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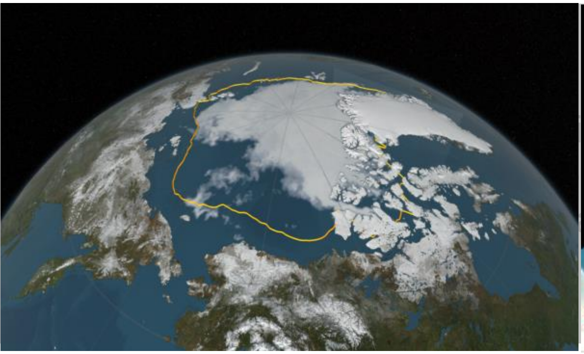

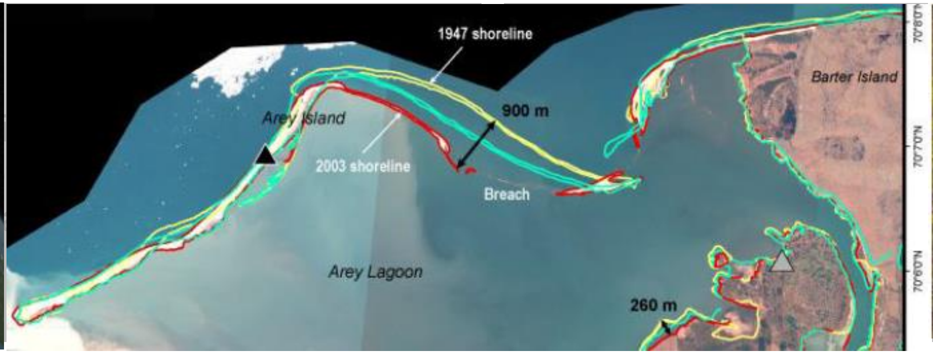

A thermo-mechanical model of permafrost for the simulation of Arctic coastal erosion

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

Sandia National Laboratories, U.S.A.

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

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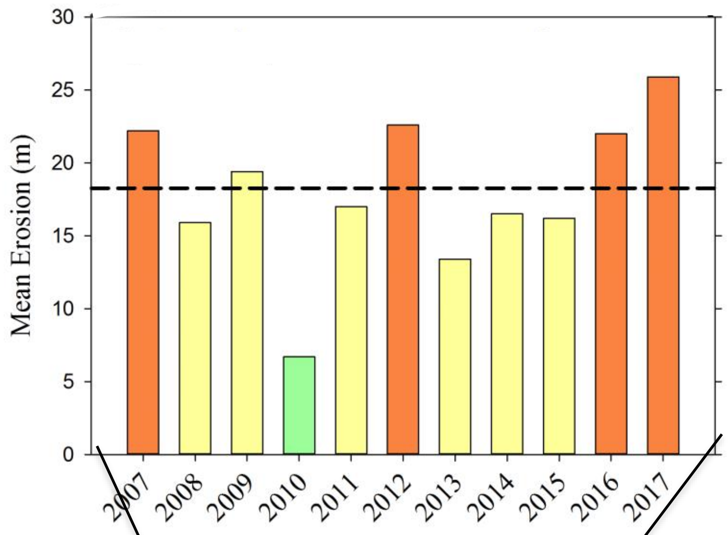
Motivation

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

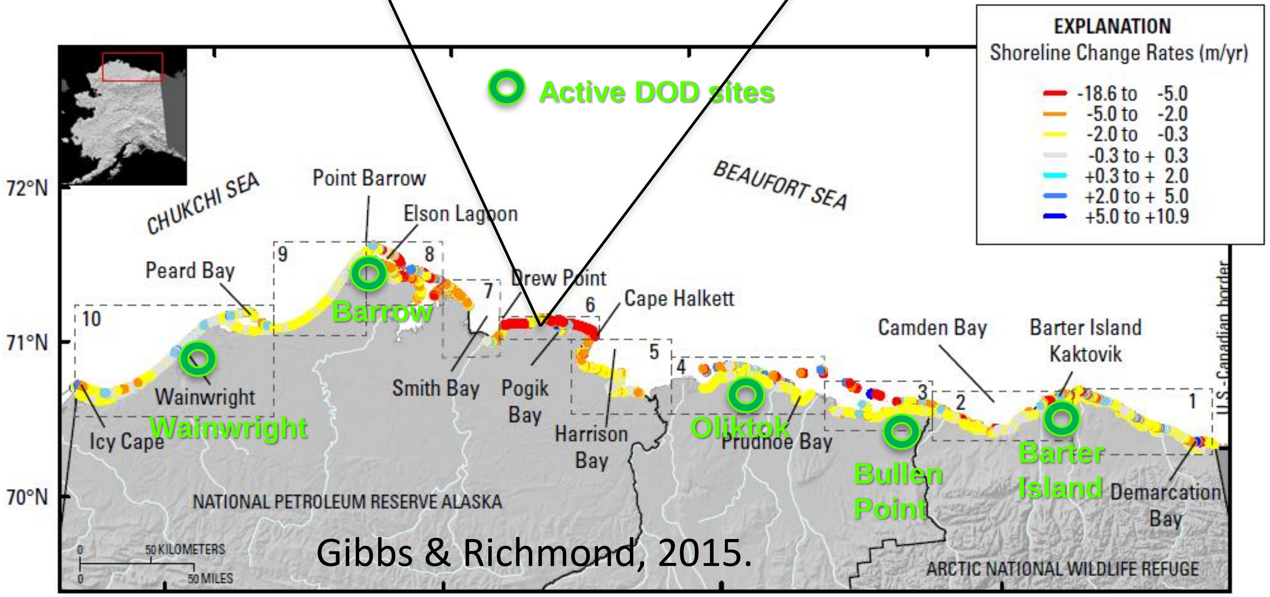
- Primary culprit is **loss of Arctic sea ice**: since 1979 sea ice has lost 51% in area and 75% in volume
  - ➢ Increasing **ice-free season**
  - ➢ Increasing **wave energy** and **storm surge**
  - ➢ Increasing **sea water** temperatures

Erosion is threatening:

- **Coastal communities**: threatened with displacement
- **Coastal infrastructure**: active DoD sites, including toxic waste sites, in northern Alaska
- **Global carbon balance**: permafrost stores greenhouse gases (CO_2, CH_4, NO_2).



