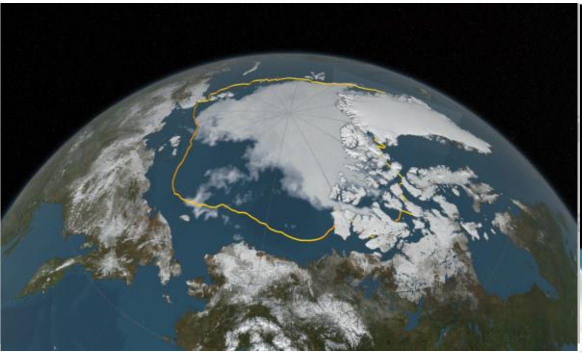

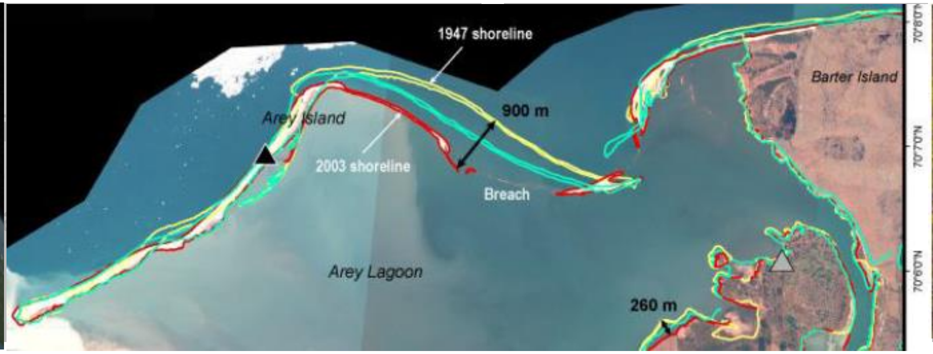

Development of a strongly-coupled thermo-mechanical model of permafrost for the simulation of Arctic coastal erosion

Alejandro Mota, Jenn Frederick, Charles Choens, Diana Bull, **Irina Tezaur**

Sandia National Laboratories, U.S.A.

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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Outline

- Motivation and background
- The Arctic Coastal Erosion (ACE) project
- Thermo-mechanical finite element model of permafrost
- Numerical results
- Summary
- Ongoing/future work

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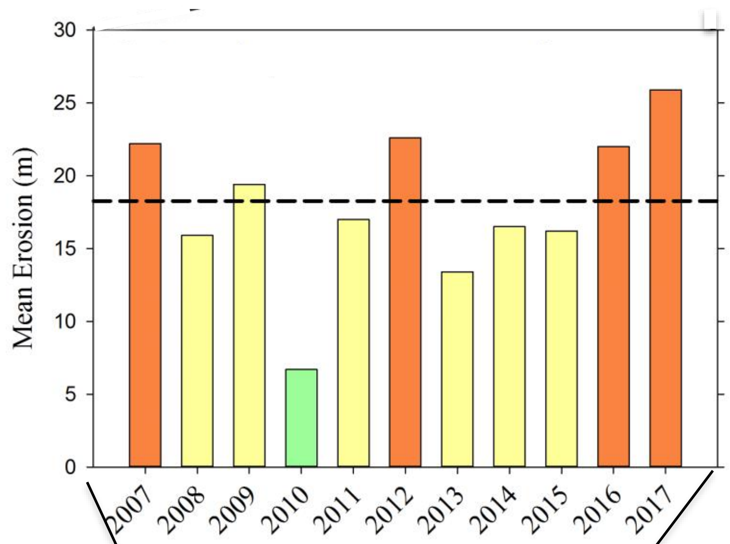
Motivation

The Arctic is warming at **2-3 times** the rate of the rest of the U.S. resulting in **accelerated rates of coastal erosion**!

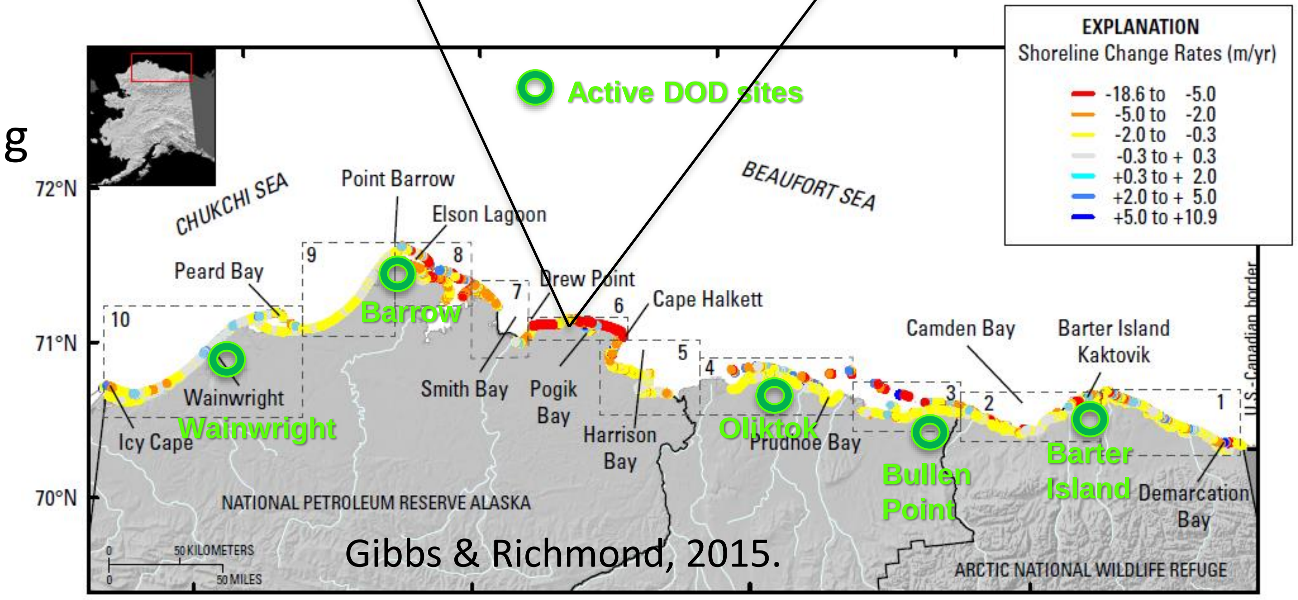
- Since 1979 **sea-ice** has lost 51% in area and 75% in volume
  - ➢ Increasing **ice-free season**
  - ➢ Increasing **wave energy** and **storm surge**
- Increasing **sea water** temperatures
- Warming **permafrost**
  - ➢ **Coastal erosion rates** in Alaskan Arctic among the **highest** in the world and **accelerating**.

Erosion is threatening:

- ➢ Coastal communities
- ➢ Coastal infrastructure
- ➢ Global carbon balance



~200 m (~2 football fields in length) in a decade!

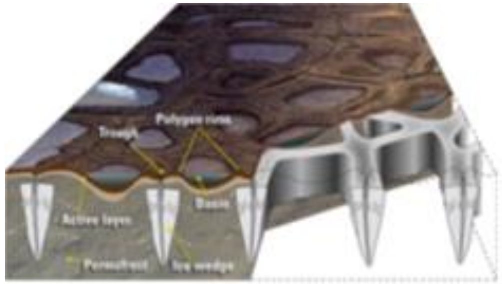


Gibbs & Richmond, 2015.

Permafrost erosion

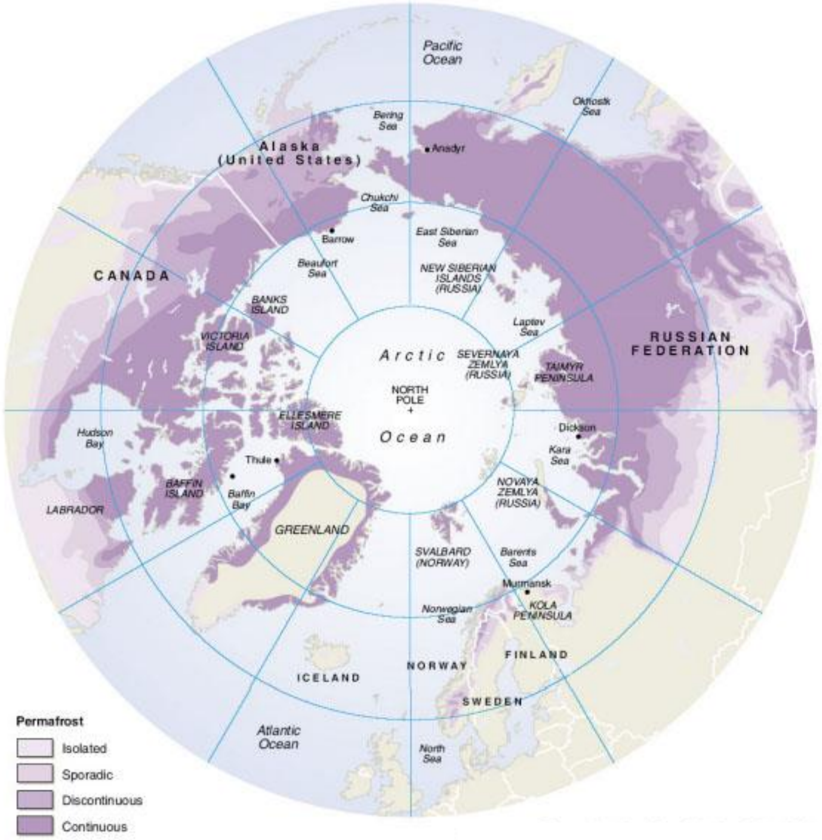
What is permafrost?

- Ground that remains frozen for 2 or more consecutive years.
- Comprised of soil, rock, silt, clay and sand, held together by ice.
- 24% of ice-free land area in Northern Hemisphere and 85% of Alaska Greenland, Canada and Siberia sits on top of permafrost.



Martin *et al.* 2009.

Left: schematic illustrating formation of ice wedges and ice-wedge polygon landscapes. *Right:* map of permafrost distribution in Arctic



Brown *et al.* 1998.

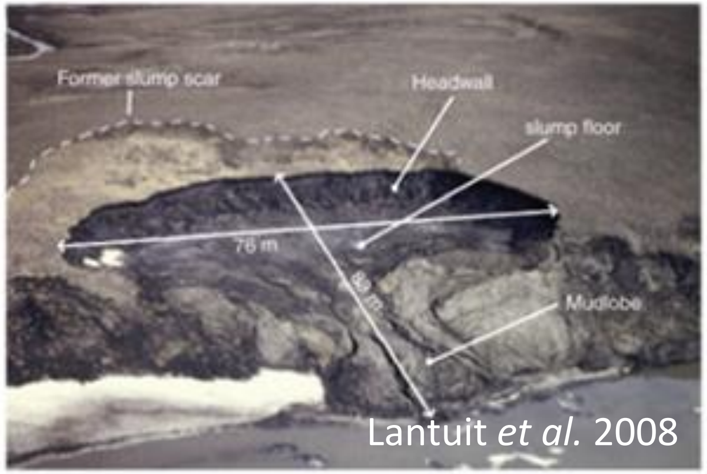
Unique coastal permafrost erosion process in Arctic:

- Predominant geomorphology: **ice-wedge polygons**
  - ➢ Ice acts to **bind** unconsolidated soils in permafrost forming ice wedges.
  - ➢ Ice wedges **grow/expand** up to ms wide and 10s meters deep.
- Melting ice causes permafrost **failure**.
  - ➢ **Storm surges** accelerate ice melt by delivering **heat** to ice/permafrost***.**

* Thermo-abrasion: permafrost material is warmed by ocean and removed by mechanical action of waves.

Permafrost failure mechanisms

- **Retrogressive thaw slumping**: a slope failure characterized by thaw of exposed ground ice and slumping of thawed soil, typically caused by thermo-denundation*.
- **Active layer detachment**: failures are translational landslides that occur in summer in thawing soil overlying permafrost, typically caused by thermo-denundation*.
- **Block failure**: a niche (recess at bluff base) progresses landward until the overhanging material fails in a shearing or toppling mode known as block failure.
  - ➢ Fallen blocks can disintegrate in the near-shore environment **within 1-2 weeks**!



Retrogressive thaw slumping

Active layer detachment

Block failure

* Subaerial erosion triggered by thawing of permafrost bluffs that proceeds under the influence of gravity.

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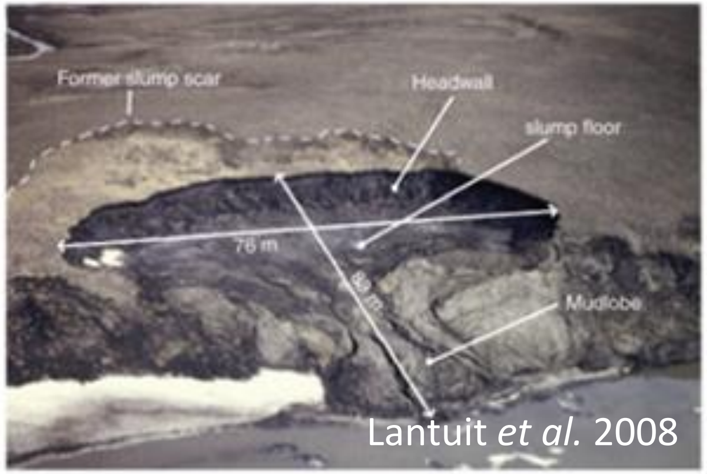


Retrogressive thaw slumping

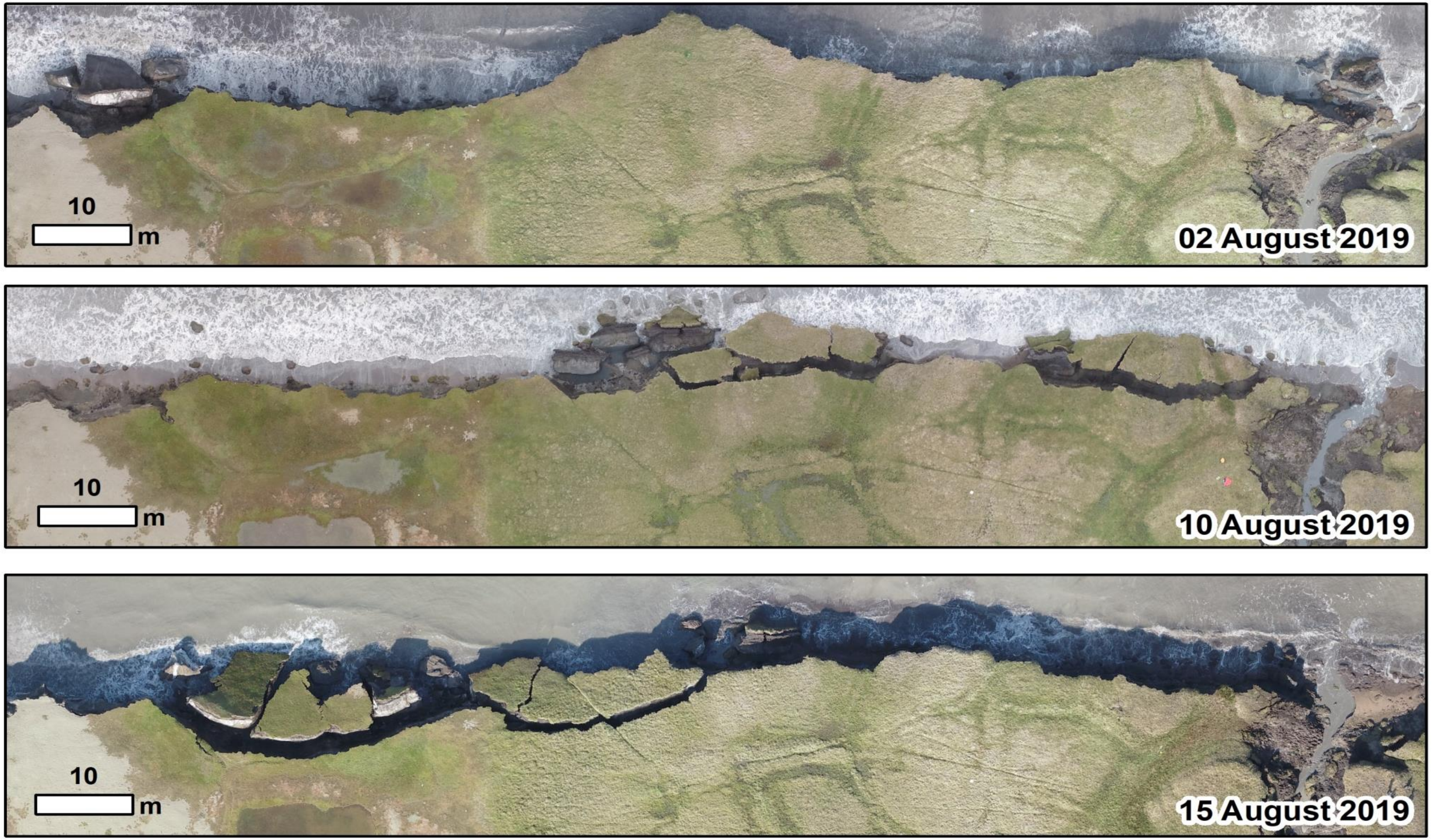
Active layer detachment

Dominant failure mechanism in northern Alaska

Block failure

* Subaerial erosion triggered by thawing of permafrost bluffs that proceeds under the influence of gravity.

Example of bluff erosion during 2019 UAV surveys*



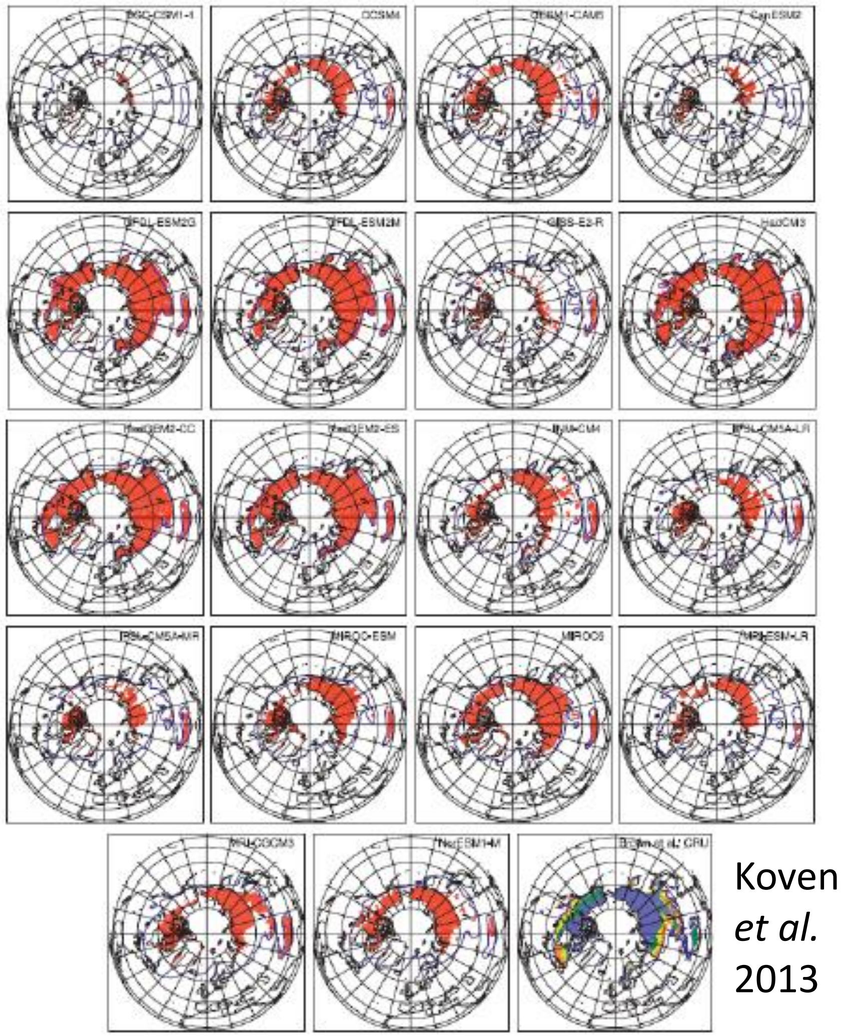
Fallen blocks can disintegrate in near-shore environment **within 1-2 weeks**!

