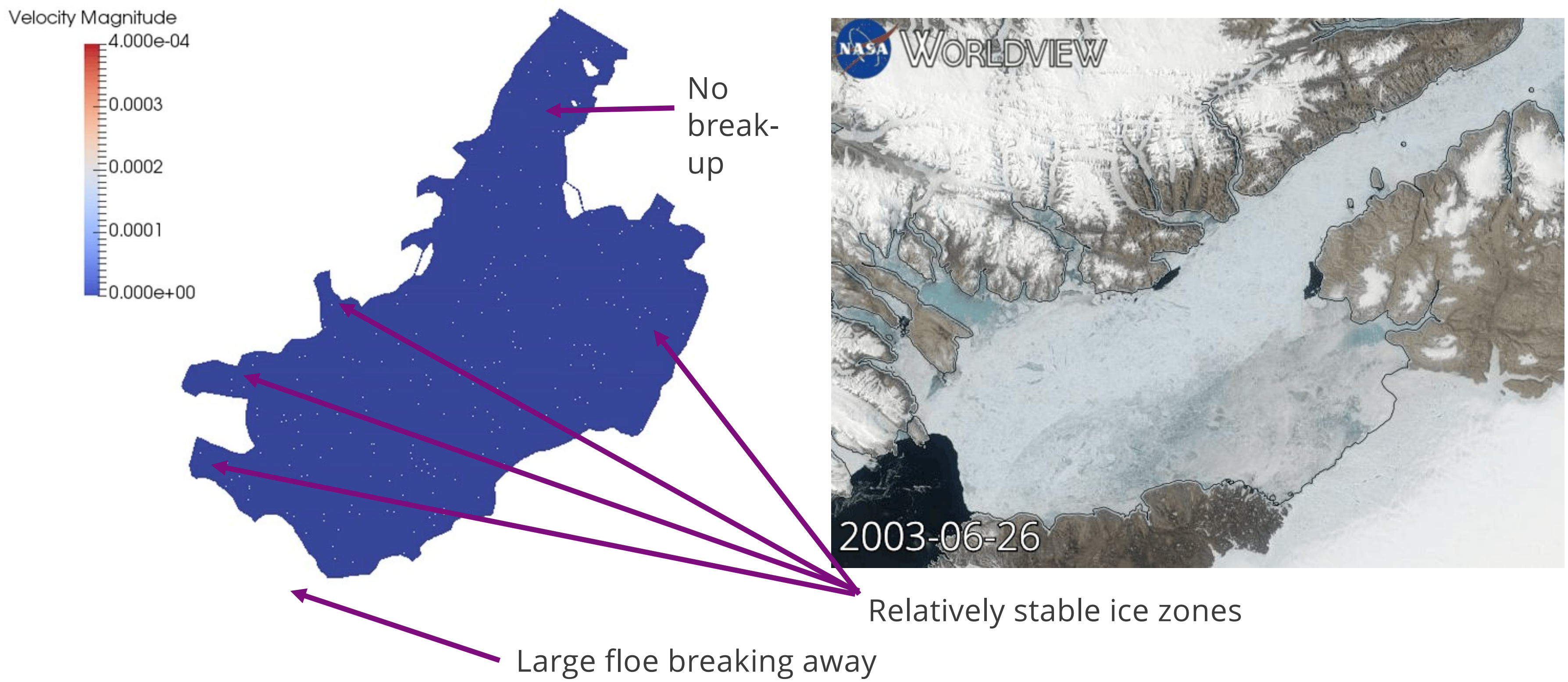
Down Channel Wind Field

# Arch Formation in the Nares Strait

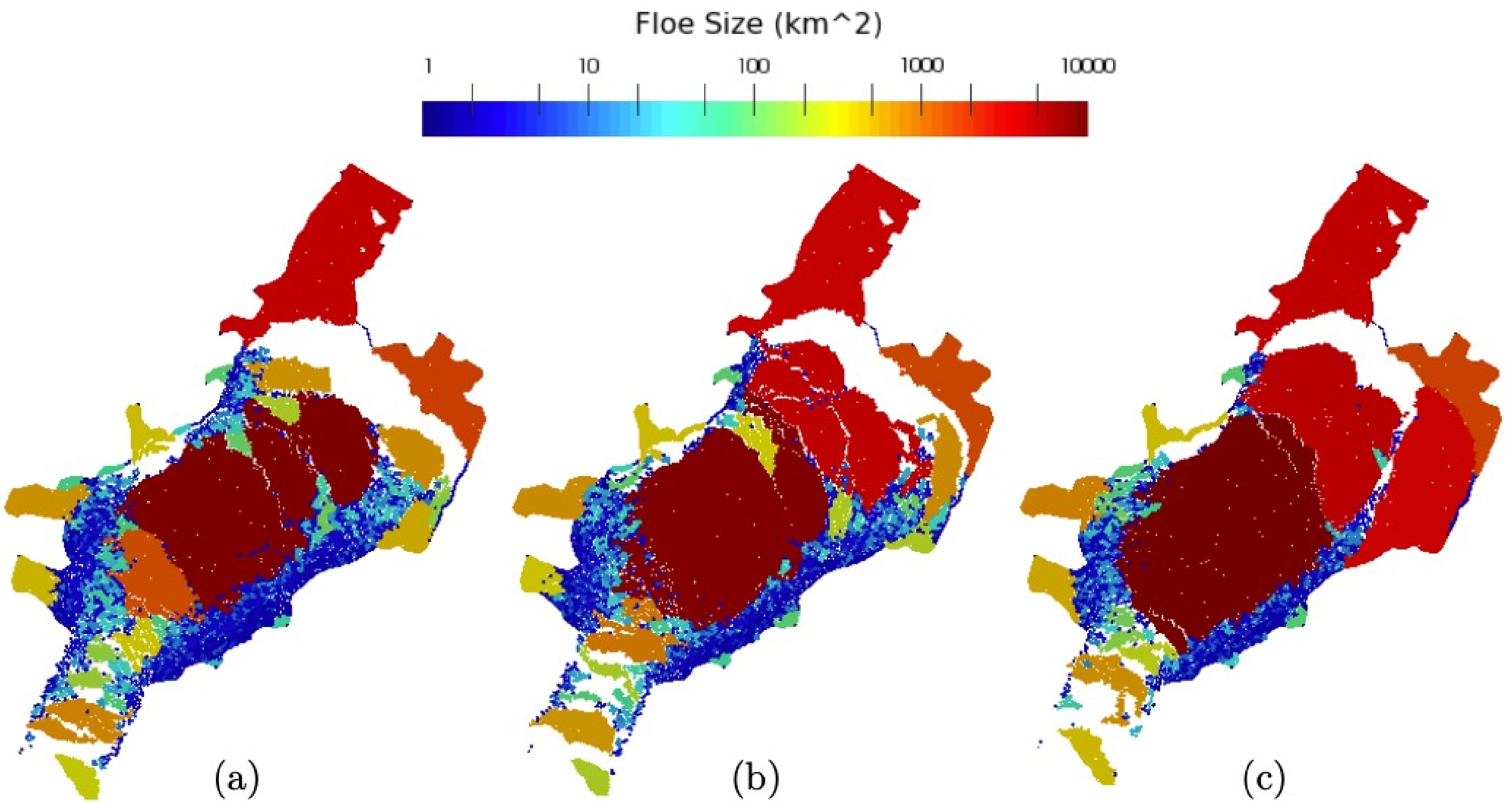



West et al, “Improving Discrete Element Simulations of Sea Ice Break Up: Applications to Nares Strait” (under review).