Certain locations lost ~200 m (~2 football fields in length) b/w 2007-2017!

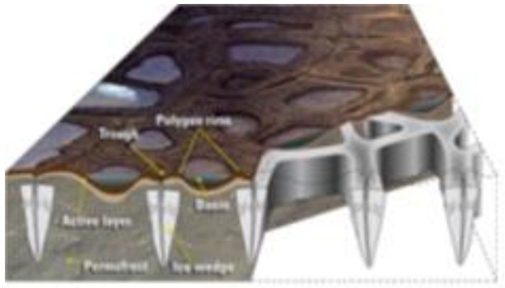


Gibbs & Richmond, 2015.

Permafrost erosion

What is permafrost?

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



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

Brown *et al.* 1998.

Martin *et al.* 2009.

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 of ice wedges causes permafrost **failure**.

Permafrost failure mechanisms

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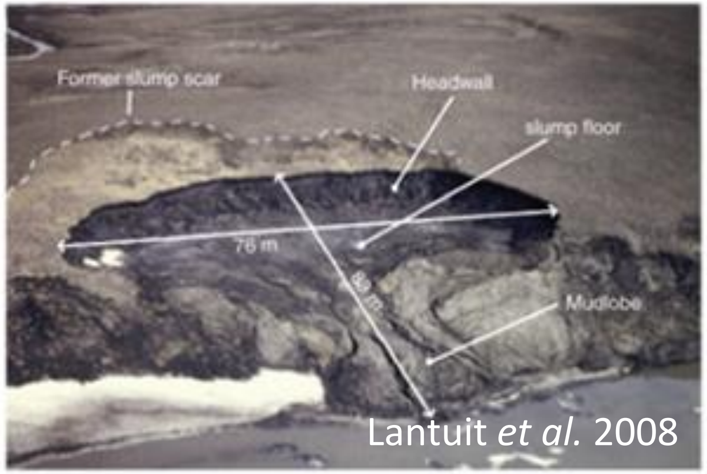
- **Retrogressive thaw slumping**: a slope failure characterized by thaw of exposed ground ice and slumping of thawed soil, typically caused by thermo-denundation[1].
- **Active layer detachment**: failures are translational landslides that occur in summer in thawing soil overlying permafrost, typically caused by thermo-denundation[1].
- **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, caused by thermo-abrasion[2].
  - ➢ Fallen blocks can disintegrate in the near-shore environment **within 1-2 weeks**!



Retrogressive thaw slumping

Active layer detachment

Block failure

[1]Thawing of permafrost bluffs that proceeds under the influence of gravity. [2]Undercutting of permafrost bluff by warming ocean.

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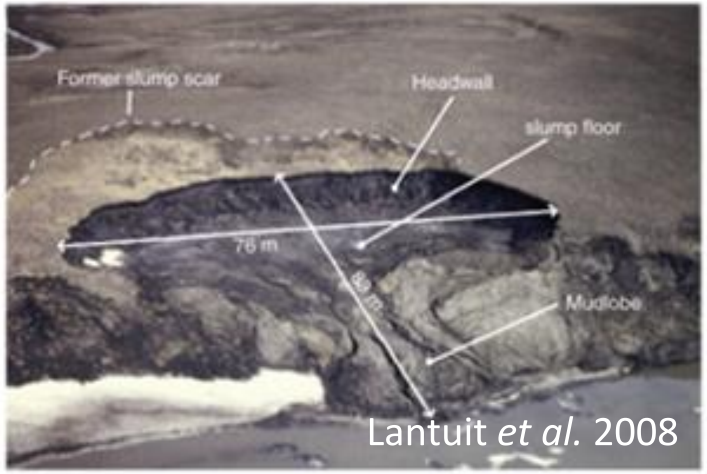