*Images courtesy of Ben Jones, UAF

State-of-the-art in permafrost modeling

When this project began in 2017, tools to **accurately predict** Arctic coastal erosion **did not exist**!

- Existing models* are **primitive**: trend projection, empirical relationships, 1D steady state heat flow,…
  - ➢ Primarily **thermal models** (no mechanics/deformation)
  - ➢ Most models assume **particular type** of **erosion** (e.g. block failure)
- Efforts have been put towards integrating permafrost models into **earth system models (ESMs):** CLM, VAMPERS, CryoGrid3, ...
- Modeling typically estimates BCs and **does not** account for geomorphologies or geophysics.
- Comprehensive **understanding** of erosion dynamics in the Arctic has **not yet emerged**.



Koven *et al.* 2013

To obtain an accurate, **predictive** Arctic coastal erosion model, a **coupling** of the influences of evolving **wave dynamics**, **thermodynamics** and **mechanics** must be developed.

* See (Frederick *et al.* 2016), Chapter 5, for extensive overview.

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Proposed solution

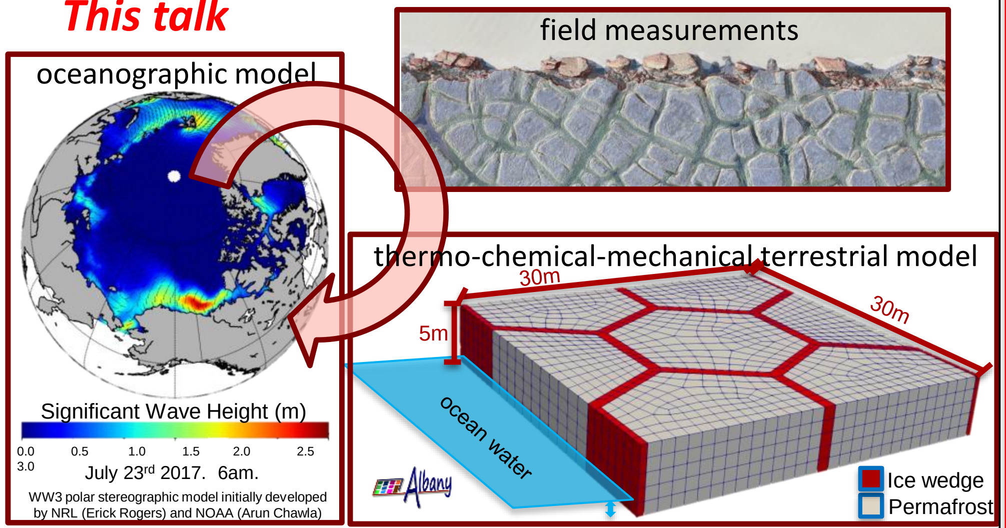
Goal of the **Arctic Coastal Erosion (ACE)** project is to deliver a **field-validated predictive model** of **thermo-abrasive erosion** for the **permafrost Arctic coastline**

2018-2020 → **Micro-scale Model**

10's of meters & storm duration

- ***Multi-physics finite element model*** of an archetype of the coastline coupled with high-fidelity model of storm intensities
  - Input variables define geomorphology & geophysics
  - Plastic deformation model of material (J2 class)
  - Geomechanical testing to determine coupled thermal-mechanical strength characteristics
  - Time-varying ocean BCs (water level, temp, salinity)
  - Eroded sediment and biogeochemical flux tracking

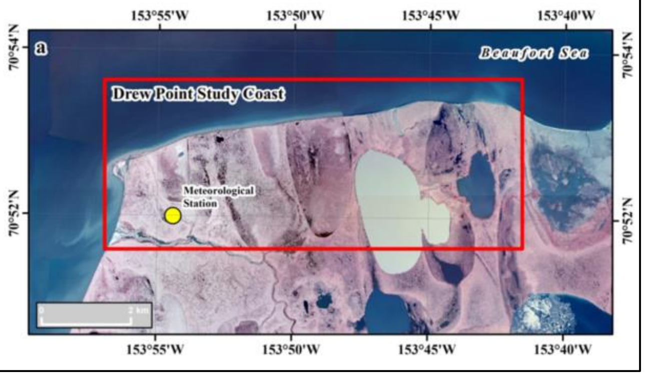
This talk



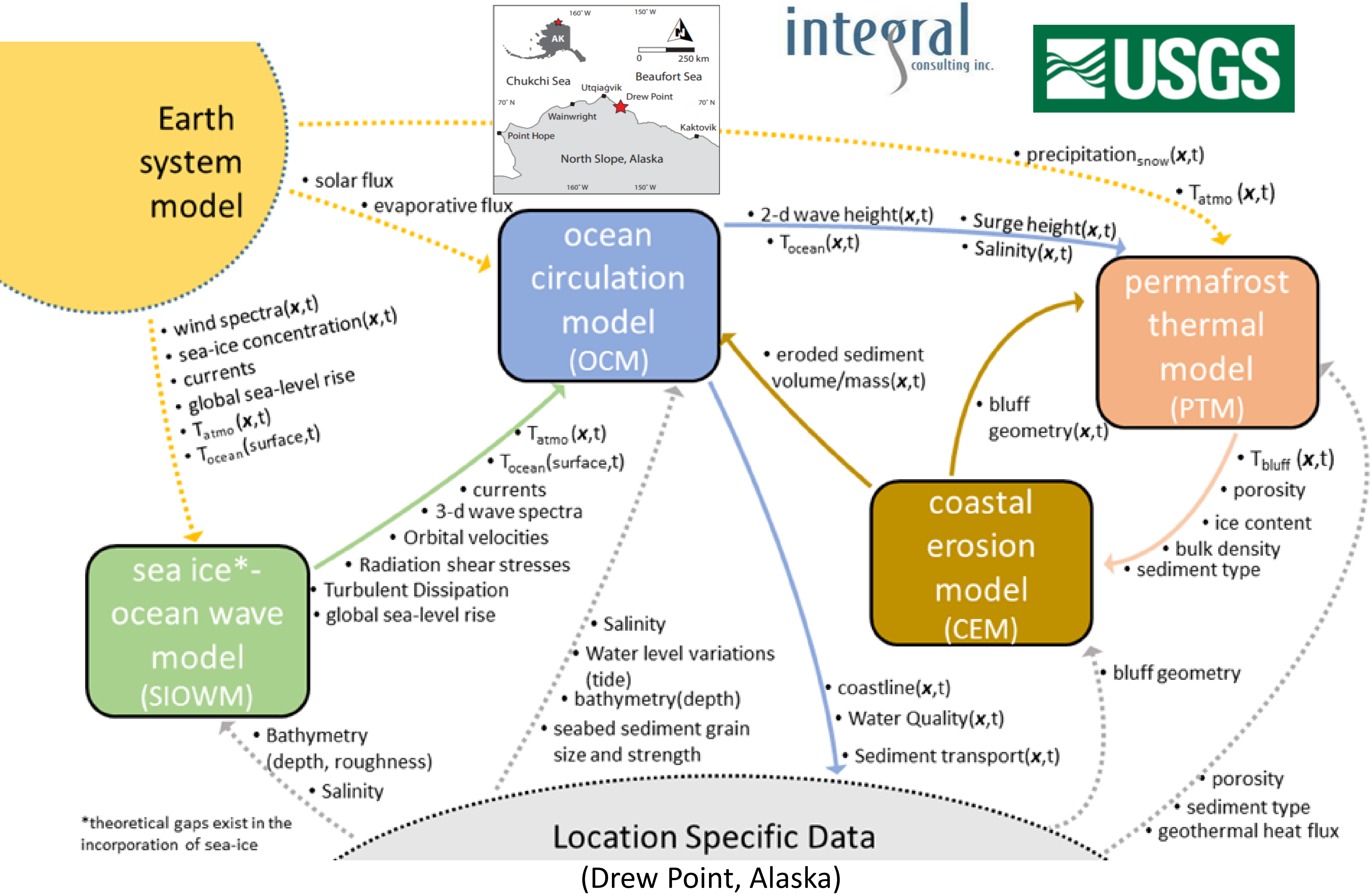
2021+ → **Meso-scale Model**

10's of km's & seasonal duration

- A "catalog" of micro-scale models that represent the statistical distributions of input variables along a ~10km stretch of coastline.
  - Probability distribution functions of geomorphology and geophysics used to weight erosion output
    - Will validate approach with decade long annual measurements at Drew Point.
  - Evaluating ocean "exposure metrics" to represent time-varying ocean



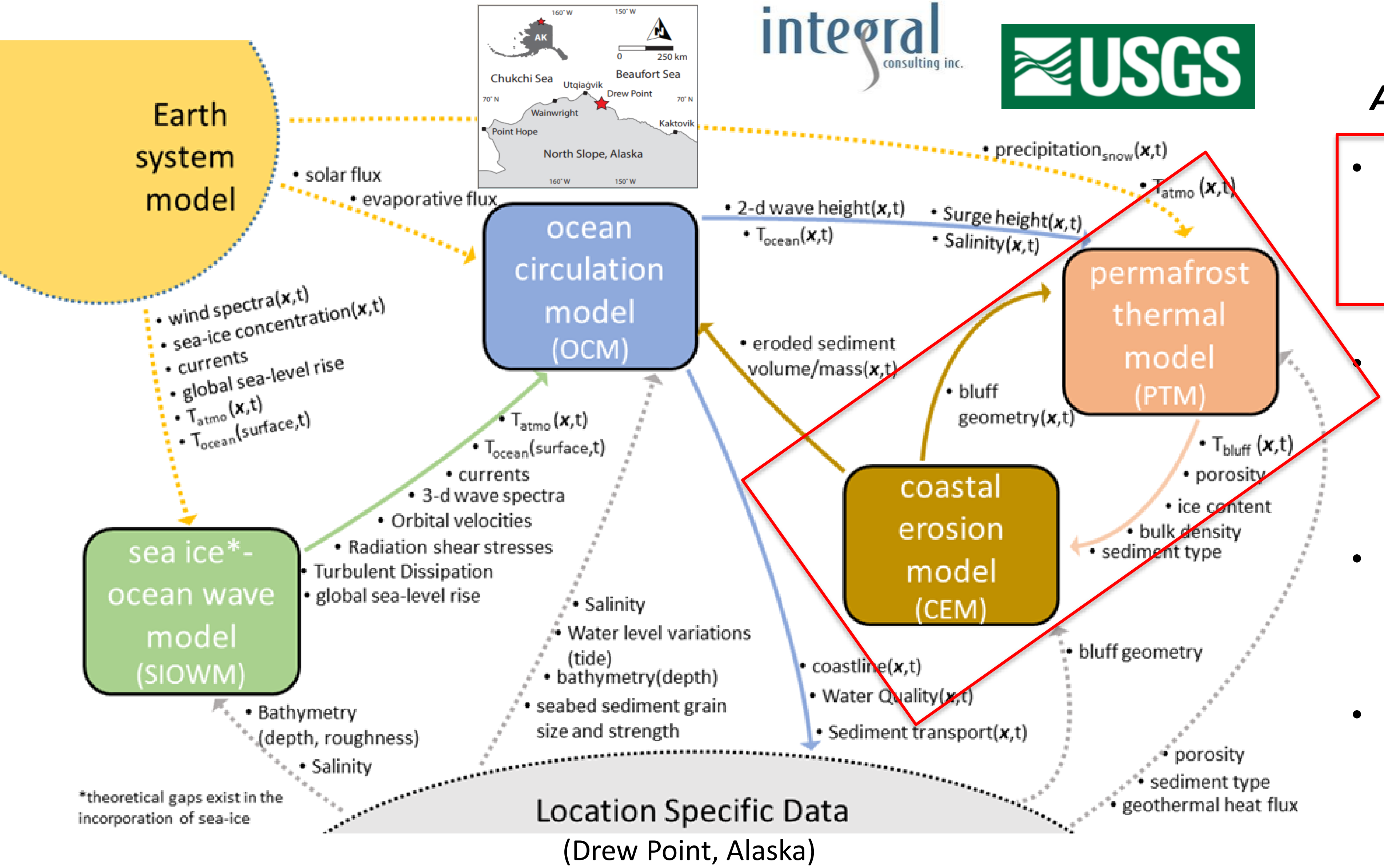
ACE Model Component Coupling



ACE project has many pieces!

- **Terrestrial model**: thermo-mechanical coupled FEM model that can simulate transient niche development.
- **Oceanographic model**: WW3 + SWAN + Delft3D wave models for providing oceanic BCs (ocean temp/height) to terrestrial model.
- **Geomechanical testing**: for characterization of permafrost parameters in terrestrial model.
- **Field campaign**: offshore oceanographic measurements, bathymetric survey, niche measurements, etc.

ACE Model Component Coupling



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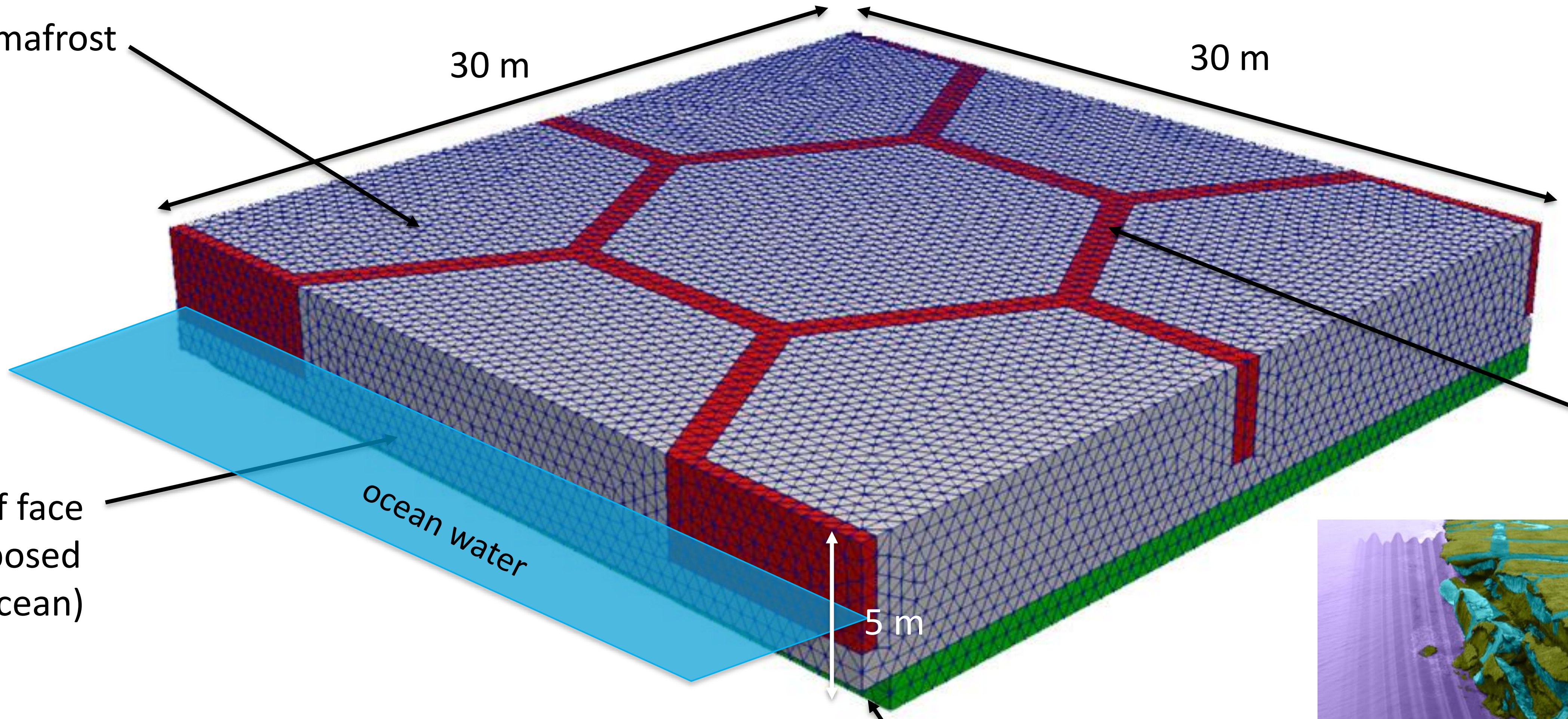
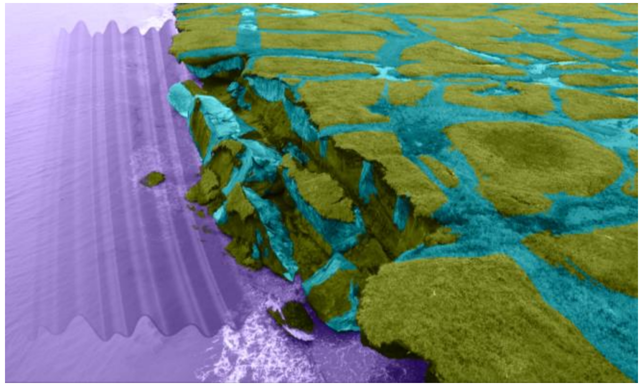
Anatomy of a canonical computational domain





* Layer of unfrozen ground that is perennially cryotic (forming part of the permafrost) in which freezing is prevented.

Mechanical model

- Finite deformation variational formulation for ***solid mechanics problem*** obtained by minimizing the energy functional :

$$\Phi[\boldsymbol{\varphi}] := \int_{\Omega} A(\boldsymbol{F},\boldsymbol{Z})\, dV - \int_{\Omega} \rho \boldsymbol{B}\cdot\boldsymbol{\varphi}\, dV - \int_{\partial_{\boldsymbol{T}}\Omega} \boldsymbol{T}\cdot\boldsymbol{\varphi}\, dS$$

$A(\boldsymbol{F},\boldsymbol{Z})$: Helmholtz free-energy density
$\boldsymbol{Z}$: material variables
$\boldsymbol{F}$: deformation gradient ($\nabla\boldsymbol{\varphi}$)
ρ: density
$\boldsymbol{B}$: body force
$\boldsymbol{T}$: prescribed traction

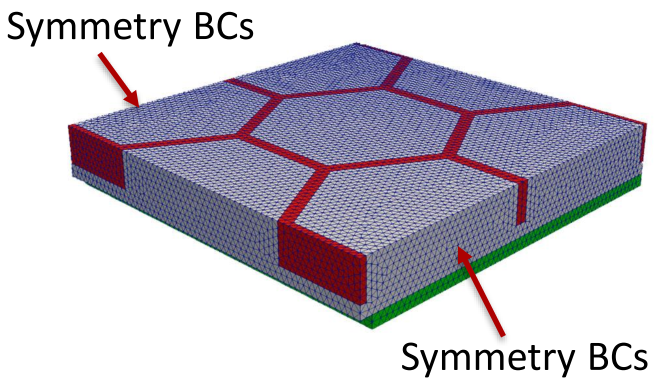
  - ➢ Computes ***displacements*** and ***new computational geometry*** (following erosion)

- ***J2 plasticity*** extended to large-deformation regime ***constitutive model*** for ***ice*** and ***permafrost***
  - ➢ Incorporates all mechanisms that lead to deformation, plastic flow and creep of polycrystalline materials like ice; minimal calibration parameters; simplest material model w/ plastic behavior.

- ***Symmetry boundary conditions*** on lateral sides

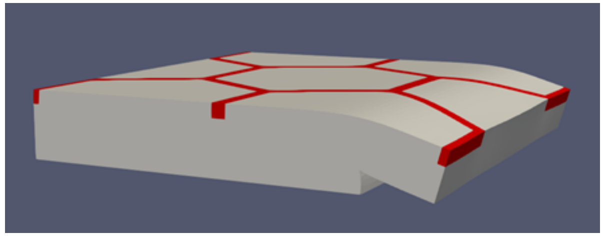
- ***Yield stress***: $\sigma_0(T) := S_s\sigma_Y^{\text{soil}} + S_f f(T)\sigma_Y^{\text{ice}}$
  - ➢ Used in erosion failure criteria

f: ice saturation ($\in [0,1]$)
$\sigma_Y^{\text{soil}}/\sigma_Y^{\text{ice}}$: yield stress of soil/ice
S_s/S_f: soil/ice volume fraction



Erosion failure criteria

- **Erosion criterion:** when material exposed to water reaches a critical exposure time.
- **Stress criterion:** when material reaches a critical value of the yield stress.
- **Kinematic criterion:** when material has tilted excessively, it is assumed to have fallen as part of block erosion.