# Comparisons with Optical Satellite Imagery



# Floe evolution in Nares Strait

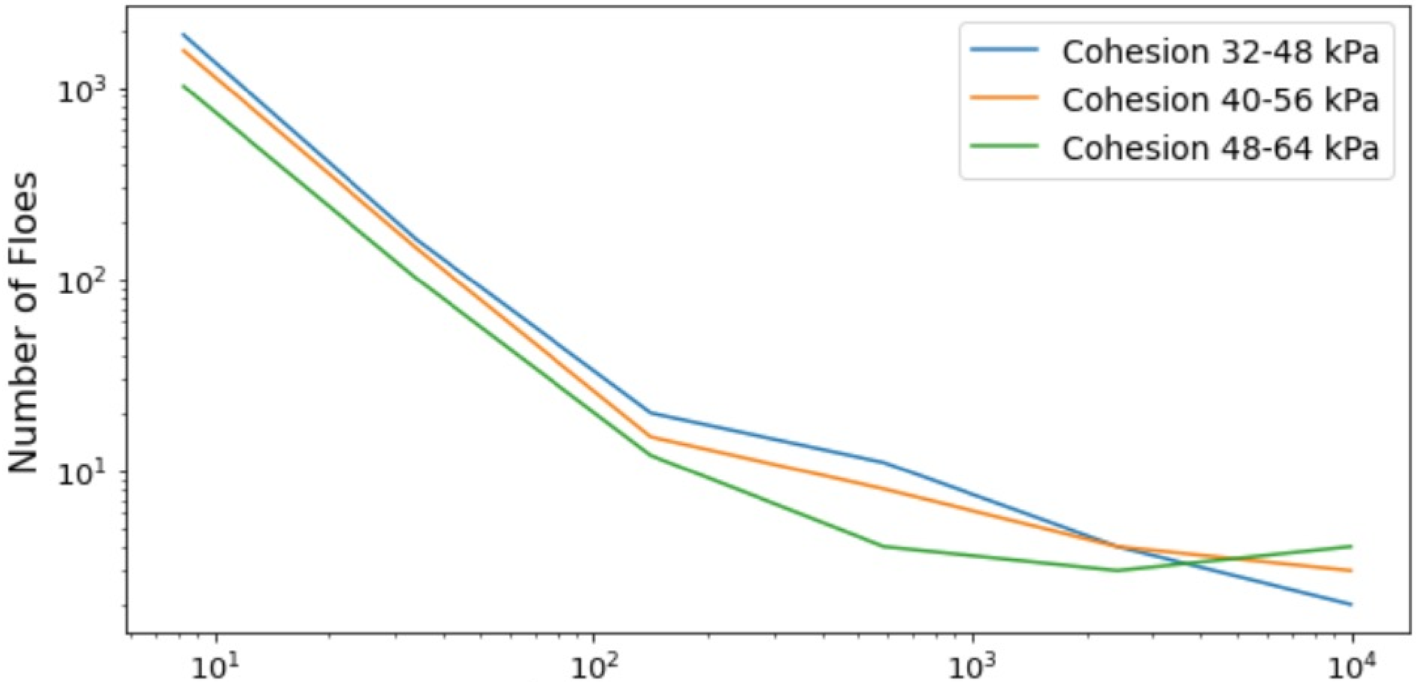



Cohesion 32-48 kPa

Cohesion 40-56 kPa

Cohesion 48-64 kPa

# Floe evolution in Nares Strait

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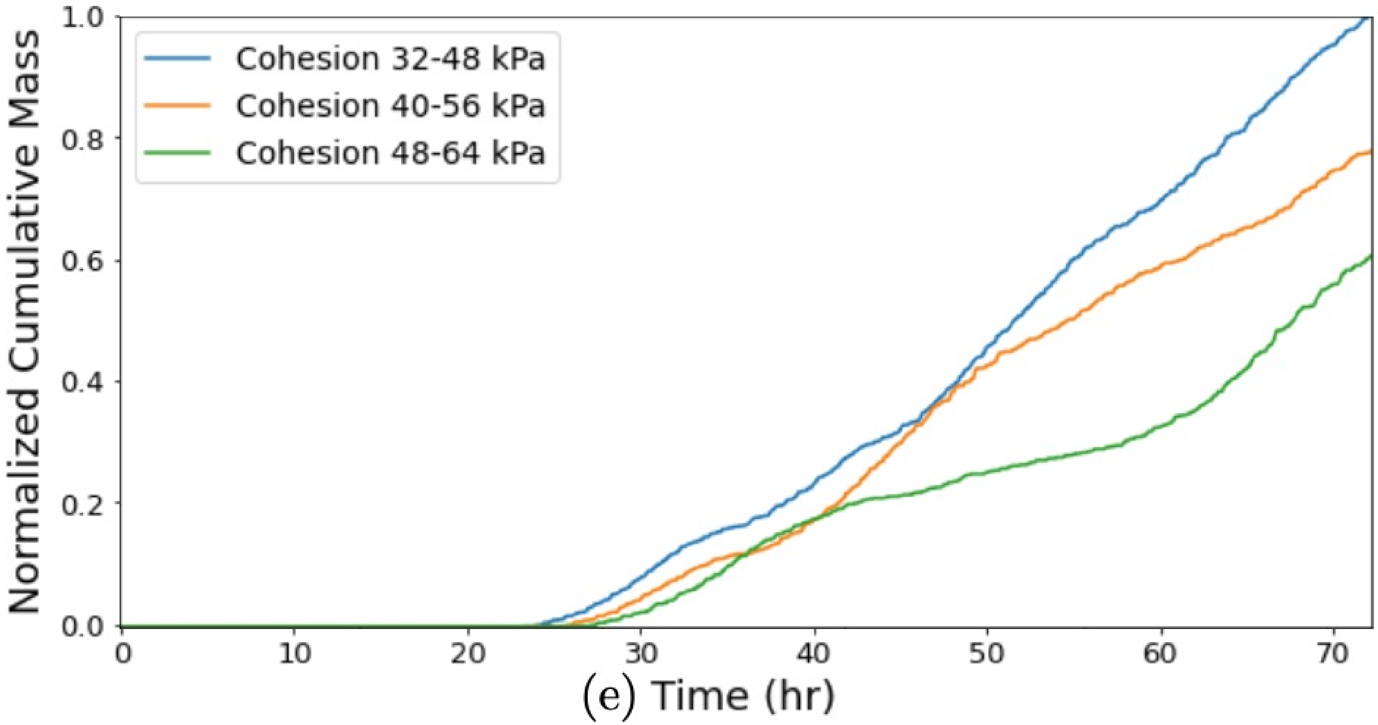
# Mass export out of Nares Strait



# Conclusions

- As interest in the Arctic continues to grow, new mod/sim tools will be needed to predict ice dynamics in the “new Arctic”, especially at regional scales
- CRREL DEM/Peridynamics code ParticLS
  - Developed with a focus on regional scale ice dynamics
  - Reproduces ice arching behavior seen in imagery
    - Model cohesion strength shown to control arching stability
  - Novel non-local stress used to evaluate failure
    - Stresses in domain fall with failure envelope
  - Floe size influenced by cohesion strength
- Ongoing efforts and future work
  - Moved to Sandia National Labs
  - Working on DEMSI for inclusion in earth system models

Questions or comments?
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