Retrogressive thaw slumping

Active layer detachment

Dominant failure mechanism in northern Alaska

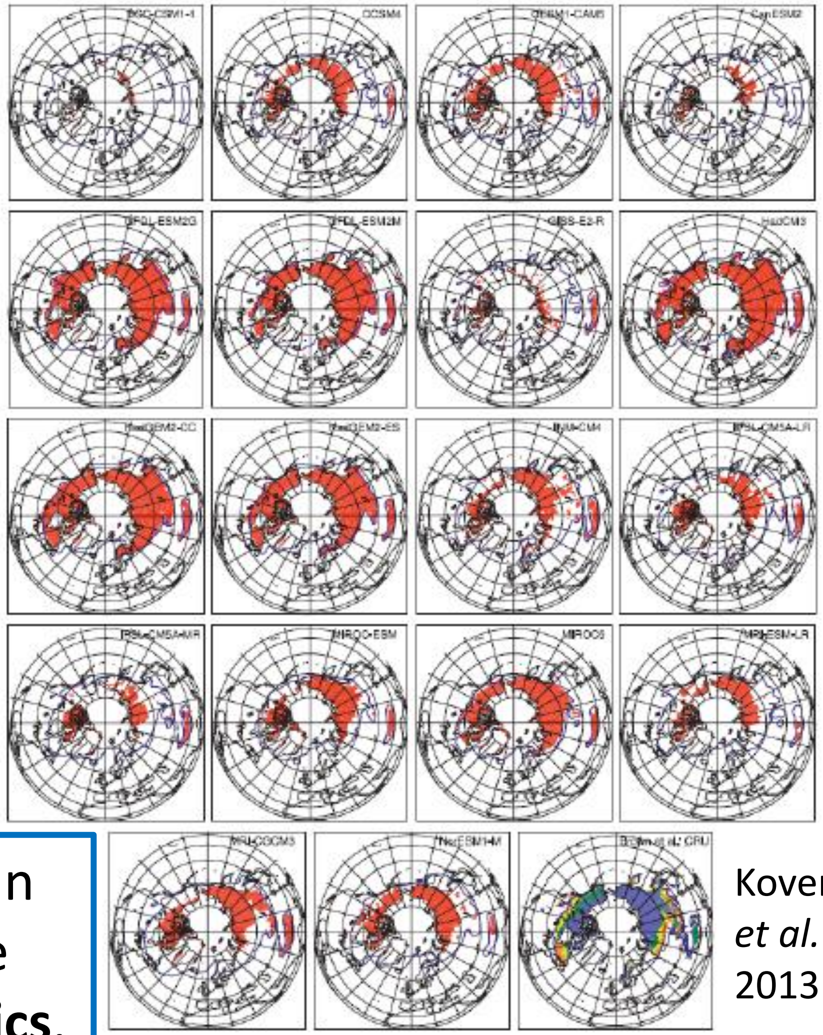
Block failure

[1]Thawing of permafrost bluffs that proceeds under the influence of gravity. [2]Undercutting of permafrost bluff by warming ocean.

State-of-the-art in permafrost modeling

Models and tools to **accurately predict** Arctic coastal erosion are **lacking**!

- Most existing models* (including Earth System Model-, or ESM-, coupled models) are **primitive**:
  - ➢ Most models were based on **trend projection** and/or **empirical relationships**
  - ➢ **Limited PDE-based models**: primarily **thermal models**, e.g., 1D steady state heat flow (no mechanics/deformation)
  - ➢ Most models assumed a **particular type** of **erosion** (e.g., block failure)
  - ➢ Models **did not** include **realistic boundary conditions** and **did not** account for permafrost **geomorphologies** or **geophysics**.



Koven *et al.* 2013

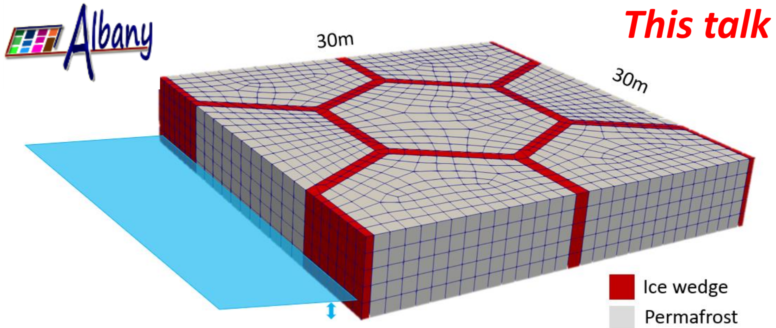
Premise behind the Arctic Coastal Erosion (ACE) project/model: an accurate, **predictive** Arctic coastal erosion model must **couple** the influences of evolving **wave dynamics**, **thermodynamics** & **mechanics**.

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

Proposed solution: a multi-scale approach

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**

This talk



Micro-Scale Model

10's of meters & storm duration

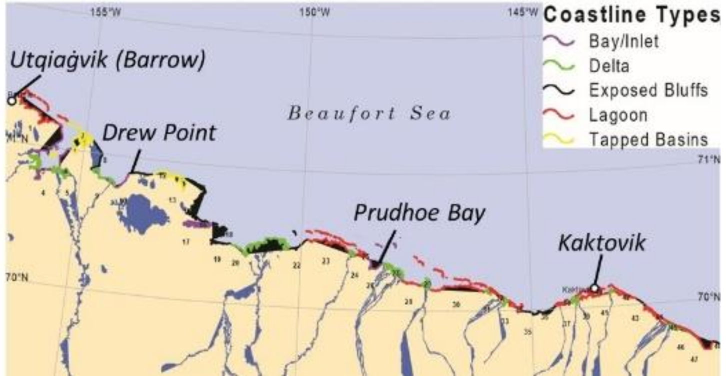
One set of input variables defining the geomorphology and geophysics of the terrestrial model.

- **Coupling** of 3D heat transfer + mechanics-based plastic deformation
- **Wave circulation BCs** representing time-varying realizations of individual storm events.