Once **failure criterion** is reached, “failed” elements are **removed** from mesh.

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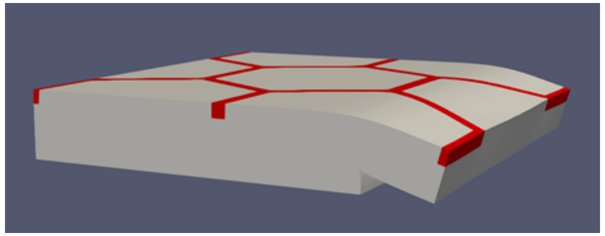

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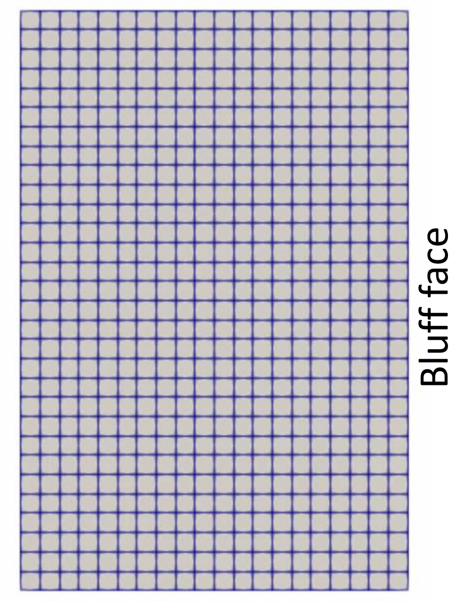

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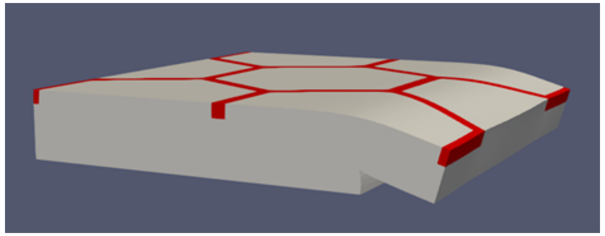

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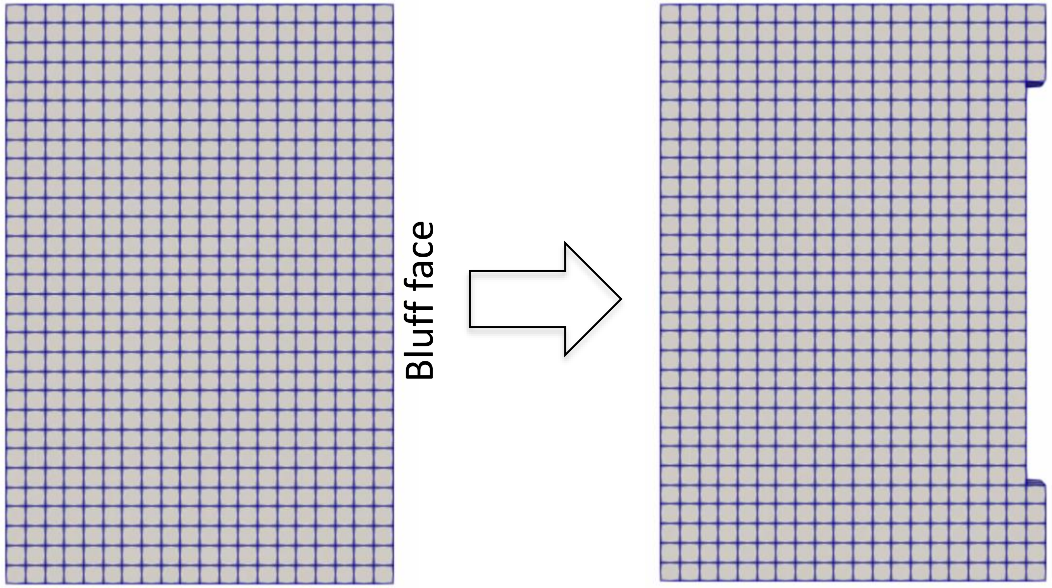

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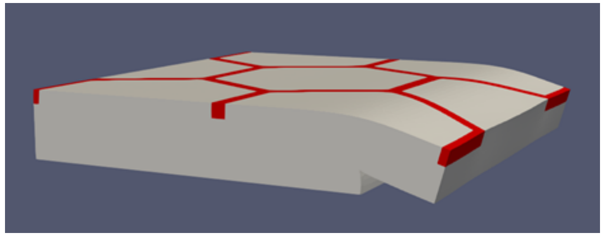

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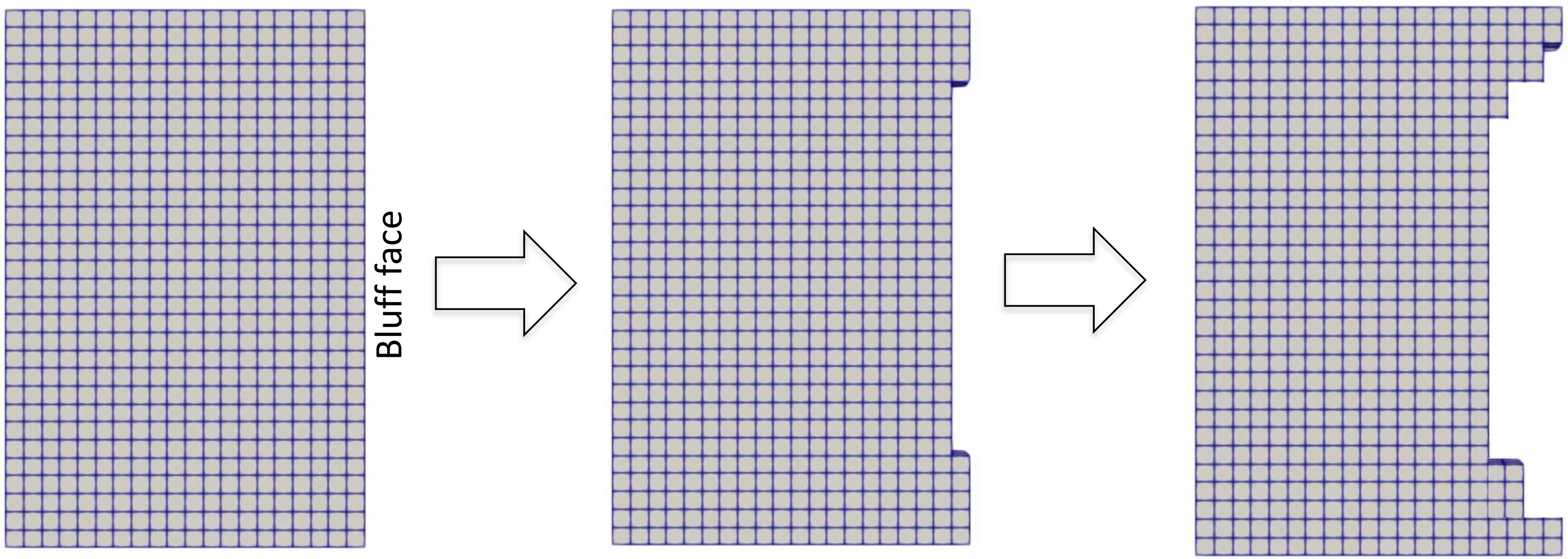

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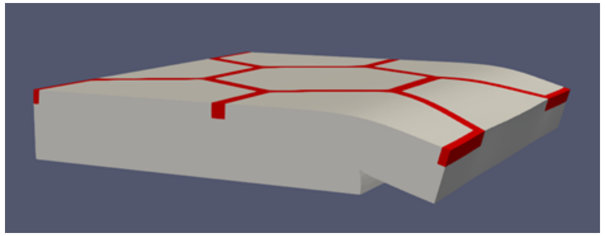

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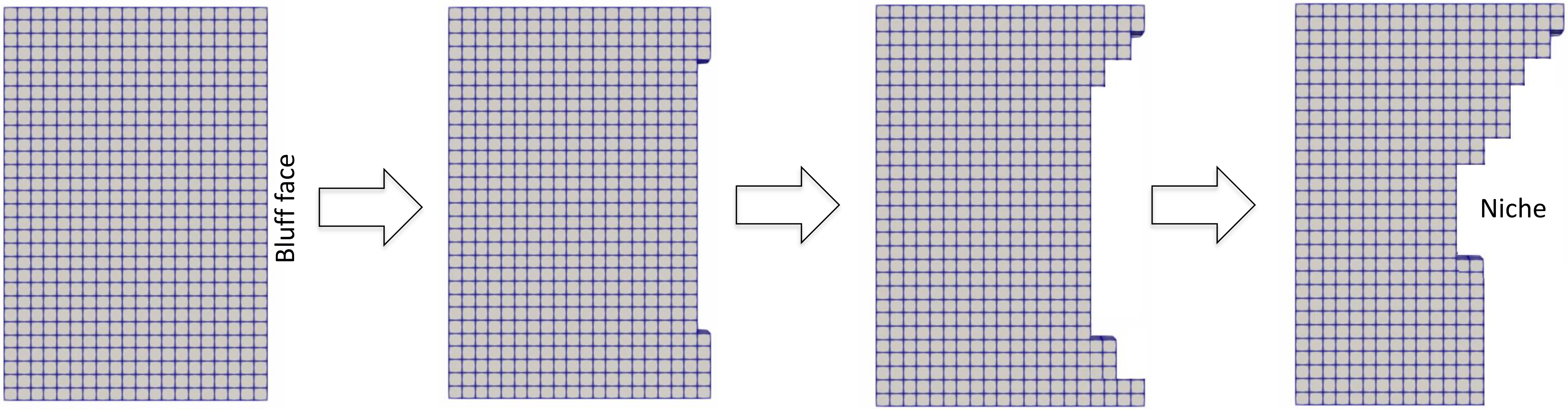
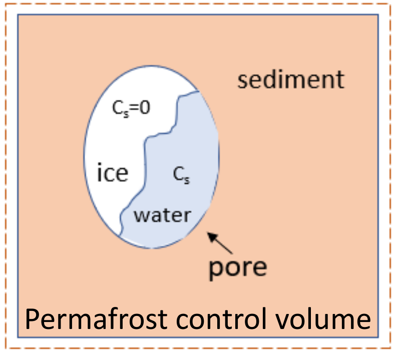


Thermal model

- ***Transient heat conduction*** in a non-homogeneous porous media with water-ice phase change:

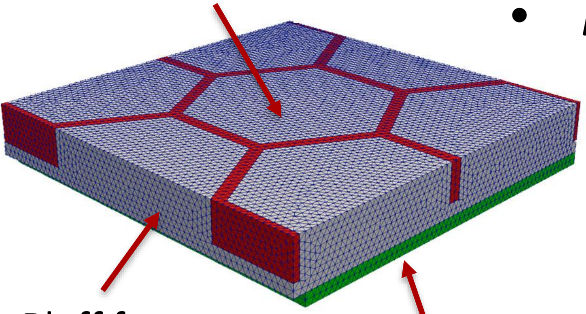
$$(\overline{\rho c_p} - \widetilde{\Theta}) \frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{K} \cdot \nabla T)$$

where $\widetilde{\Theta} := \rho_f L_f \frac{\partial f}{\partial T}$ incorporates phase through soil freezing curve, $\frac{\partial f}{\partial T}$ *.

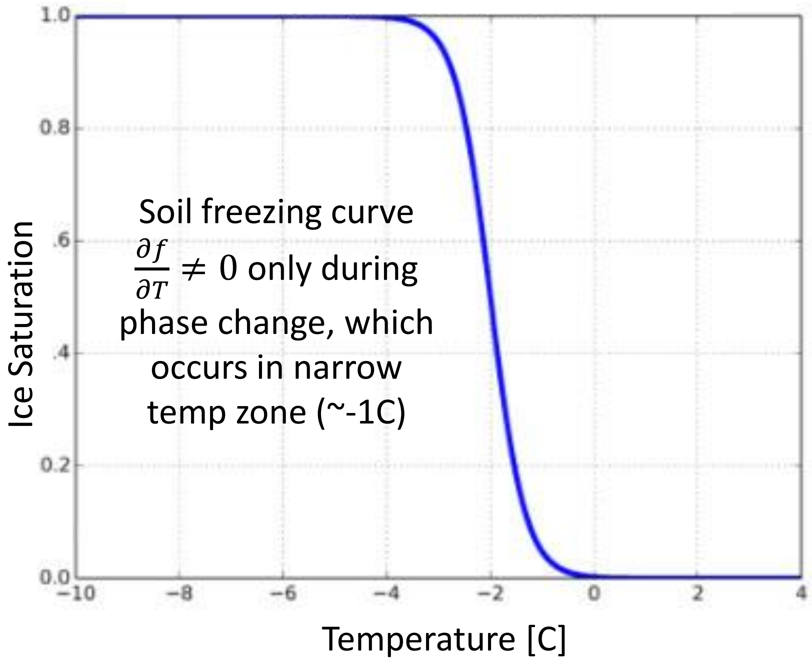


$\bar{\rho}$: density from mixture model
$\overline{c_p}$: specific heat from mixture model
$\boldsymbol{K}$: thermal diffusivity tensor
ρ_f: ice density
L_f: latent heat of water-ice phase change
f: ice saturation ($\in [0,1]$)
$\frac{\partial f}{\partial T}$: soil freezing curve (depends on salinity)

- ➢ Computes ***temperature*** T and ***ice saturation*** $f = f^{old} + \frac{\partial f}{\partial T} \Delta T$.



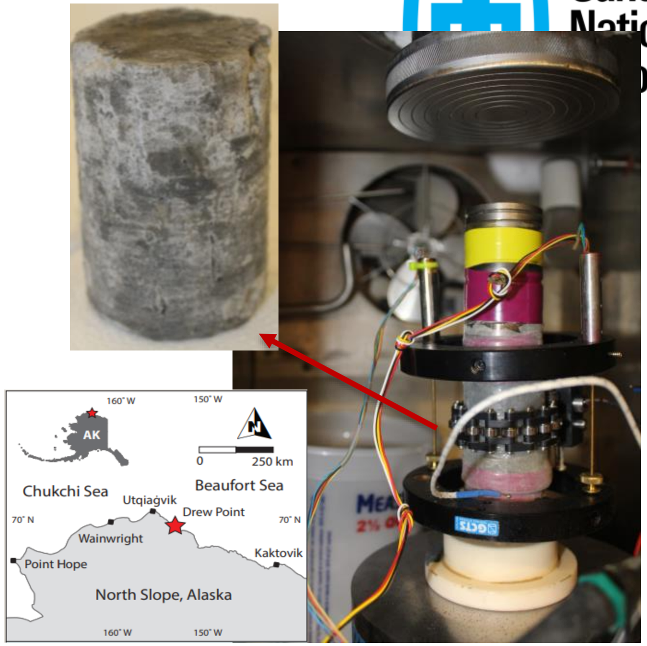
- ***Boundary conditions*** (from wave model/data)
  - ➢ Local geothermal heat flux from below
  - ➢ Mean annual air temp from above
  - ➢ Air/ocean temp at bluff face

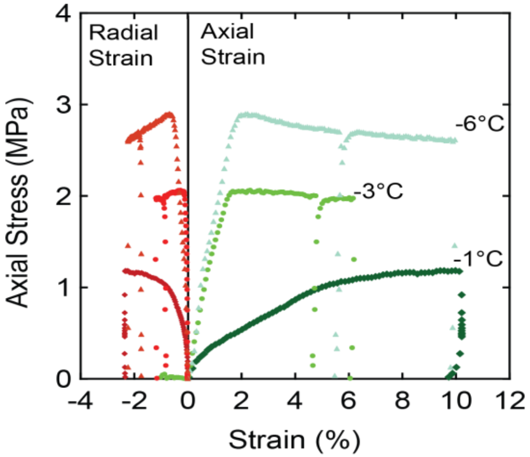


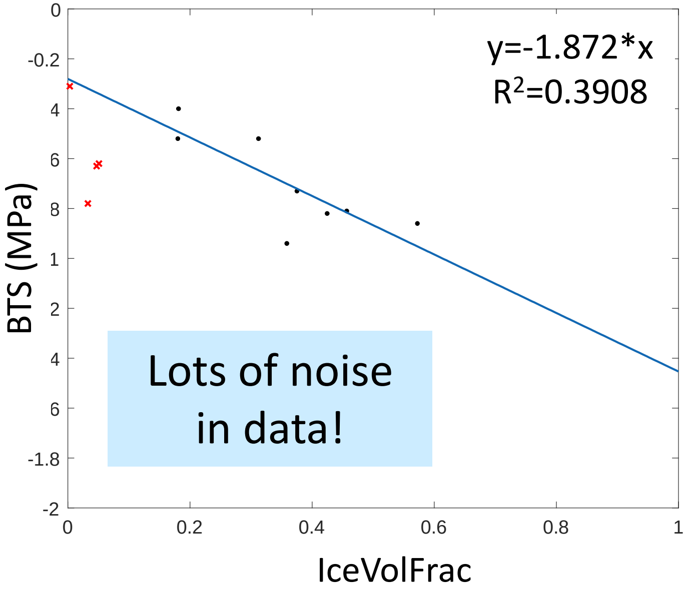
* Follows approach of (M. Ramos *et al.*, 1996), (Z. Wang *et al.*, 2011), etc: latent heat is energy source/sink for heat equation.

Parameters & inputs

- Permafrost properties depend on ***ice content***, ***unfrozen water content*** and ***frost susceptibility***.
- ***Few mathematical relationships exist*** that describe changes in tensile strength, shear strength and cohesion of ice/permafrost with changes in temperature.
- Series of ***experiments*** (UCS[1], BTS[2], DT[3]) on frozen soil samples at different temps (-6C, -3C, -1C) and ice content from Drew Point, AK were performed at SNL's Geomechanics Laboratory to estimate:
  - Strength: 1-3 MPa
  - Young's modulus: 0.01-0.16 GPa
  - Poisson's ratio: 0.1-0.35
  - Porosity values: 40-95%



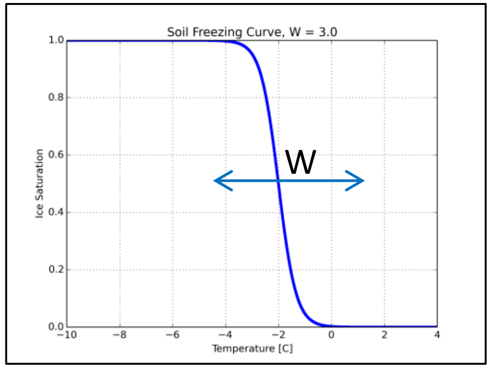




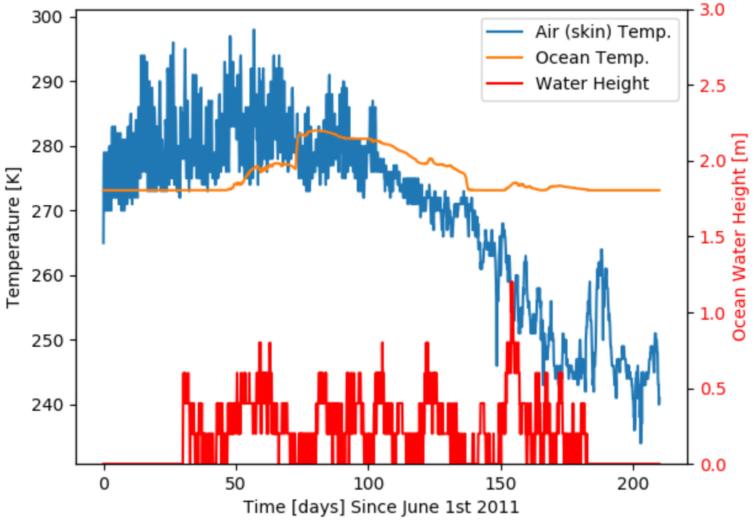
Parameters & inputs

Parameters estimated from laboratory data:

- Elastic modulus, Poisson’s ratio, yield strength
- Sand/silt/clay fractions with depth
- Porosity with depth



BC Data for Drew Point

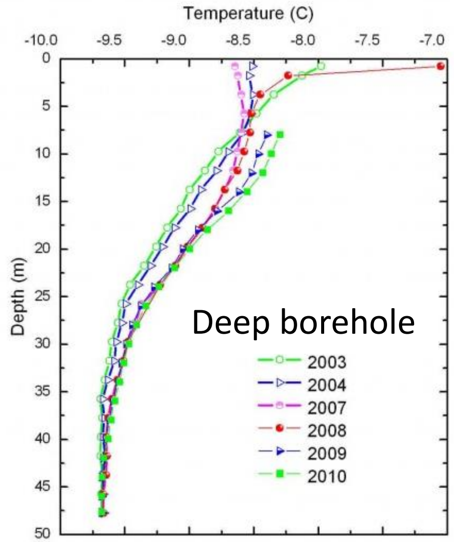


Parameters from literature:

- Ice/water/sediment densities, thermal conductivities, heat capacities
- Freezing curve/width as function of sediment type
- Bluff salinity with depth

Parameters estimated from observational data at Drew Point, AK:

- Skin temp w/ time, initial bluff temp (USGS weather station data)
- Geothermal heat flux (borehole at Barrow, AK)
- Polygon dimension, ice wedge thickness and depth, bluff height, living organic layer thickness (Aug. 2019 field campaign)



Parameters from wave model (WW3+SWAN+Delft3D):

integral consulting inc.