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

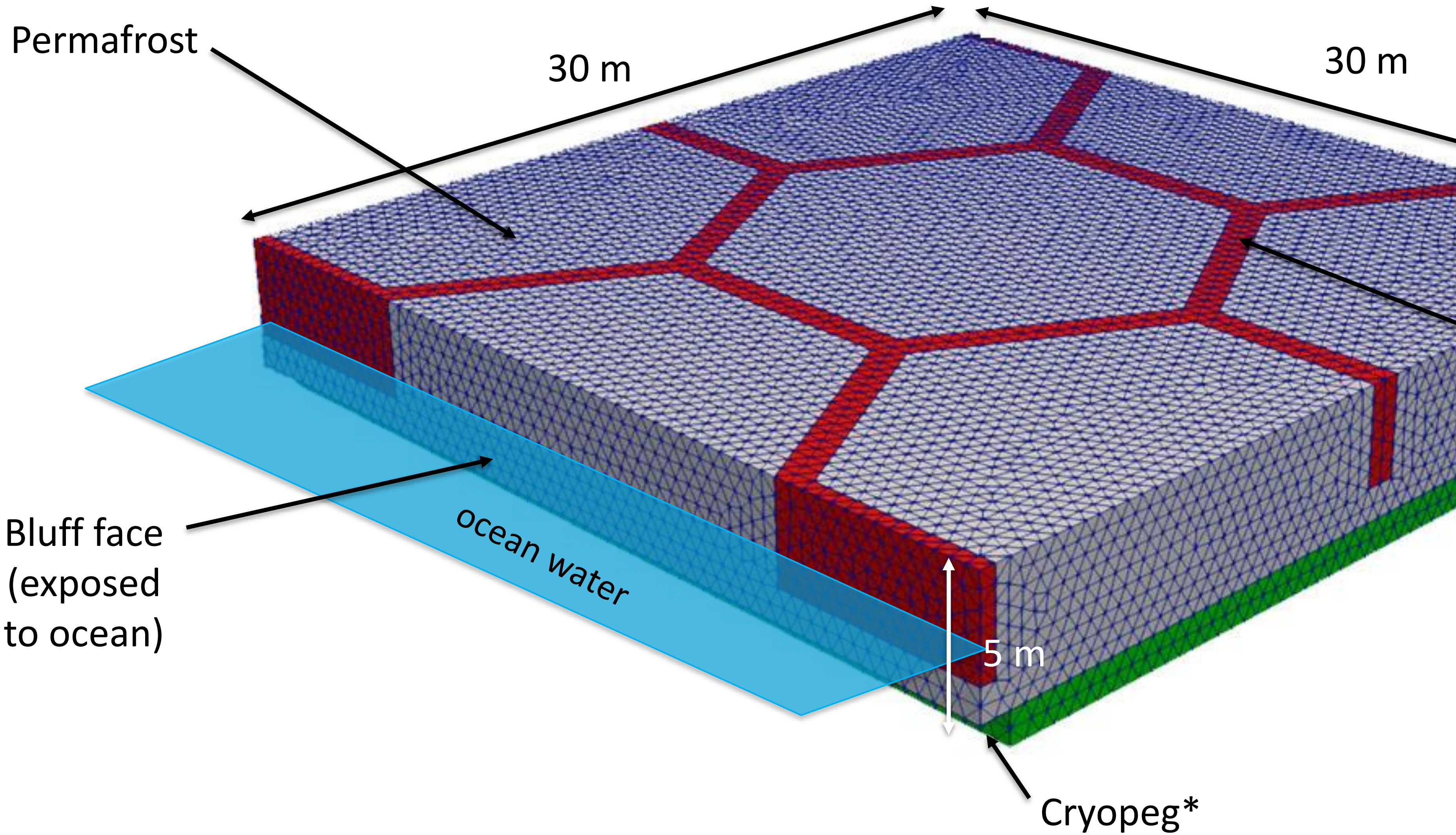
100's of kilometers & annual (+) durations

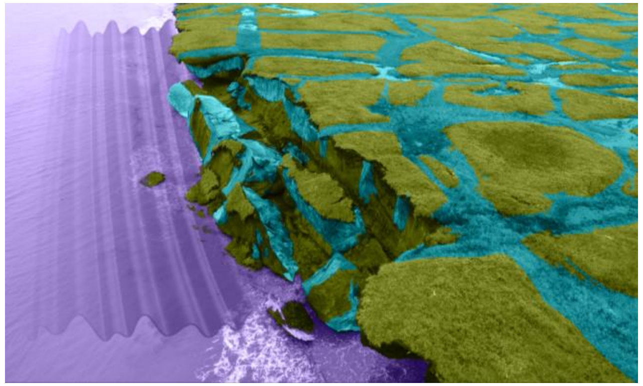
A number of meso-scale models representing different coastline types (delta, exposed bluffs, lagoons, etc.) along the AK coastline.

Longer term vision: upscale micro-scale model to meso- and macro-scales

Create "catalog" of smaller-scale models for diff. Arctic locations, use catalog to derive (physics-based) statistical parameterizations of things like aggregate retreat rates

Anatomy of a canonical computational domain

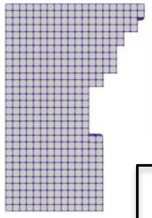




* Layer of unfrozen ground that is perennially cryotic (forming part of the permafrost) in which freezing is prevented.

Coupled thermo-mechanical formulation

- Failure modes come from **constitutive relationships** in FEM model (no empirical relationships!)
- Thermal & mechanical problems can use **different time-steppers** (e.g., implicit-explicit coupling)
- Elements are **removed** from the mesh, to simulate **erosion**
- Model takes in **realistic** oceanic, atmospheric & geothermal heat flux **boundary conditions** (BCs) from wave model & observational data
- **Tightly coupled** strength + thermal states: coupling happens at the level of the material model

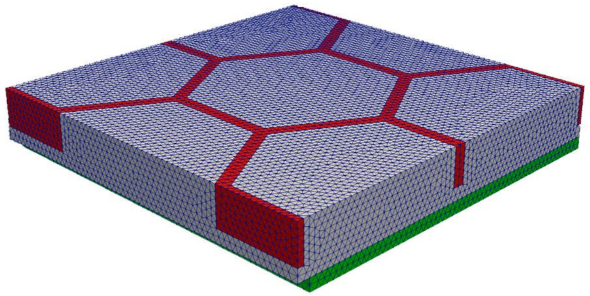


Thermal:

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

Outputs: temperature field, ice saturation

Ice saturation



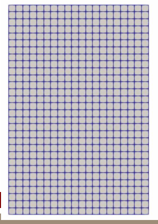
Albany

Mechanical:

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

Outputs: displacements, eroded geometry

Eroded geometry



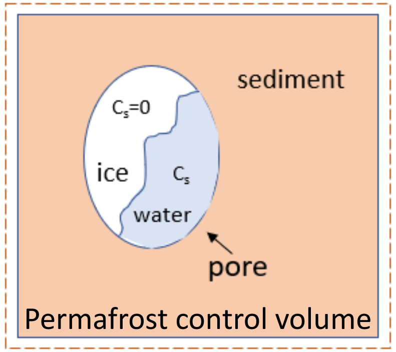
Thermal model

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

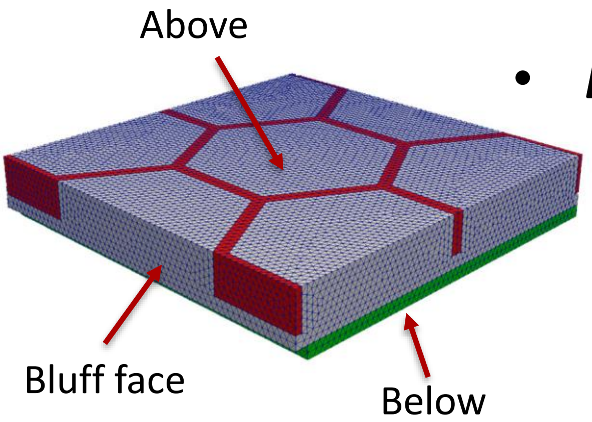
$$(\overline{\rho c_p} + \widetilde{\Theta})\frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{K} \cdot \nabla T)$$

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

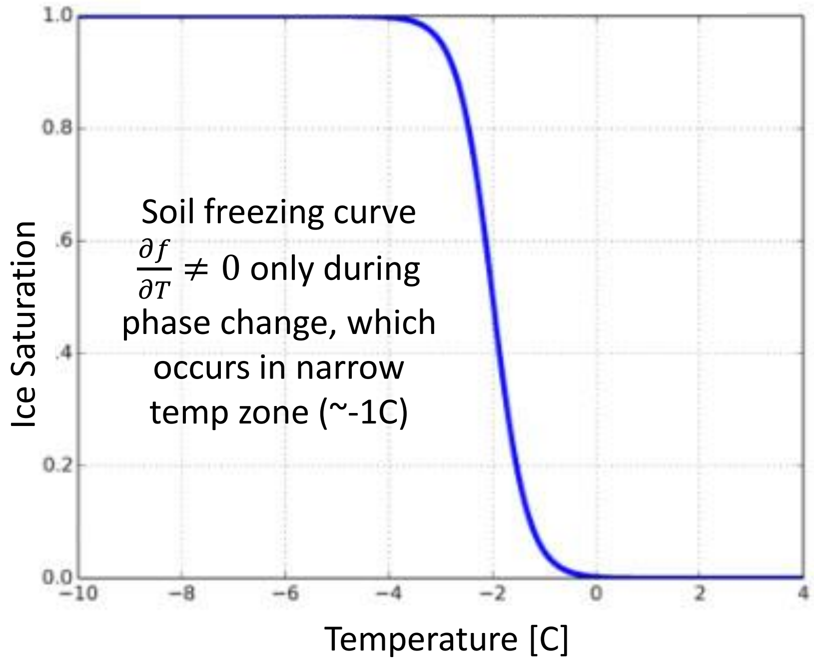
  - Computes ***temperature*** T and ***ice saturation*** f (needed by mechanical model)



$\bar{\rho}$: 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)



- ***Boundary conditions*** (from wave model/data)
  - Local geothermal heat flux from below[1]
  - Mean annual air temp from above[2]
  - Air[2]/ocean[3] temp at bluff face



[1] Data from borehole at Barrow, AK. [2] USGS weather station data. [3] From WaveWatch3+SWAN+Delft3D model.

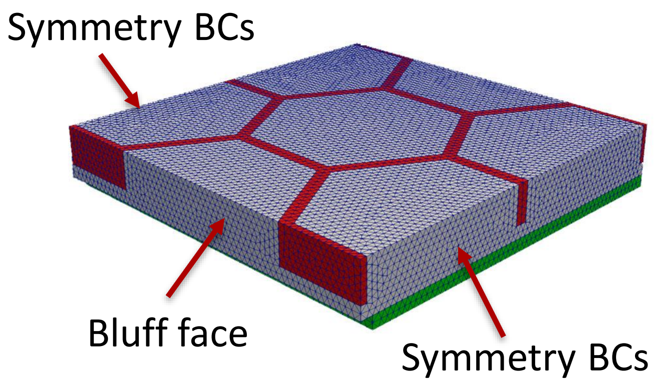
Mechanical model

- Finite deformation ***time-dependent*** 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)
- ***J_2 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[1]
  - Simplest material model with plastic behavior
  - Modified to be a function of ice saturation f (from thermal model)
- ***Boundary conditions:***
  - ***Symmetry BCs*** on lateral sides
  - ***Wave pressure Neumann BC*** on bluff face[2] (from wave model).



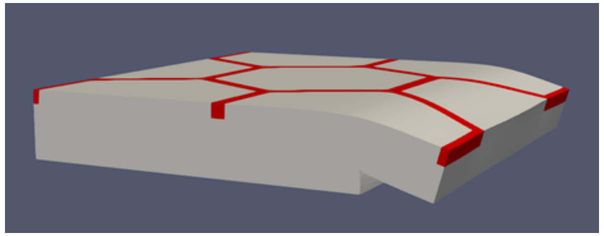
[1] Determined by laboratory tests on frozen soil samples from targeted location. [2] Partenscky, 1988.