- Ocean temperature, salinity and sea-level w/ time (for thermal BCs)

Coupled thermo-mechanical formulation

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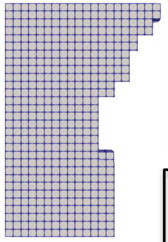
Potential key advantages:

- Tightly coupled strength and thermo-chemical states
- Failure modes develop from constitutive relationships in FEM model (no empirical relationships!)
- 3D unsteady heat flow can include chemistry

Unique characteristic of coupled model: coupling happens at the level of material model

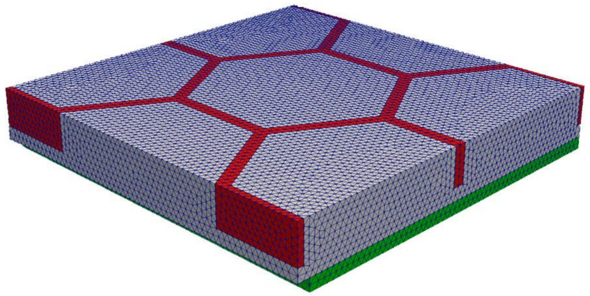


Eroded geometry

Thermal:

Inputs: geometry, sediment type, ice volume, water volume, pore size, salinity

Outputs: temperature field, ice saturation

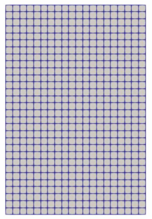


Ice saturation

Mechanical:

Inputs: ice saturation, strength relationship as function of thermal state, stress-strain relationships of permafrost and ice

Outputs: displacements, eroded geometry



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Finite element implementation within *Albany*

Sandia National Laboratories

The ***thermo-mechanical Arctic Coastal Erosion (ACE)*** model is implemented within the ***LCM project*** in Sandia's open-source parallel, C++, multi-physics, finite element code, ***Albany***.

- ***Component-based*** design for rapid development.
- Contains a wide variety of ***constitutive models***.
- Extensive use of libraries from the open-source ***Trilinos*** project.
  - ➢ Use of the ***Phalanx*** package to decompose complex problem into simpler problems with managed dependencies.
  - ➢ Use of the ***Sacado*** package for ***automatic differentiation.***
- Coupled to the ***DOE's Energy Exascale Earth System Model (E3SM)*** through Albany Land-Ice (ALI) component.
- All software available on ***GitHub***.

https://github.com/SNLComputation/LCM

https://github.com/trilinos/trilinos

Mechanics-only simulation*

Sandia National Laboratories

frontiers in Earth Science

ORIGINAL RESEARCH
published: 12 May 2020
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Geometric and Material Variability Influences Stress States Relevant to Coastal Permafrost Bluff Failure

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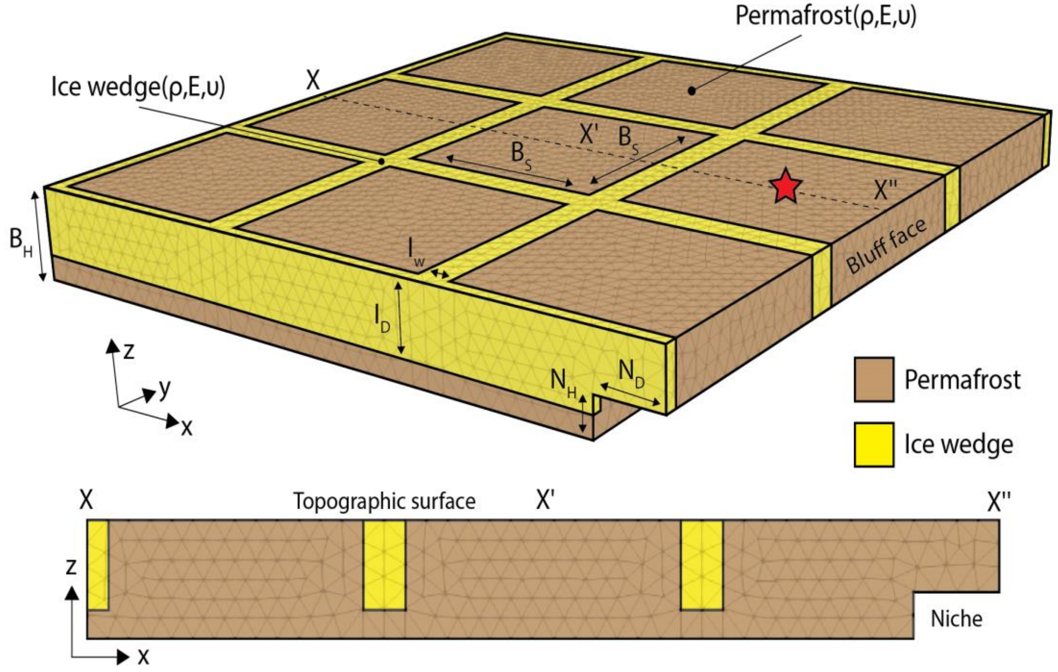
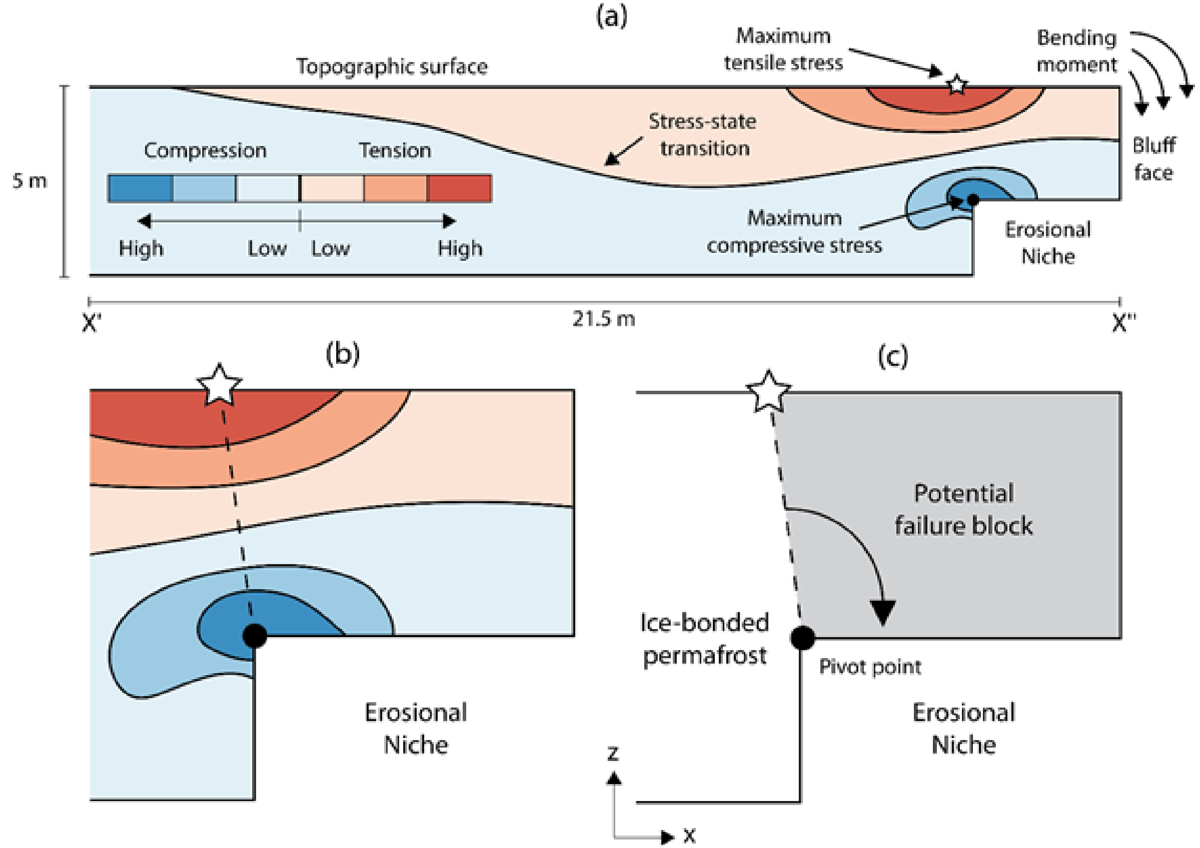
Scientific knowledge and engineering tools for predicting coastal erosion are largely confined to temperate climate zones that are dominated by non-cohesive sediments. The pattern of erosion exhibited by the ice-bonded permafrost bluffs in Arctic Alaska, however, is not well-explained by these tools. Investigation of the oceanographic, thermal, and mechanical processes that are relevant to permafrost bluff failure along Arctic coastlines is needed. We conducted physics-based numerical simulations of mechanical response that focus on the impact of geometric and material variability on permafrost bluff stress states for a coastal setting in Arctic Alaska that is prone to toppling mode block failure. Our three-dimensional geomechanical boundary-value problems output static realizations of compressive and tensile stresses. We use these results to

From recently-published *Frontiers in Earth Science* special issue.

Mechanics-only simulation*



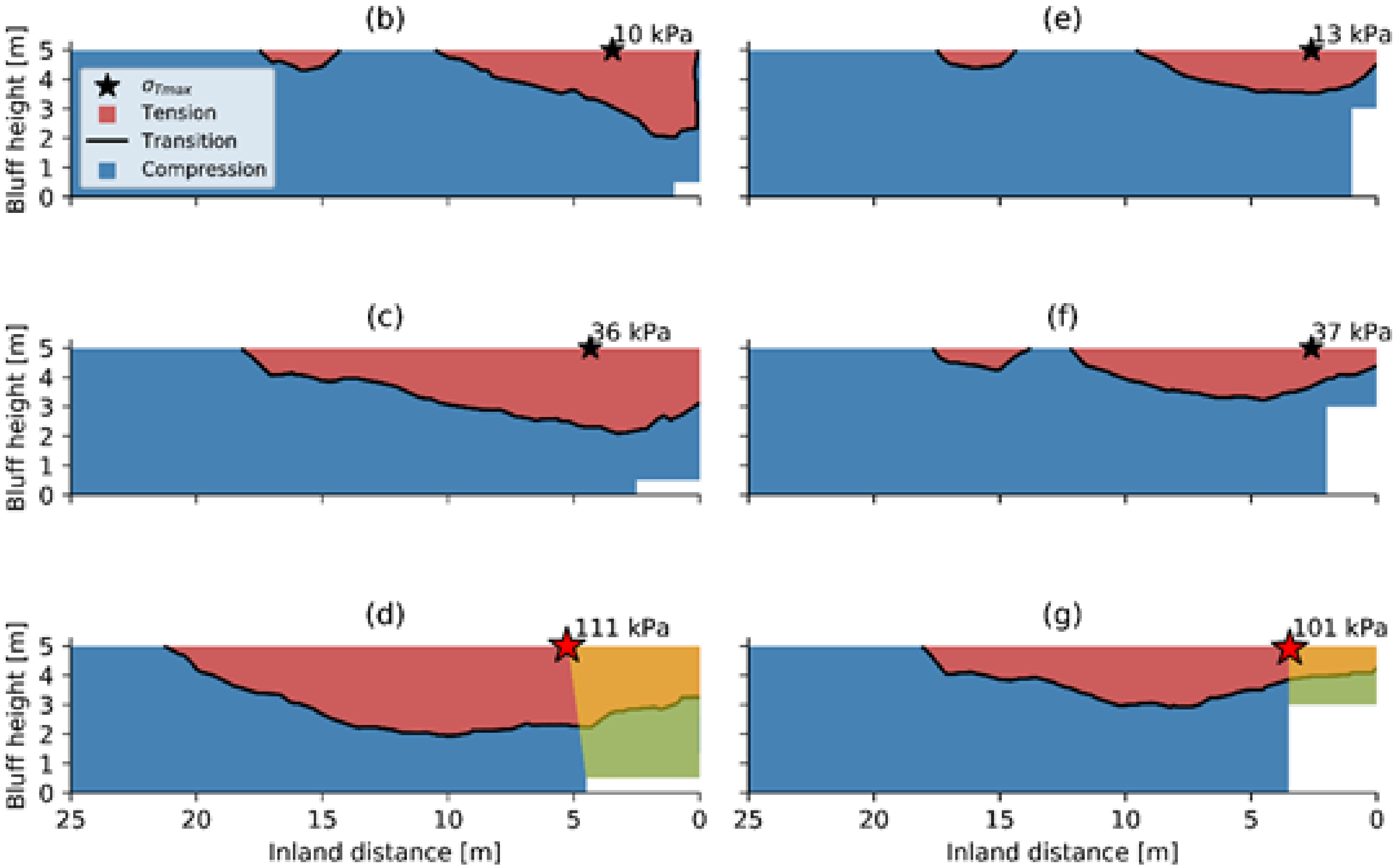
- **3D elastic mechanics-only** simulations assessed impact of **bluff geometry** and **material variability** on stress states leading up to bluff failure
  - ➢ Only load is gravitational.



- Simulations facilitated examination of **stress patterns** within bluff and identification of **location** and **magnitude** of **max tensile stress** ($\sigma_{T_{\max}}$)

Mechanics-only simulation*: main takeaways

Niche dimension affects location and magnitude of simulated **max tensile stress ($\sigma_{T_{\max}}$)** more than the bluff height, ice wedge polygon size, ice wedge geometry, bulk density and Poisson's ratio



- Inland extent of niche was advanced for 6 erosional niche heights from 0.1-3 m

Taller and **narrower** erosional **niches** promote smaller failure masses compared to those with shorter and deeper niches

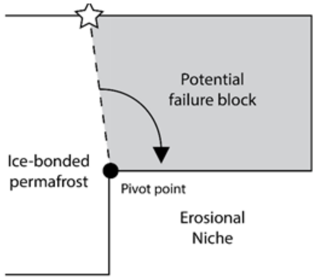
- Lower bound for tensile stress from lab measurements: 100 kPa
- Orange/green shading highlights potential failure areas.

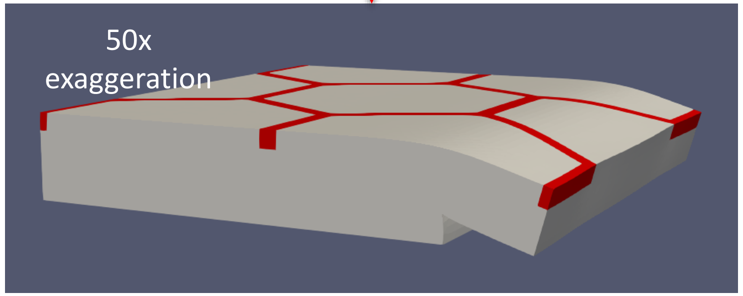
* M. Thomas *et al.* *Frontiers in Earth Science* 8, April 2020.

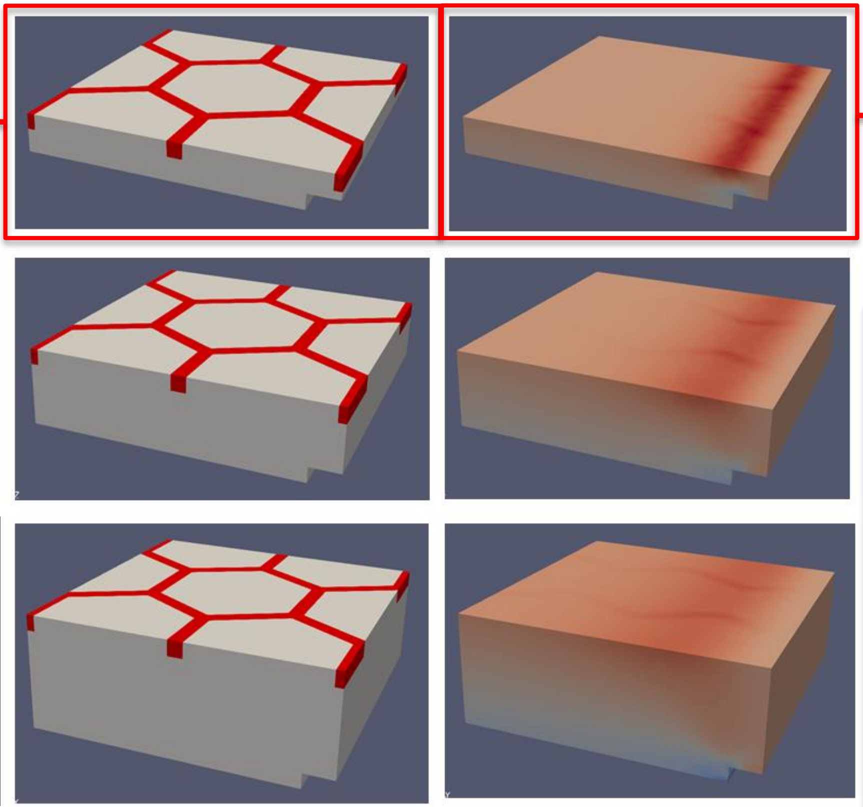
Mechanics-only simulation*: main takeaways

Taller and **narrower** erosional **niches** promote smaller failure masses compared to those with shorter and deeper niches

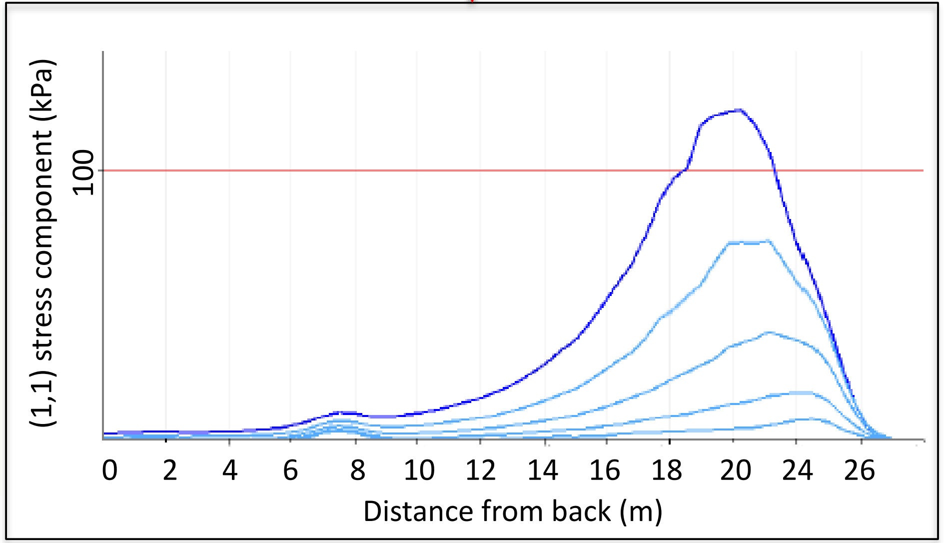
As niche advances into the block, an overhanging section in the block acts as ***cantilever***.