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

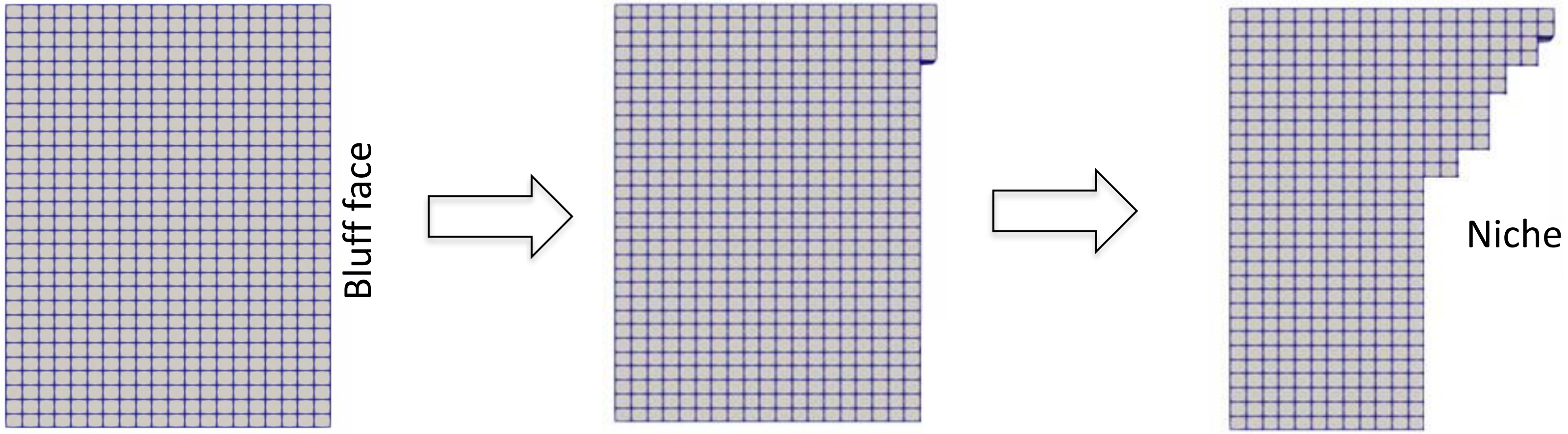
- **Sub-grid scale erosion criterion:** when material is exposed to water, thermal parameters are modified proportional to water force.
- **Stress criterion:** removes material when it reaches a critical value of the yield stress

$$\sigma_0(T) := S_s \sigma_Y^{\text{soil}} + S_f f(T) \sigma_Y^{\text{ice}}$$



- **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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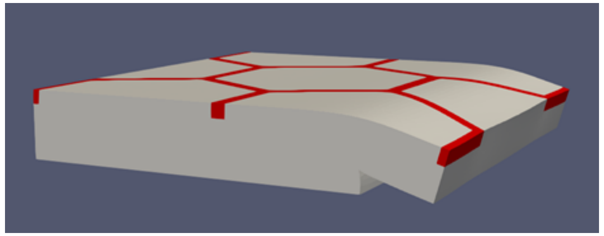

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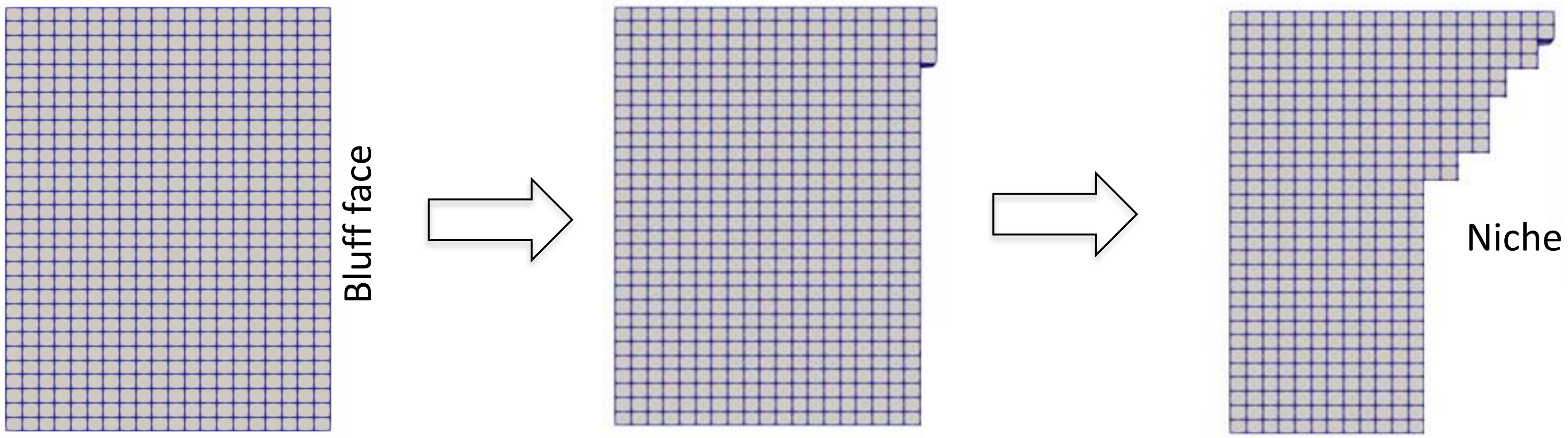


Erosion happens in the mechanics problem but is **influenced by** the **thermal problem**.

Finite element implementation within *Albany*

Sandia National Laboratories

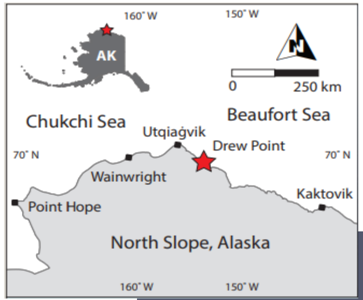
The ***thermo-mechanical Arctic Coastal Erosion (ACE)*** model is implemented within the ***LCM project*** in Sandia's open-source parallel, C++, multi-physics, finite element code, ***Albany***.

- ***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***.