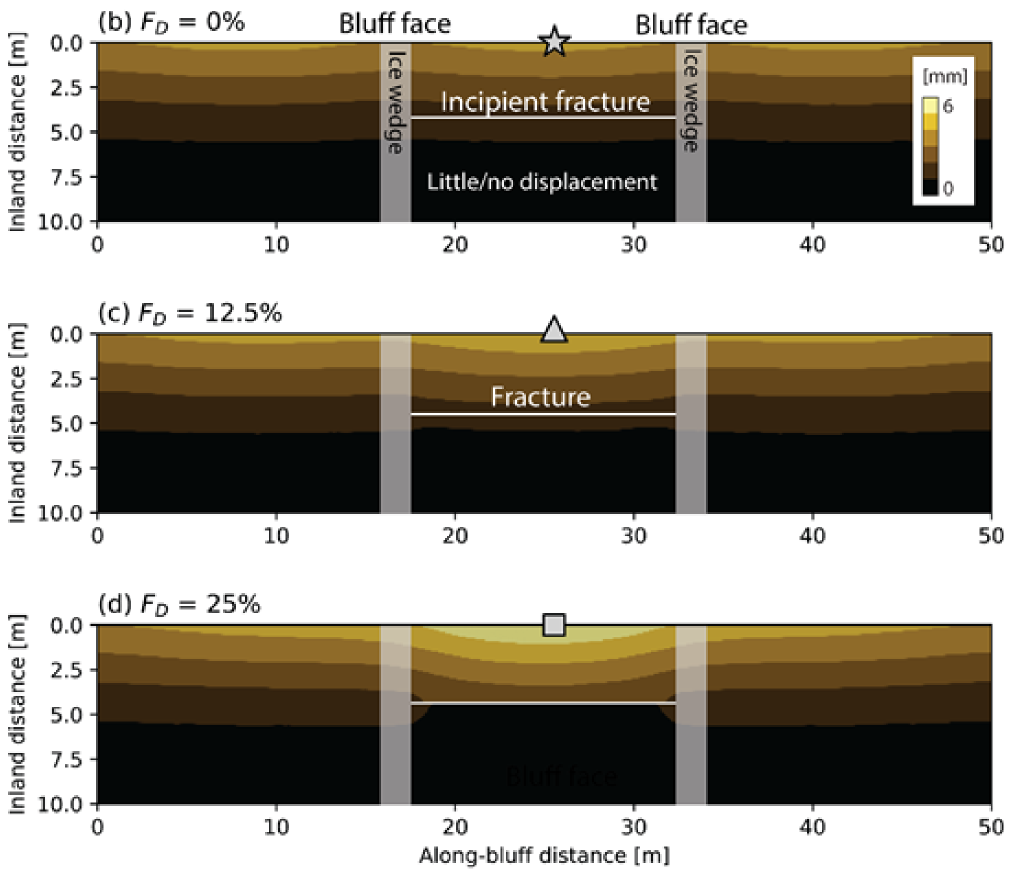


Highest ***tensile stresses*** develop on top surface where cantilever meets rest of block



Mechanics-only simulation*: main takeaways

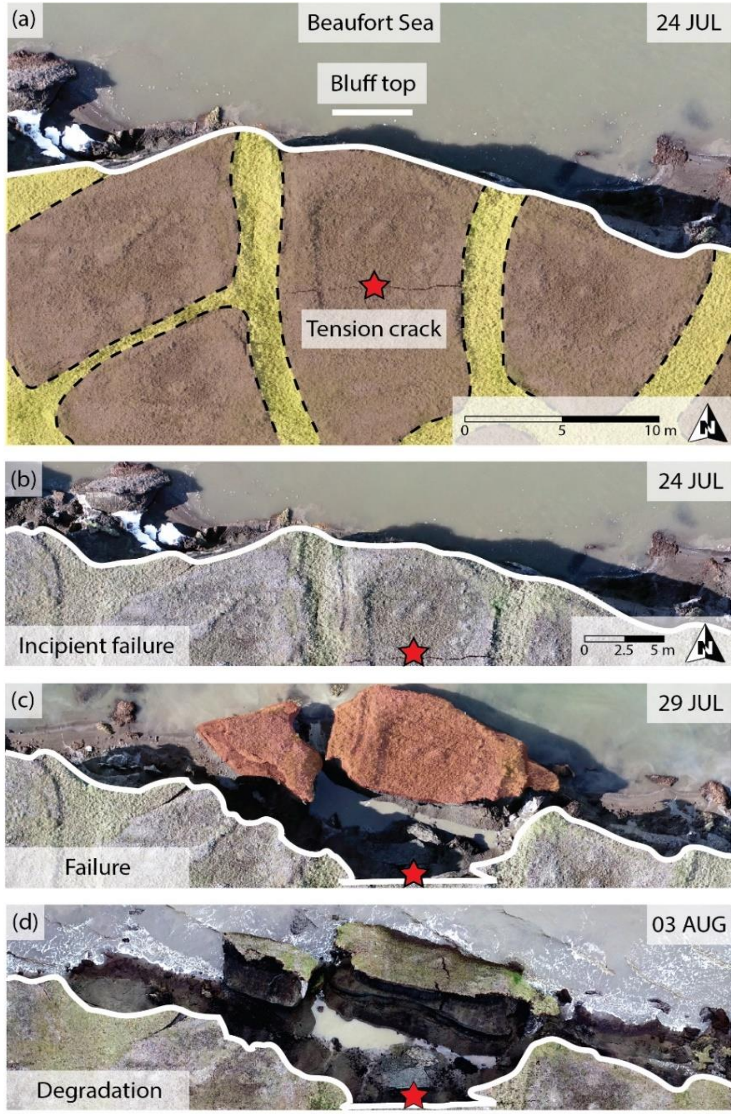
- It has been observed that **failure** can occur along **tension cracks** in ice wedge polygon centers.



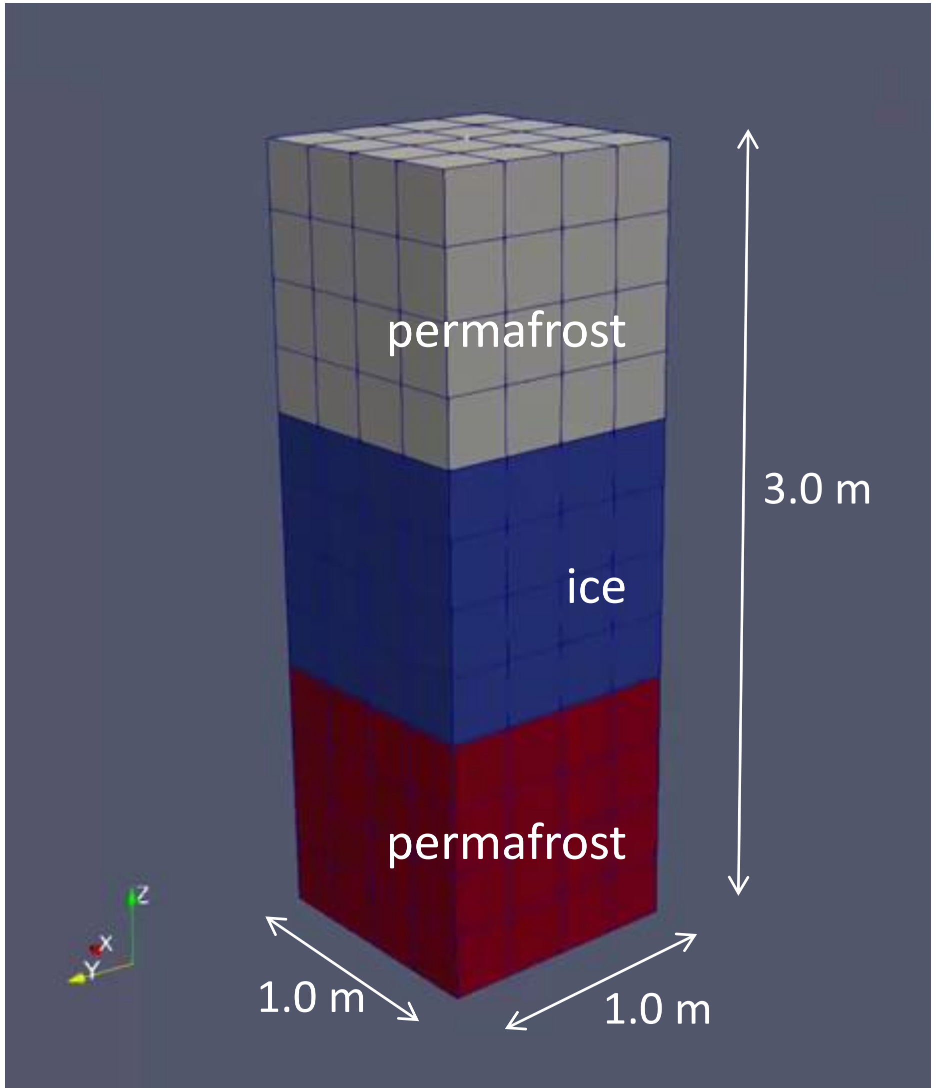
- Simulations suggest **tension cracks** can form within the range of niche depths/heights considered here.

- Even relatively **shallow vertical cracks** can **concentrate strain** within ice-bonded permafrost bluffs.

F_D: fracture depth



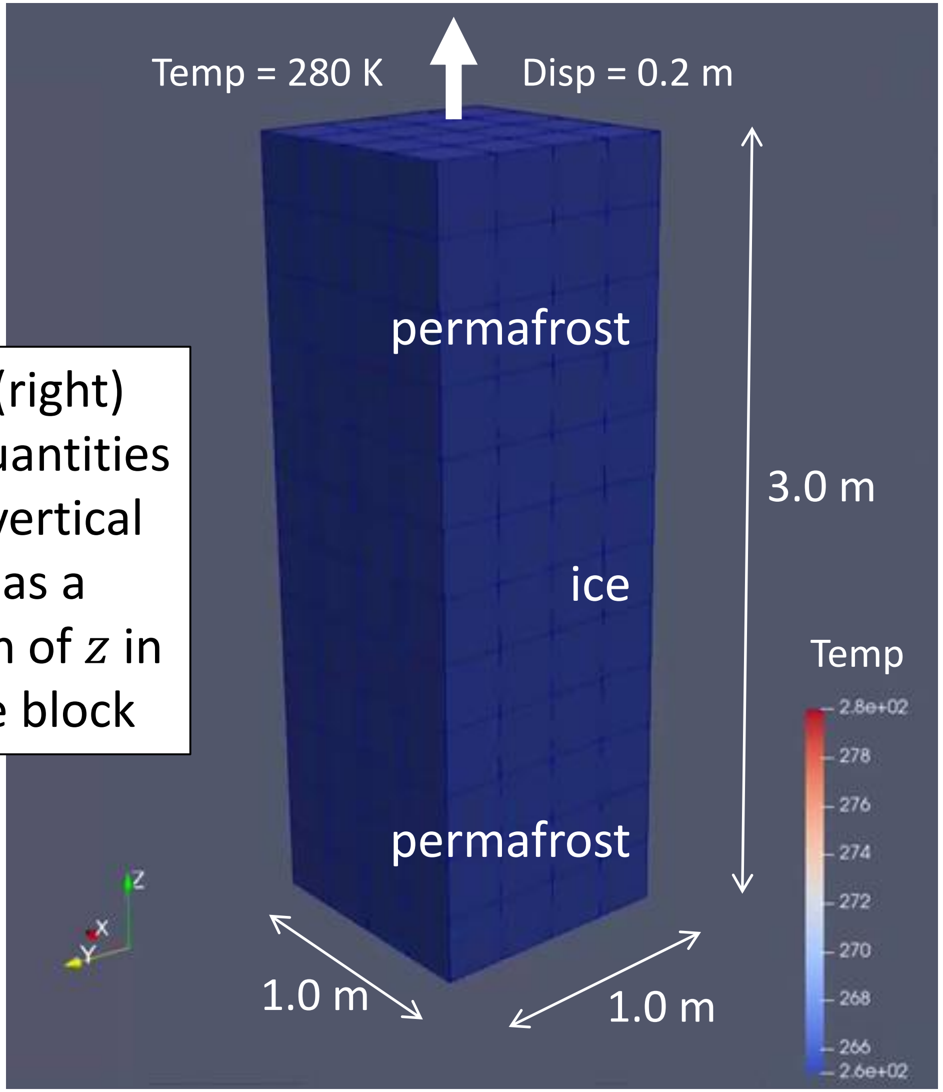
Thermo-mechanical coupling: cuboid problem



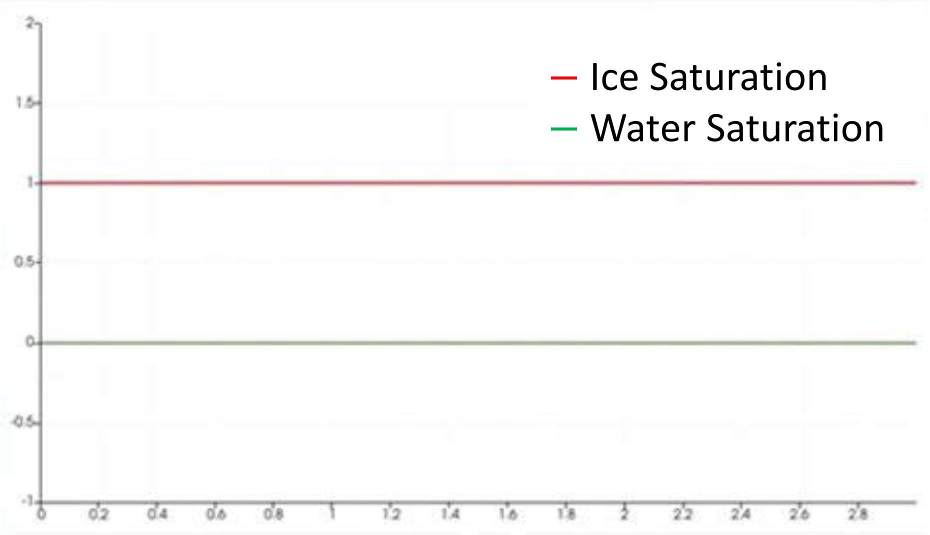
- Cuboid is comprised of block of **ice** material, **wedged** between two blocks of **permafrost** material.
- Cuboid subjected to **simultaneous heating** and **stretching** from the **top**
- Cuboid is **affixed** to the **bottom** and with **symmetry boundary conditions** on the **sides**.
- **Temperature** is initialized to 265K.

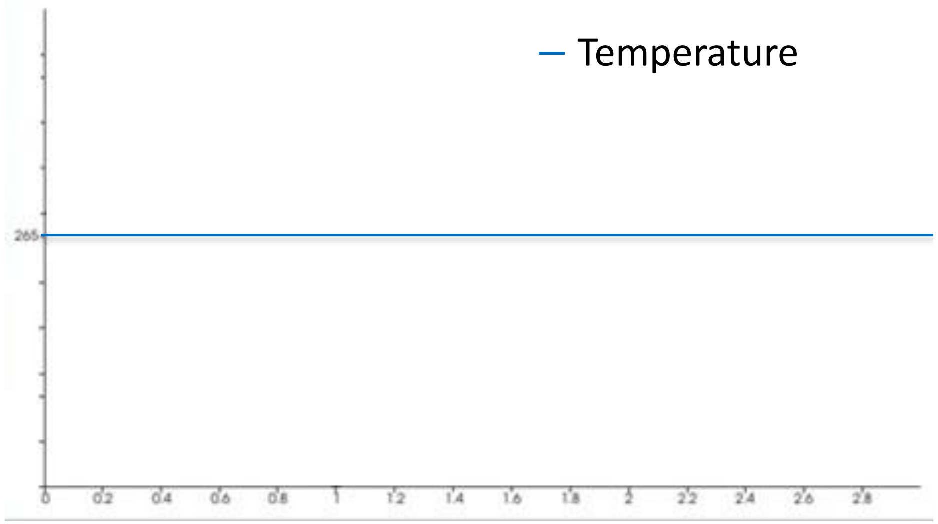
Albany

Thermo-mechanical coupling: cuboid problem

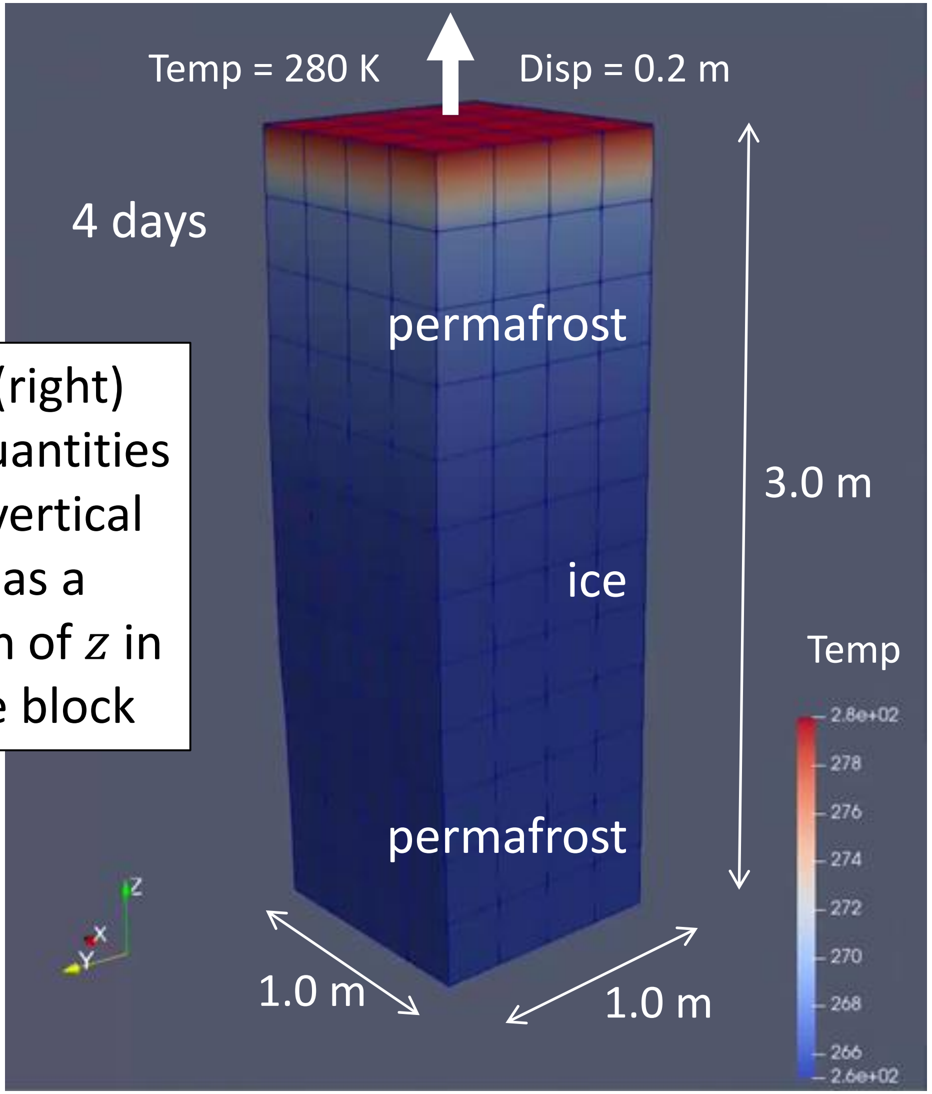


Plots (right) show quantities along vertical line as a function of z in the ice block

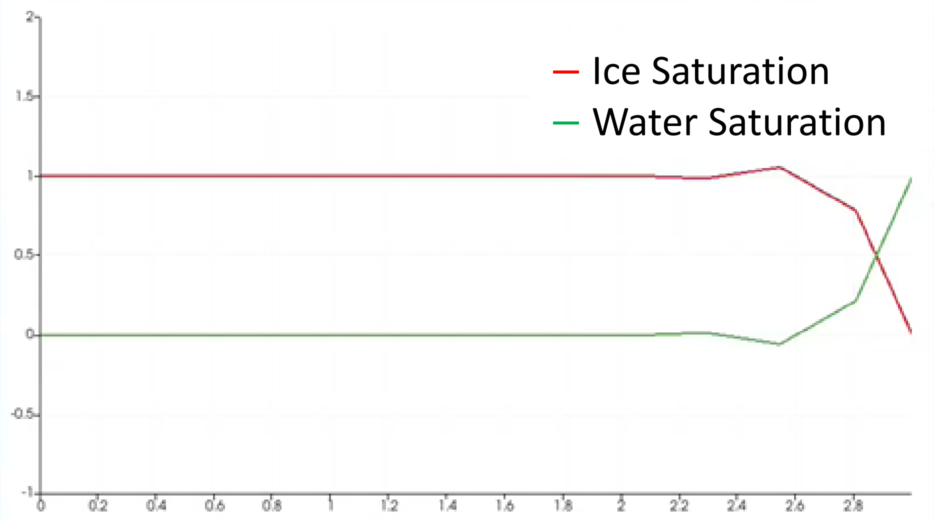


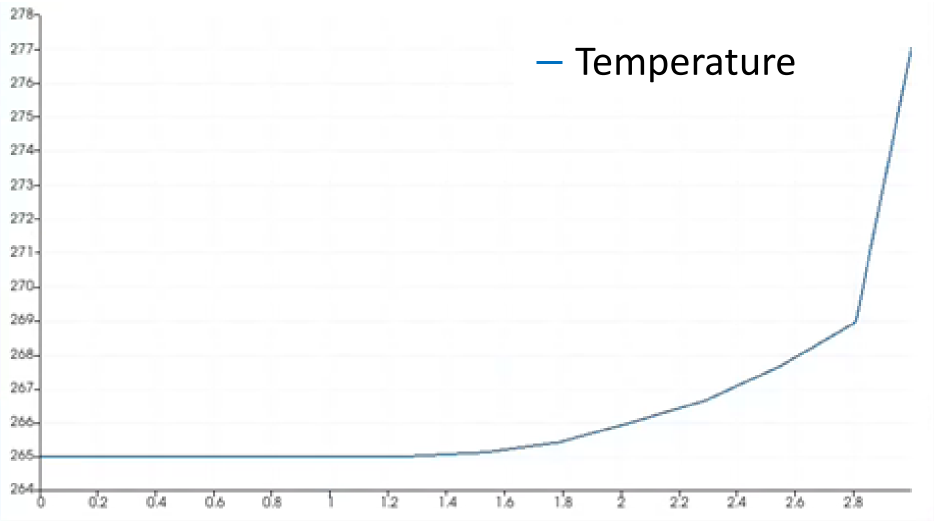


Thermo-mechanical coupling: cuboid problem



Plots (right) show quantities along vertical line as a function of z in the ice block





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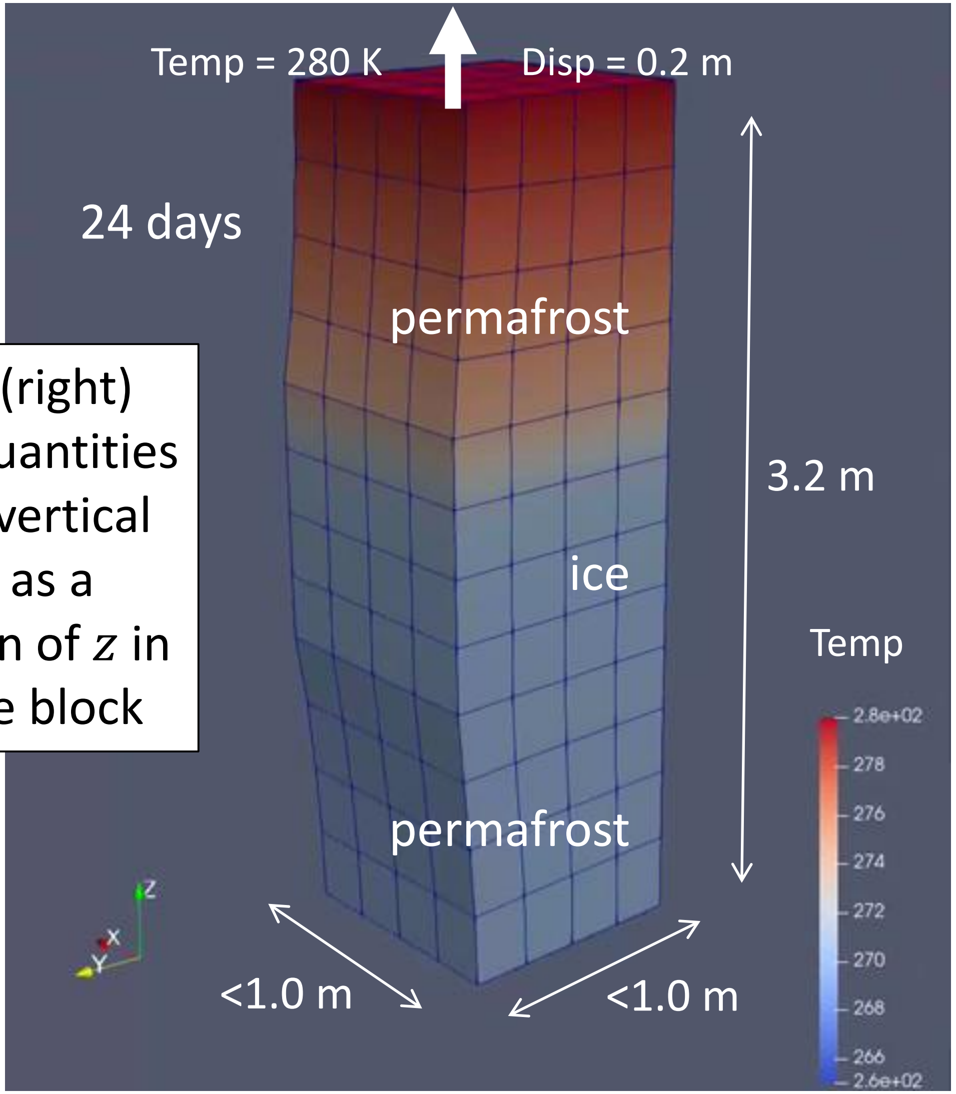
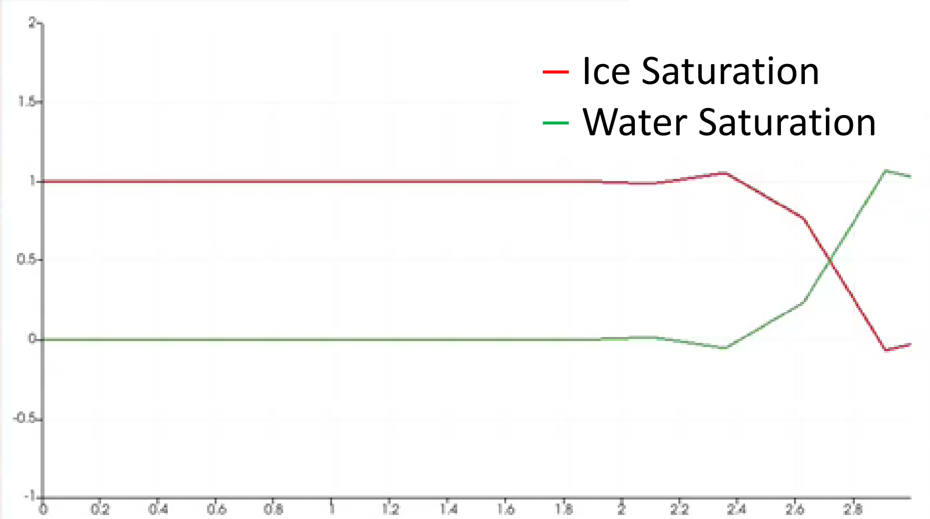
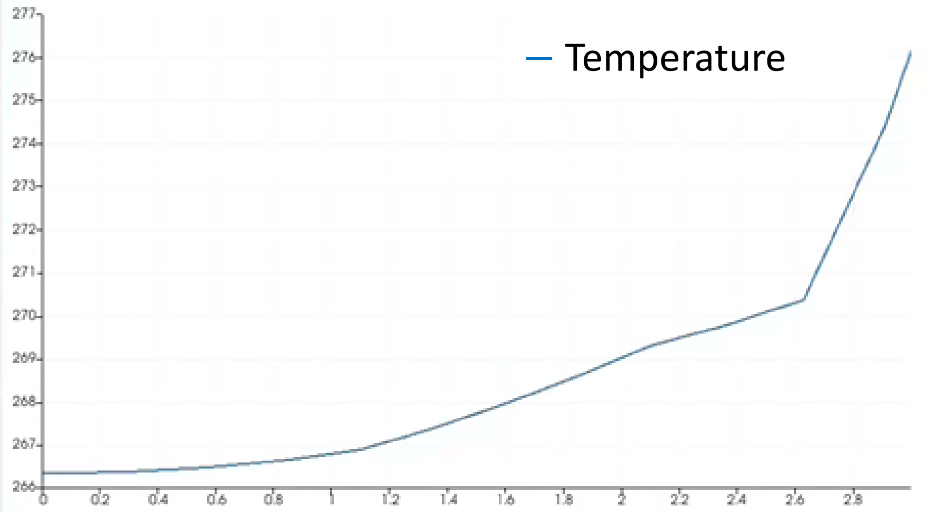


Plots (right) show quantities along vertical line as a function of z in the ice block





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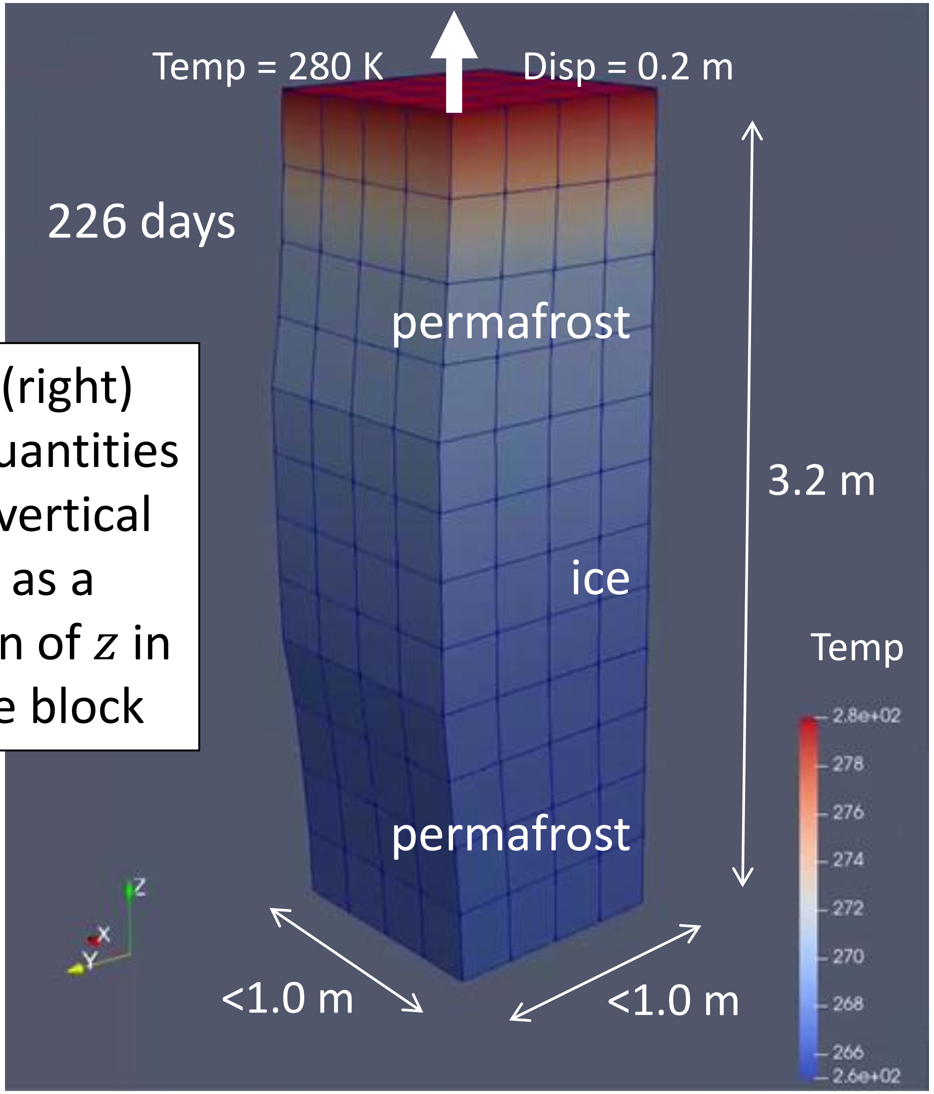

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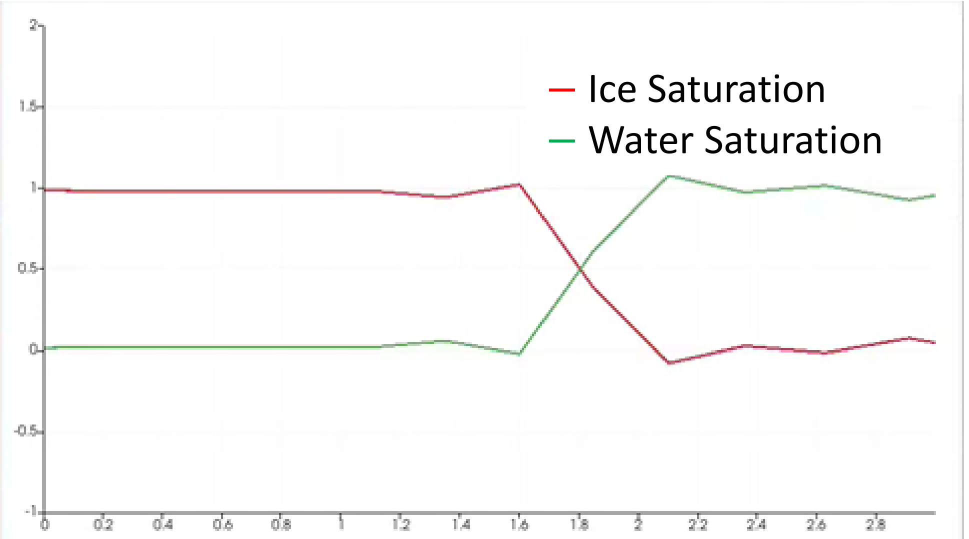

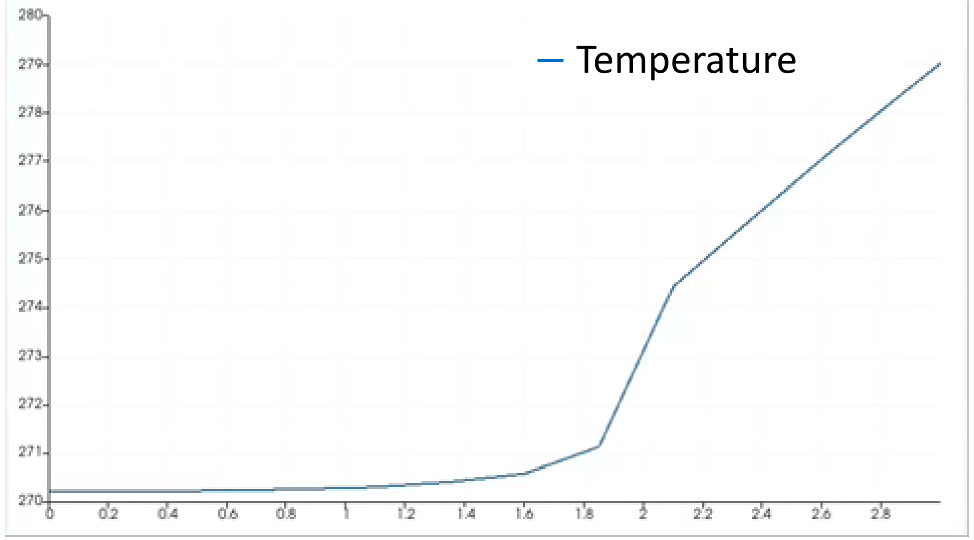

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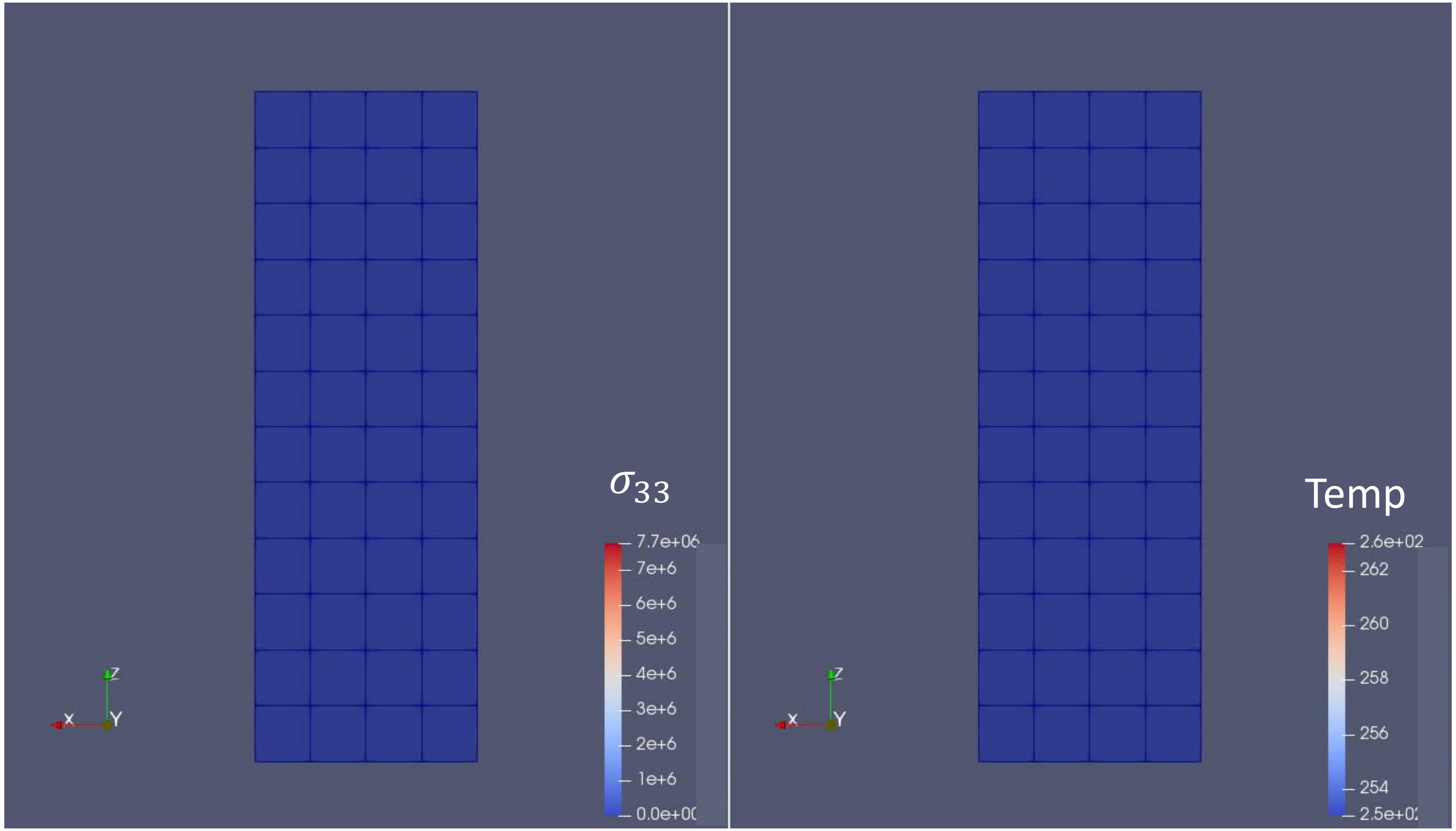
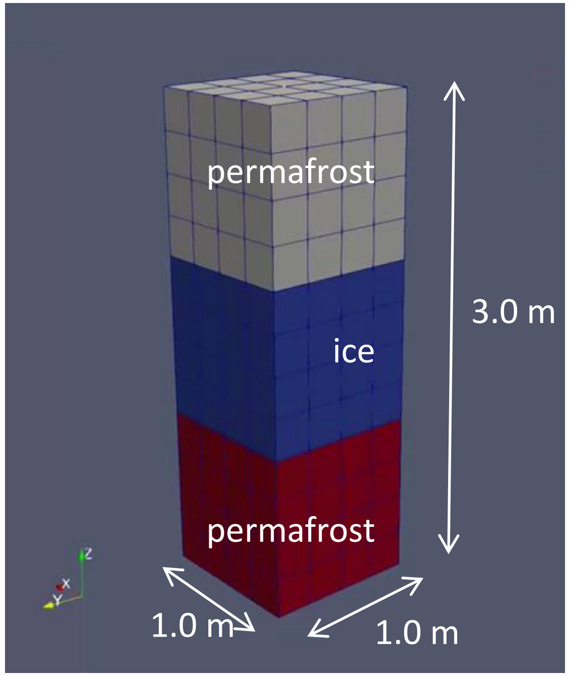