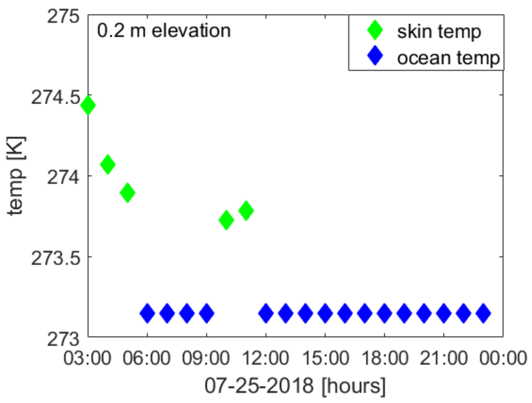
https://github.com/SNLComputation/LCM

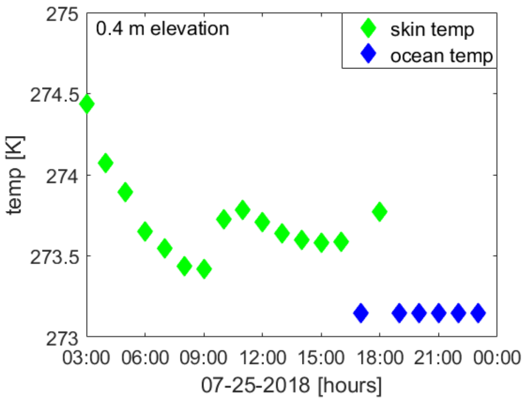
https://github.com/trilinos/trilinos

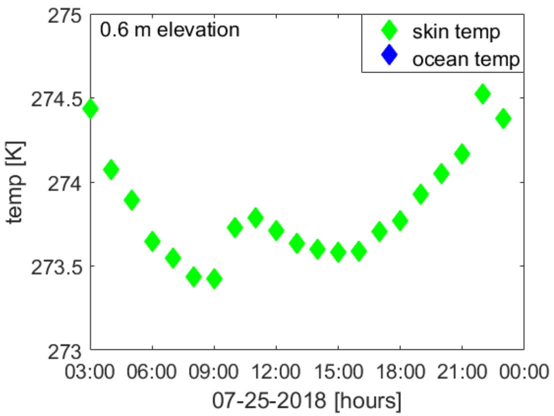
2.5D slice at Drew Point, Alaska*

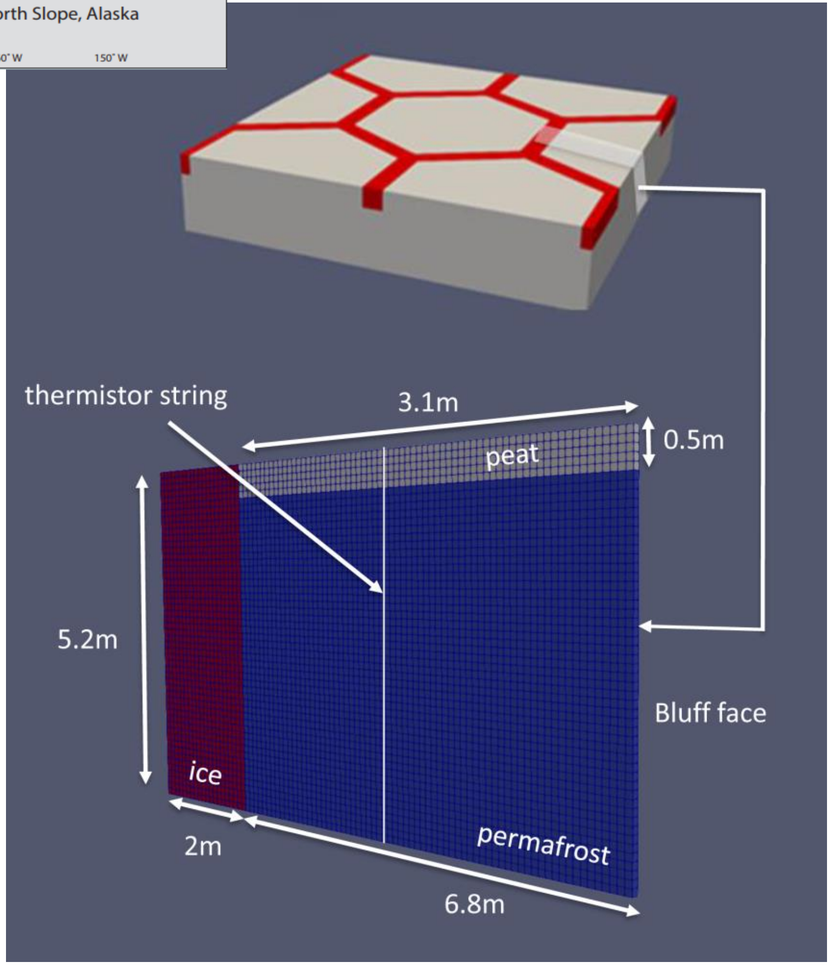


- Computational domain is ***2.5D cross-section*** of archetypal 3D bluff geometry discretized using a uniform hex grid.
  - ➢ Slice of permafrost is exposed to ***realistic BC data*** occurring at Drew Point, Alaska in July 2018 (pseudorealistic problem)