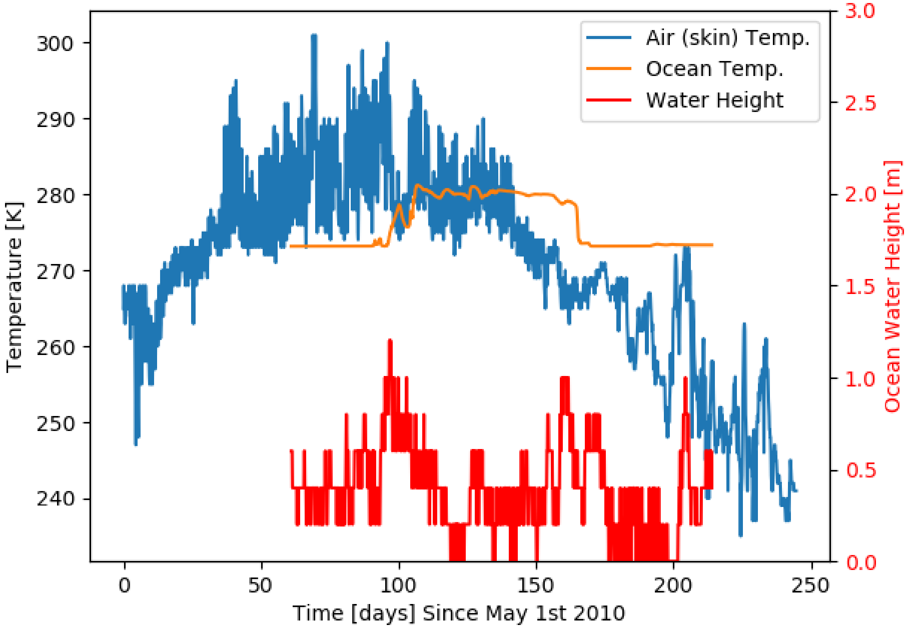


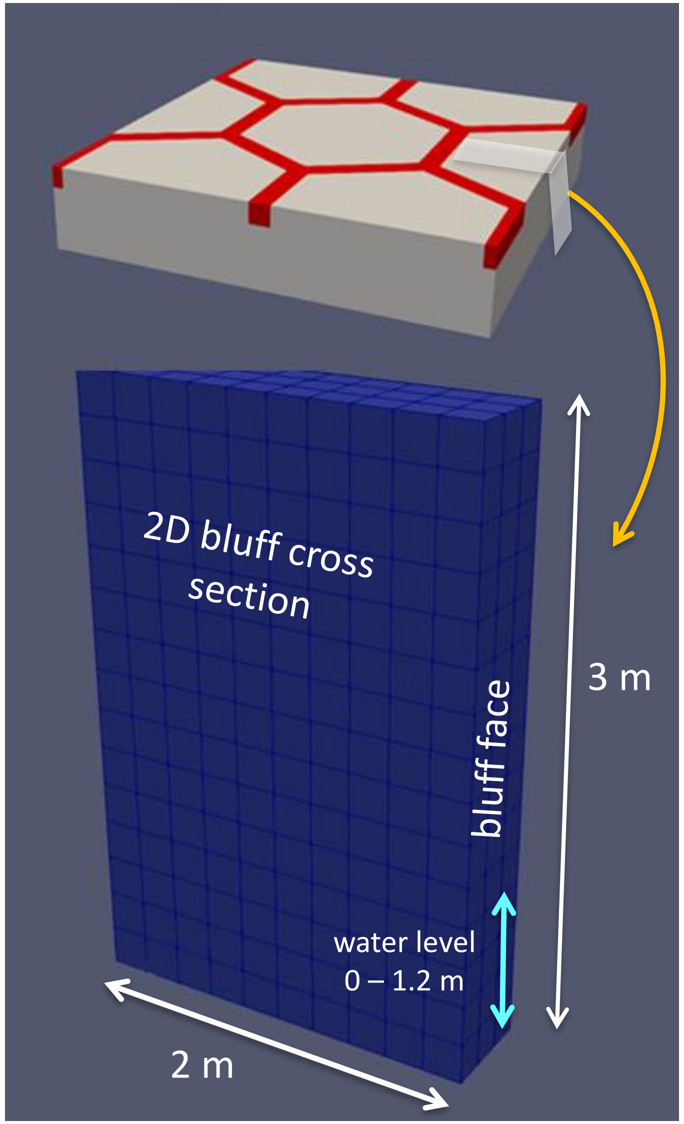
As cuboid is heated and stretched at top, heat propagates down, ***melting ice*** and causing ***failure***.

Thermo-mechanical coupling: 2.5D slice

- Computational domain is ***2.5D cross-section*** of archetypal 3D bluff geometry
- ***Time period***: May-Dec. 2011
- ***Air (skin) temperature*** from ASR dataset at 3hr resolution
- ***Ocean temp*** & ***height*** from WW3+SWAN at 20 min resolution
- ***Ice-free period***: July-Oct.
- ***Material properties:*** from laboratory experiments

Our ***initial verification study*** uses real oceanic/ atmospheric BC data but assumes material is ***ice only***.





Thermo-mechanical coupling: 2.5D slice

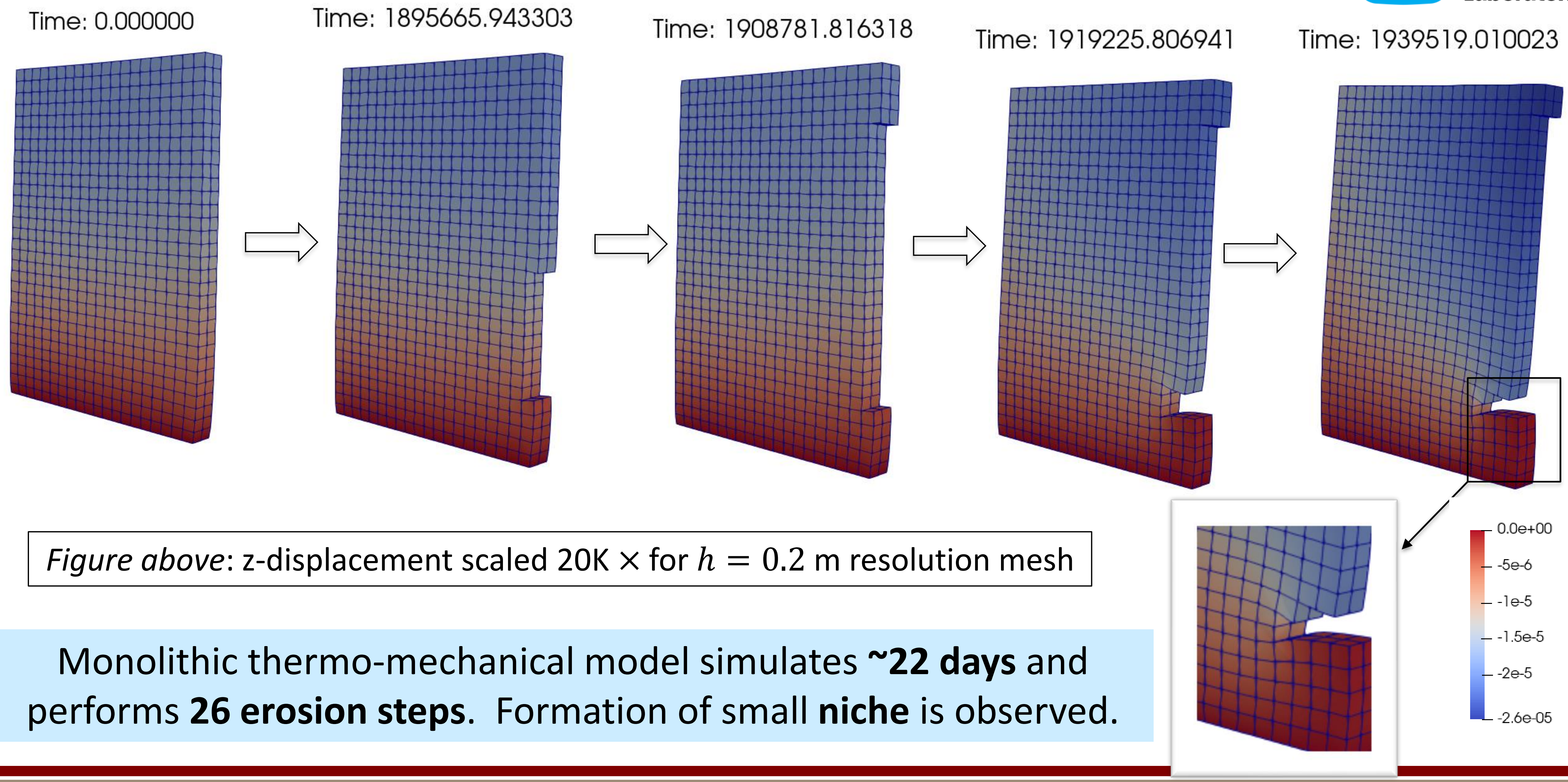


Figure above: z-displacement scaled 20K $\times$ for $h = 0.2$ m resolution mesh

Monolithic thermo-mechanical model simulates **~22 days** and performs **26 erosion steps**. Formation of small **niche** is observed.

Thermo-mechanical coupling: 2.5D slice

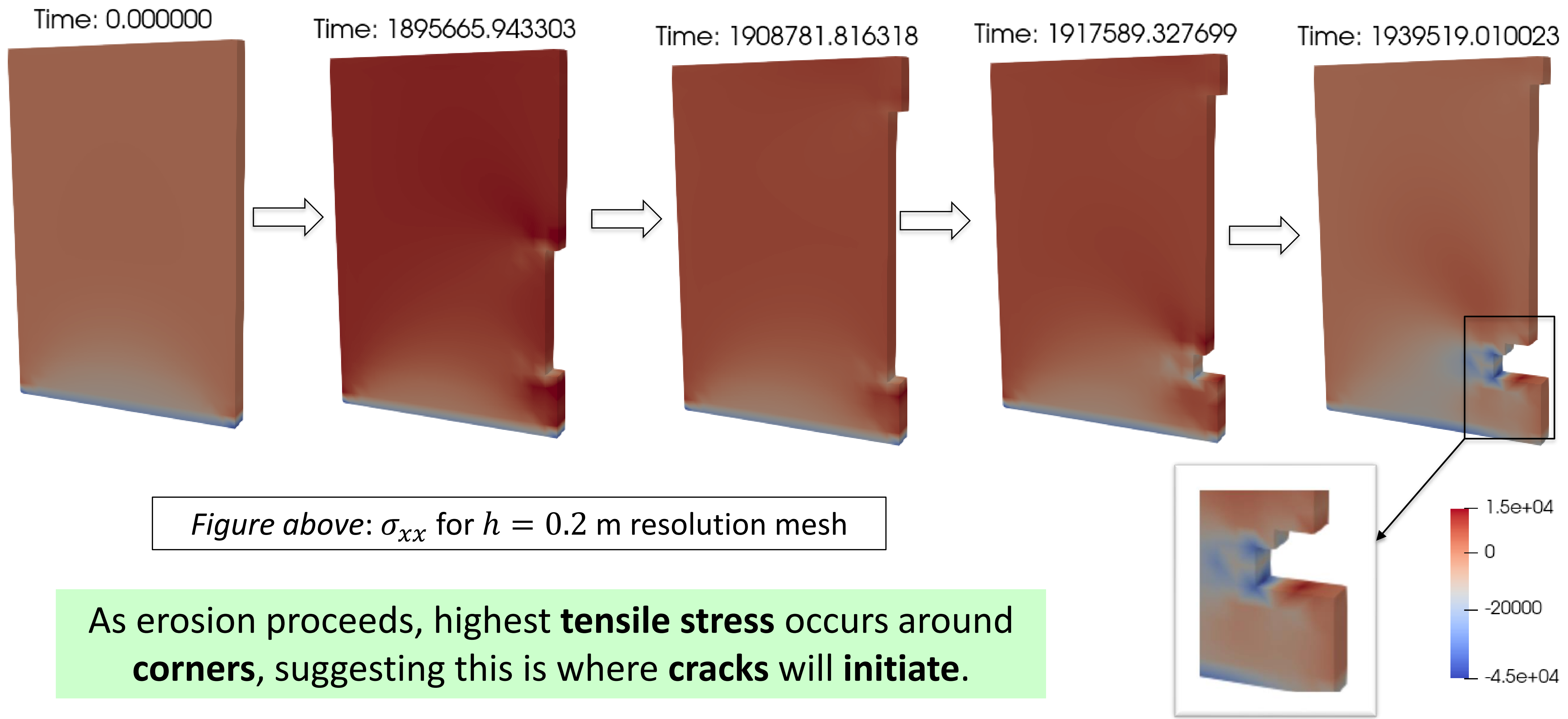


Figure above: σ_{xx} for $h = 0.2$ m resolution mesh

As erosion proceeds, highest **tensile stress** occurs around **corners**, suggesting this is where **cracks** will **initiate**.

Thermo-mechanical coupling: 2.5D slice

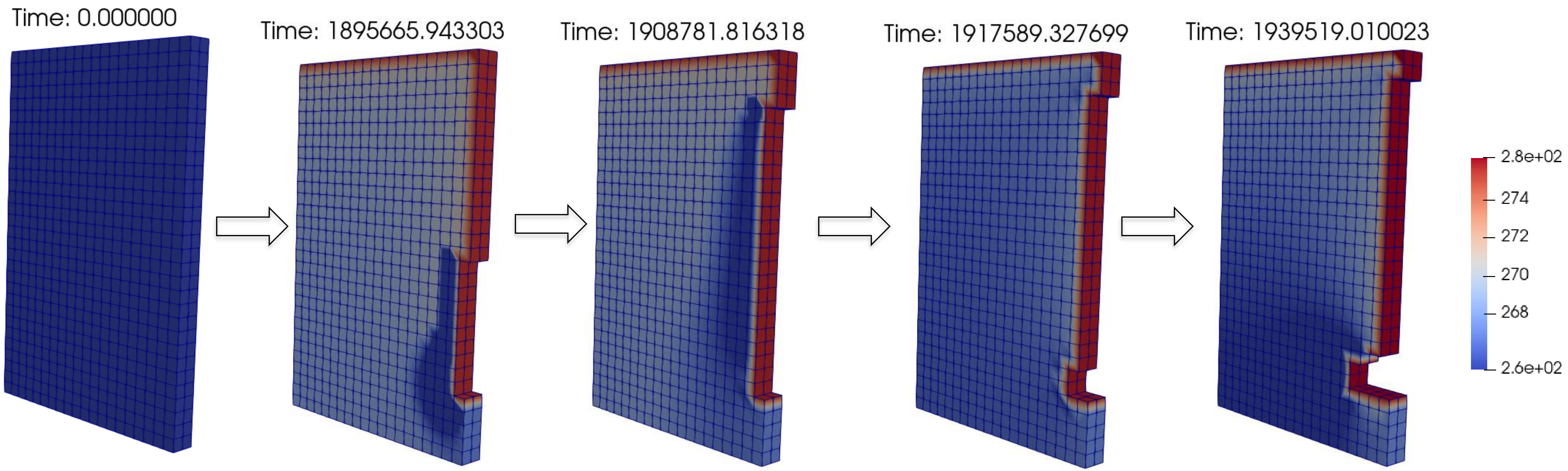


Figure above: temperature for $h = 0.2$ m resolution mesh

Atmospheric and oceanic **boundary conditions** are driving the **melting** of the ice

Thermo-mechanical coupling: 2.5D slice

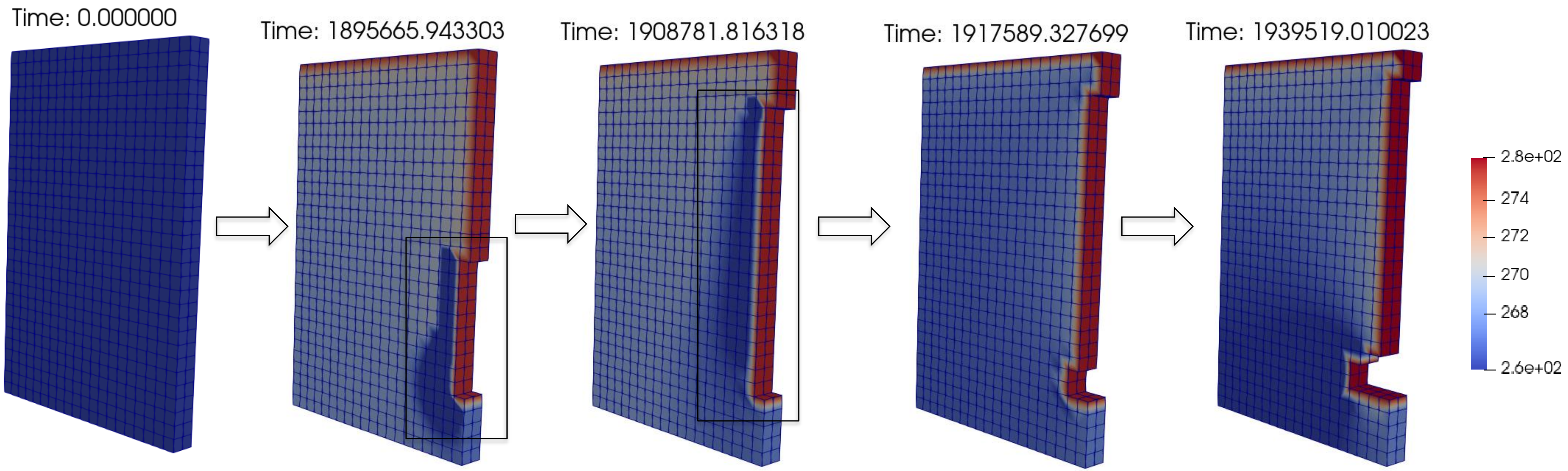
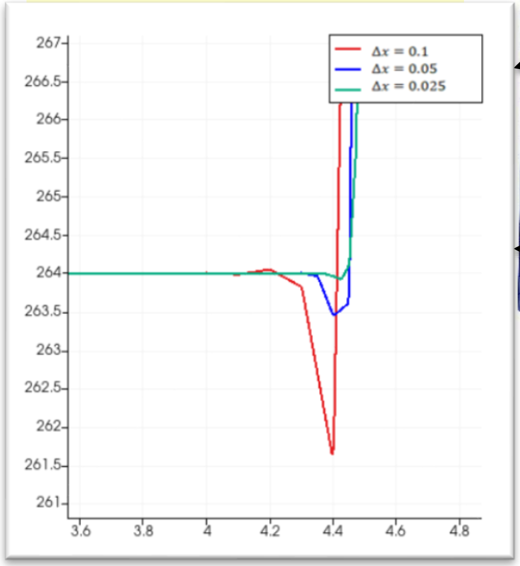


Figure above: temperature for $h = 0.2$ m resolution mesh

Atmospheric and oceanic **boundary conditions** are driving the **melting** of the ice

Thermo-mechanical coupling: 2.5D slice

Spurious oscillations due to an unresolved boundary layer → finer mesh or stabilization needed



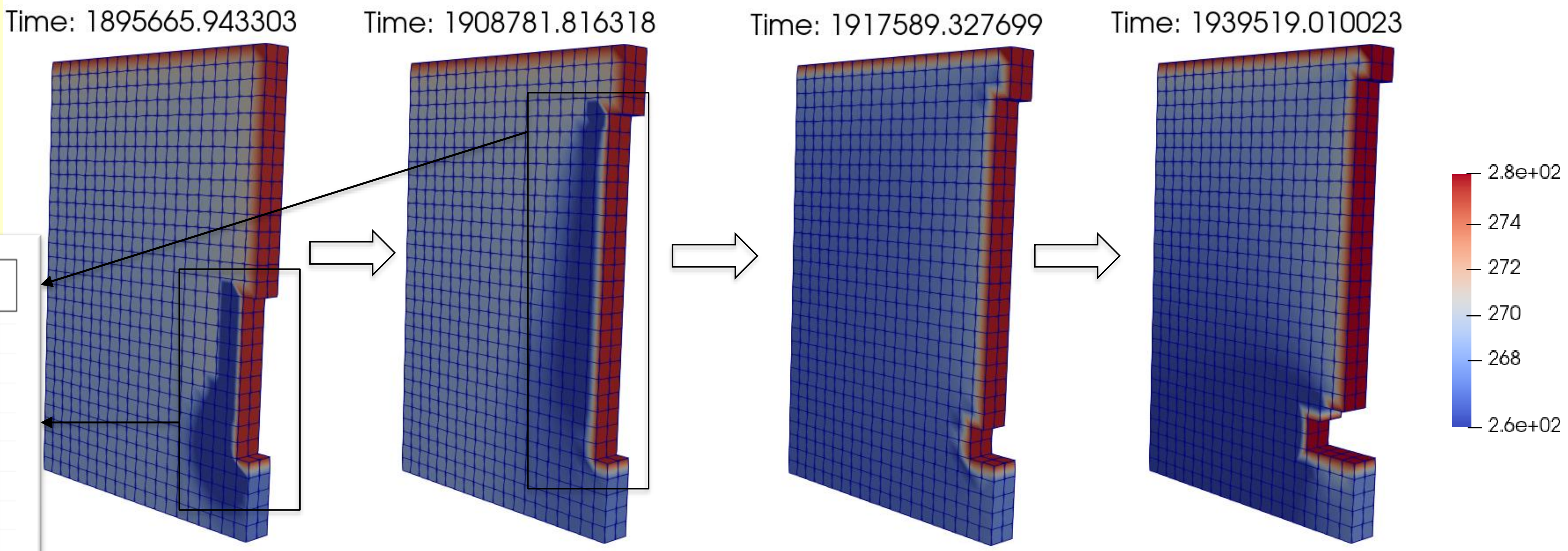


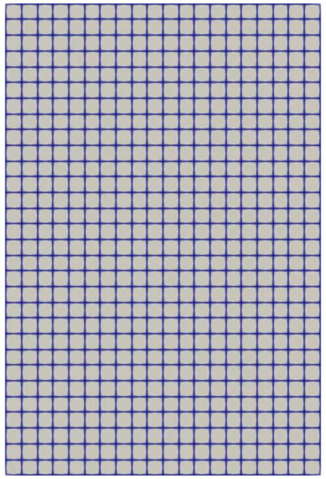
Figure above: temperature for $h = 0.2$ m resolution mesh

Atmospheric and oceanic **boundary conditions** are driving the **melting** of the ice

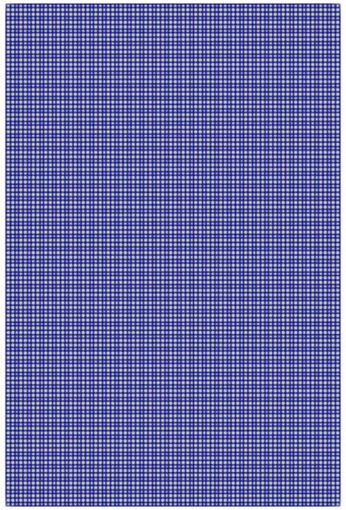
Thermo-mechanical coupling: 2.5D slice

Some issues to resolve:

- Results are very ***mesh dependent***.
- For finer mesh resolutions, ***"teeth" patterns*** are observed in the eroded geometry.
  - These do not seem to be physical and need to be understood.
- Regardless of the mesh resolution, simulations ***do not make it past ~22 days***.
  - ***Nonlinear solver*** struggles and ***fails***, likely due to large differences in scales between the mechanical and thermal equations.
  - ***Sequential thermo-mechanical*** coupling approach is expected to alleviate this difficulty.
    - Sequentially coupled solver will be ***dynamic***.



$h = 0.2$ meters



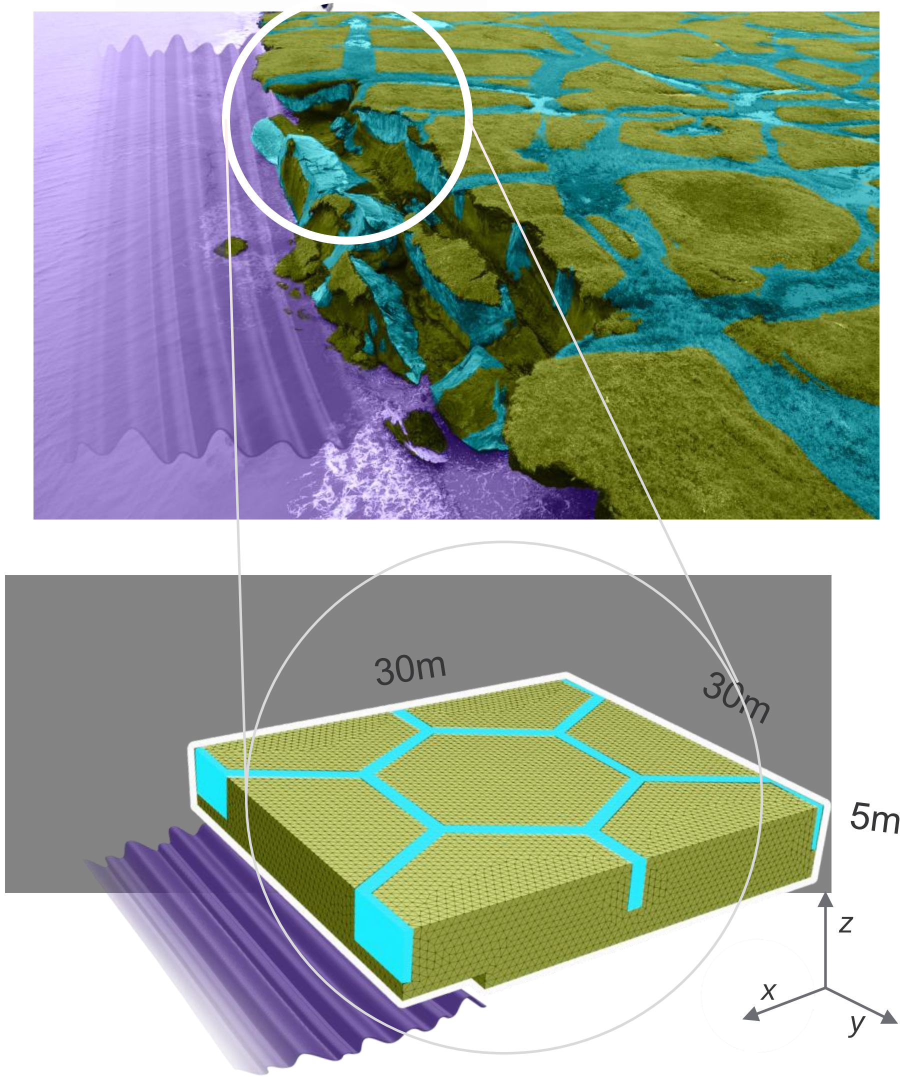
$h = 0.05$ meters

Outline

- Motivation and background
- The Arctic Coastal Erosion (ACE) project
- Thermo-mechanical finite element model of permafrost
- Numerical results
- **Summary**
- Ongoing/future work

Summary

- We have developed a ***thermo-mechanical*** coupled FEM model, ***ACE***, that can simulate ***transient niche development*** and ***permafrost erosion*** within Albany.
- The model was ***calibrated*** using data from a series of ***experiments*** on frozen soil samples from Drew Point, Alaska that were performed at SNL's Geomechanics Laboratory to estimate, as well as ***observational data*** collected at the same location.
- The model incorporates ***boundary conditions*** from the ***WW3+SWAN+Delft3D*** wave models and observational data from an August 2019 field campaign at Drew Point, Alaska.



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- Motivation and background
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- Numerical results
- Summary
- **Ongoing/future work**

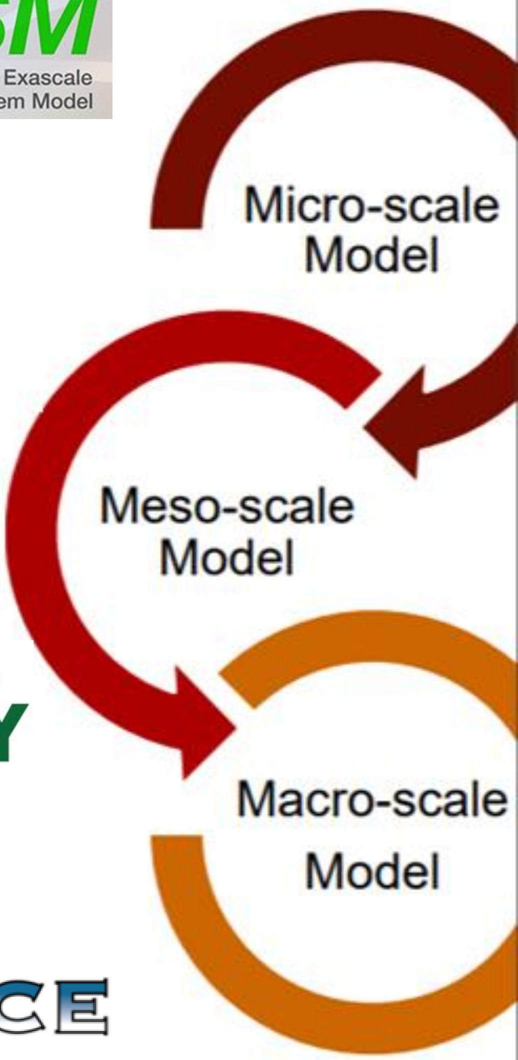
Ongoing/future work

Near term:

- Resolve ***numerical difficulties*** with ACE thermo-mechanical model.
  - ➢ ***Mitigating approach***: sequential coupling between mechanics and thermal equations
- Integrate ***chemical transport*** into ACE model.
- ***Realistic erosion calculations*** using ACE model and Drew Point data.
- ***Tuning/sensitivity studies*** to determine sensitivity ranges at Drew Point.
- ***Validation*** runs to illustrate model skill using FY18-19 data from Drew Point.

Longer term:

- Use ACE model to ***understand coastal processes*** in the ***Arctic***.
- Infer ***statistical meso-scale model*** and relevant ***physics-based parameterizations*** from ACE micro-model, towards integration into ESMs.
  - ➢ ACE is member of the newly-funded DOE sponsored ***InteRFACE project**** focused on coastal processes in Arctic.



* Interdisciplinary Research for Arctic Coastal Environments

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[3] P. Martin *et al.* "Wildlife response to environmental Arctic change: predicting future habitats of Arctic Alaska". Report to WildREACH: Predicting Future Habitats of Arctic Alaska Workshop, Farbanks, Alaska, 2008.

[4] J. Brown and O. Ferrians and J. Heginbottom, E. Melnikov. "Circum-Arctic map of permafrost and ground conditions. Boulder, CO: National Snow and Ice Data Center, Digital Media, 1998.

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[6] T. Ravens, B. Jones, J. Zhang, C. Arp, J. Schmutz. "Process-based coastal erosion modeling for Drew Point, North Slope, Alaska". Journal of Waterway, Port, Coastal, and Ocean Engineering, 138, 2, 122-130, 2012.

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[8] M. Thomas, A. Mota, B. Jones, C. Choens, J. Frederick, D. Bull. "Bluff geometry and material properties influence stress rates relevant to coastal permafrost block failure". Frontiers in Earth Science 8, 2020.

[9] A. Mota, J. Frederick, D. Bull, I. Tezaur. "Thermo-chemo-mechanical coupling for Arctic Coastal Erosion", in preparation.

Acknowledgements

Research Team

SNL: D. Bull (PI), J. Frederick, A. Mota, C. Choens, I. Tezaur, L. Criscenti

USGS: M. Thomas, B. Jones

UAF: J. Kasper, E. Brown

Integral Consulting: C. Jones, C. Flanary

U Texas: J. McClelland, E. Bristol, C. Connolly

Start of Backup Slides

Potential impacts

- **3D model** capable of predicting erosion from the material's constitutive relationships capturing all types of **deformation** (**block & denudation**) leading to:
  - ➢ **Data-driven** understanding of the characteristics that cause erosion
  - ➢ A tool to guide **military** and **civil infrastructure** investments
  - ➢ An improved understanding of **coastal food web impacts** and **carbon-climate feedbacks**

- **Redistributed eroded sediment** in the environment enables:
  - ➢ Prediction of deposition locations
  - ➢ Estimates of fluxes (biogeochemical, toxins, etc.)

Approach for moving from mechanistic micro-scale to stochastic meso-scale model sets stage for **integration** into **global climate models** built upon parametric analyses of input variables


PC: Andrew Burton, NPR

Oceanography in Mechanistic Model

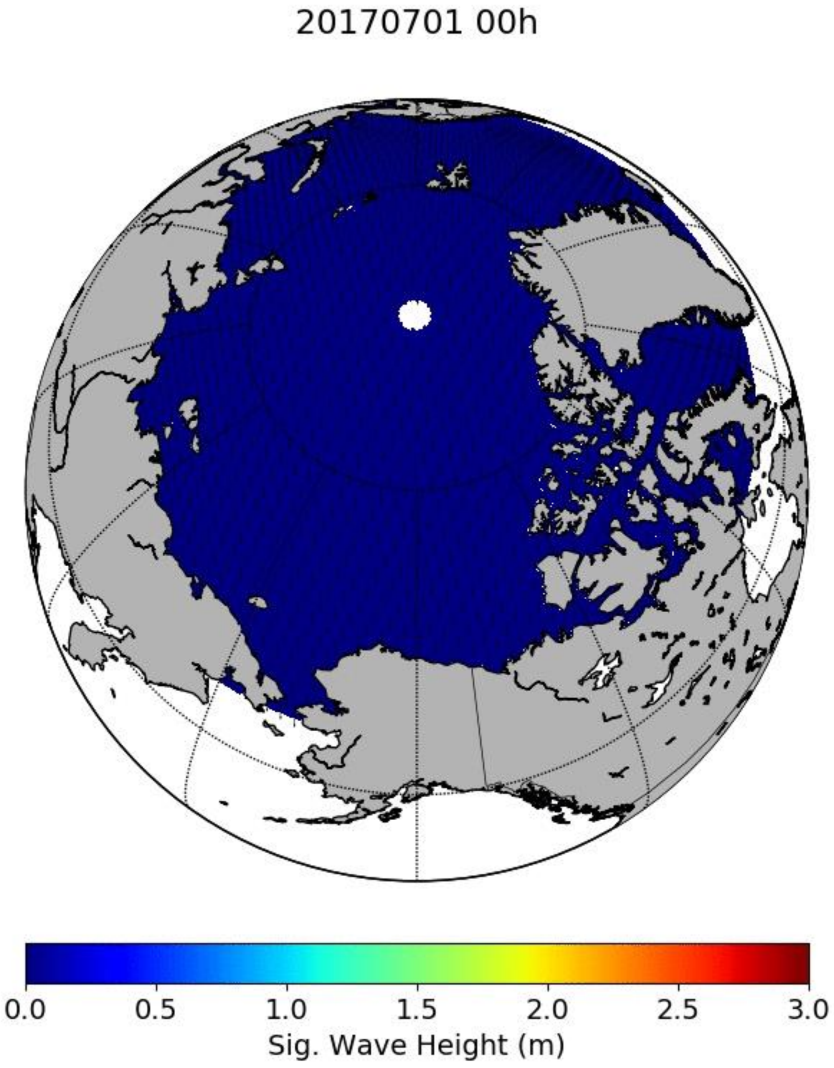
Sandia National Laboratories

WW3 — Development of wave field in the Arctic to develop nearshore BCs
- surface winds
- ice cover
- temperature (surface and ocean)
- solar radiation
- persistent currents

SWAN — Wave set-up conditions 2-way coupled with circulation
- high resolution near shore environment
- capture set-up (storm surge and runup)
- wave energy inclusive of induced current effects

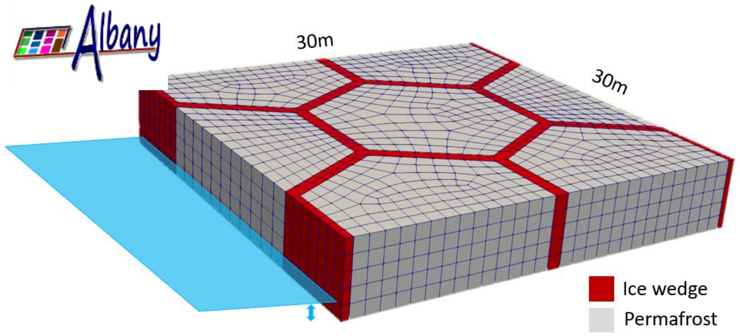
Delft3D — Circulation and thermodynamic mixing 2-way coupled with waves
- ability to model mixing of temperature and salinity clines
- capture induced currents in nearshore

- Potential Key Advances
  - Inclusion of ice coverage for fetch limited wave growth
  - Knowledge of wave energy along broad coastline
  - Set-up determination inclusive of bathymetry and wave energy
  - Ability to accurately predict temperature at bluff face through mixing of clines in the ocean



WW3 polar stereographic model initially developed by NRL (Erick Rogers) and NOAA (Arun Chawla)

Multi-scale approach



Micro-Scale Model

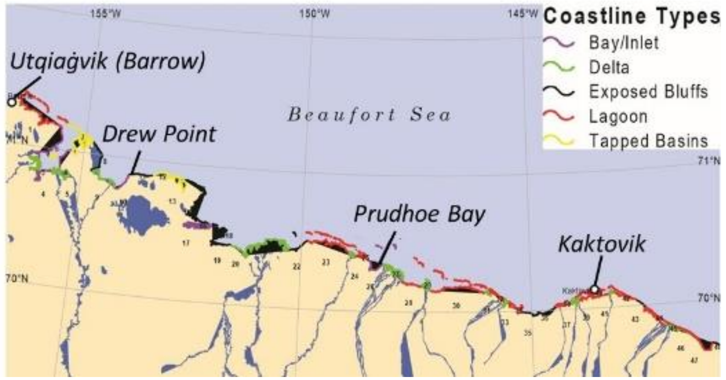
10’s of meters & storm duration

One set of input variables defining the geomorphology and geophysics of the terrestrial model.

Meso-Scale Model

10’s of kilometers & monthly duration

A number of micro-scale models that represent the stochastic distributions of input variables along a confined coastline.



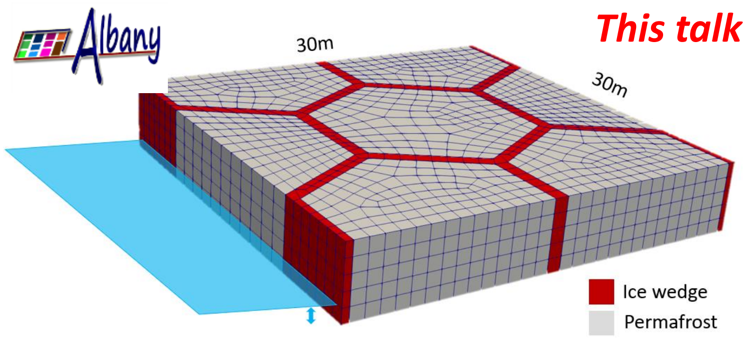
Macro-Scale Model

100’s of kilometers & annual (+) durations

A number of meso-scale models that represent the diversity of coastline types (delta, exposed bluffs, lagoons, etc.) along the AK coastline.

- Working towards a series of fully coupled studies to determine **terrestrial model sensitivities** to:
  - Height of water on bluff face
  - Exposure time of bluff face to water
  - Temperature of water
  - Salinity of water

Multi-scale approach



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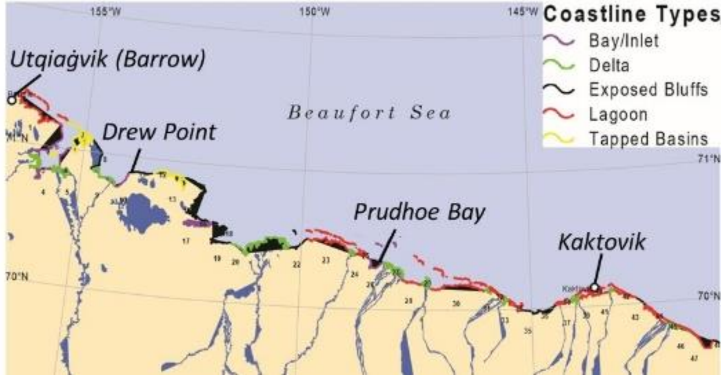

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