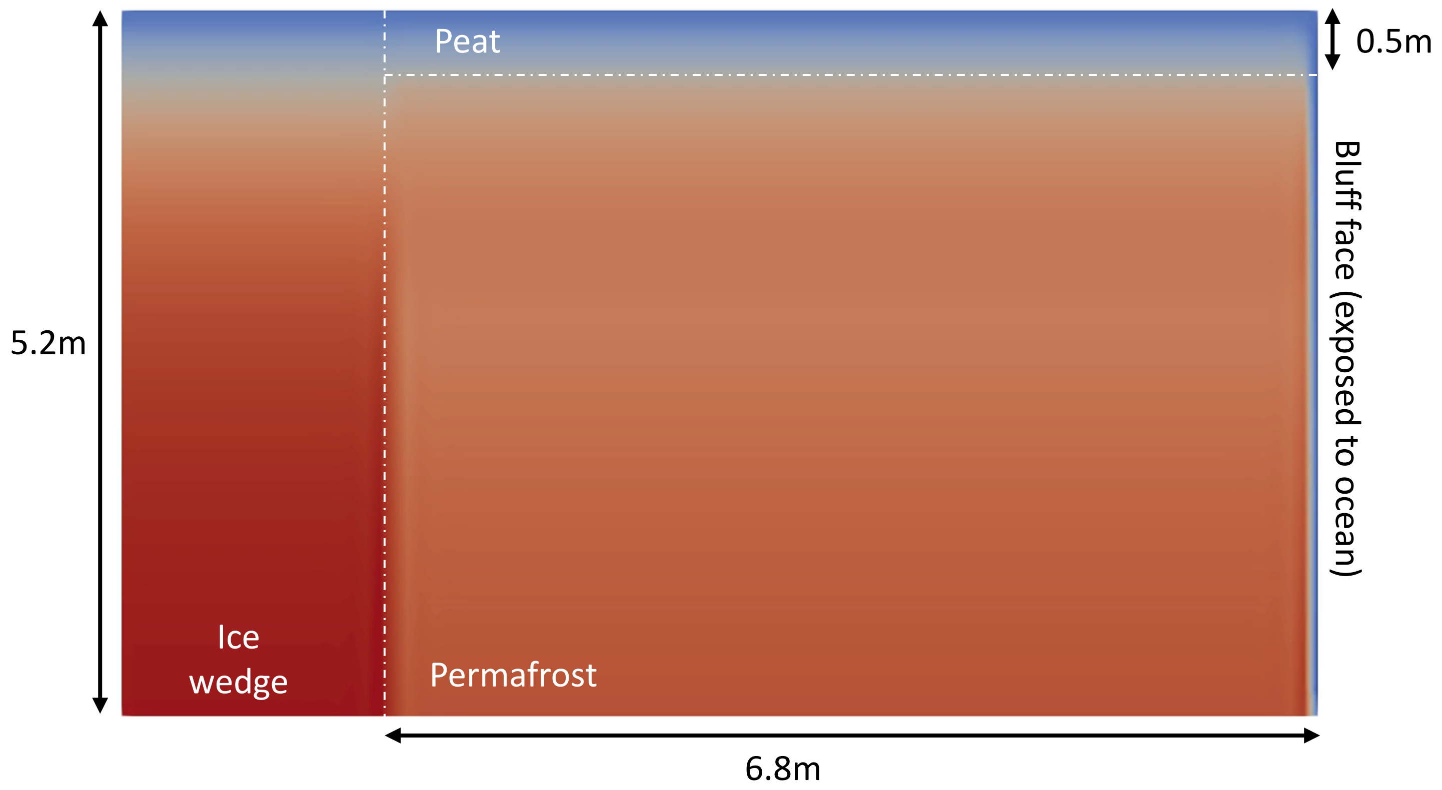


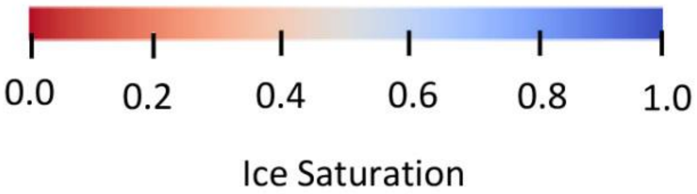


  - ➢ ***Initial temperature field*** obtained from vertical thermistor string placed into DP1-1 ice core at Drew Point.
- ***Material properties*** determined from laboratory experiments on frozen soil samples from Drew Point, Alaska
- ***Implicit*** Newmark for mechanical, ***explicit*** forward Euler for thermal (stable $\Delta t \ = \ 1$ hour)

* For details, see: Frederick, Mota, Tezaur, Bull, *J. Comput. Appl. Math*. 2021.

2.5D slice at Drew Point, Alaska*



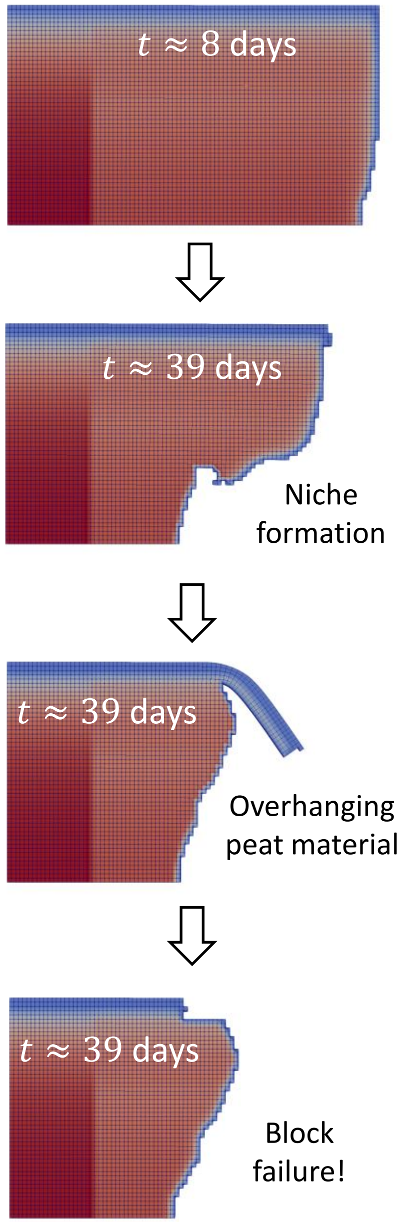


Qualitative comparison to observations

Simulation showing **niche progression** beginning at the bluff toe and **block failure/collapse event***

- ~3m deep ***niche*** forms before a ***block collapse event*** similar to observed collapse at Drew Point, Alaska in early fall 2018.

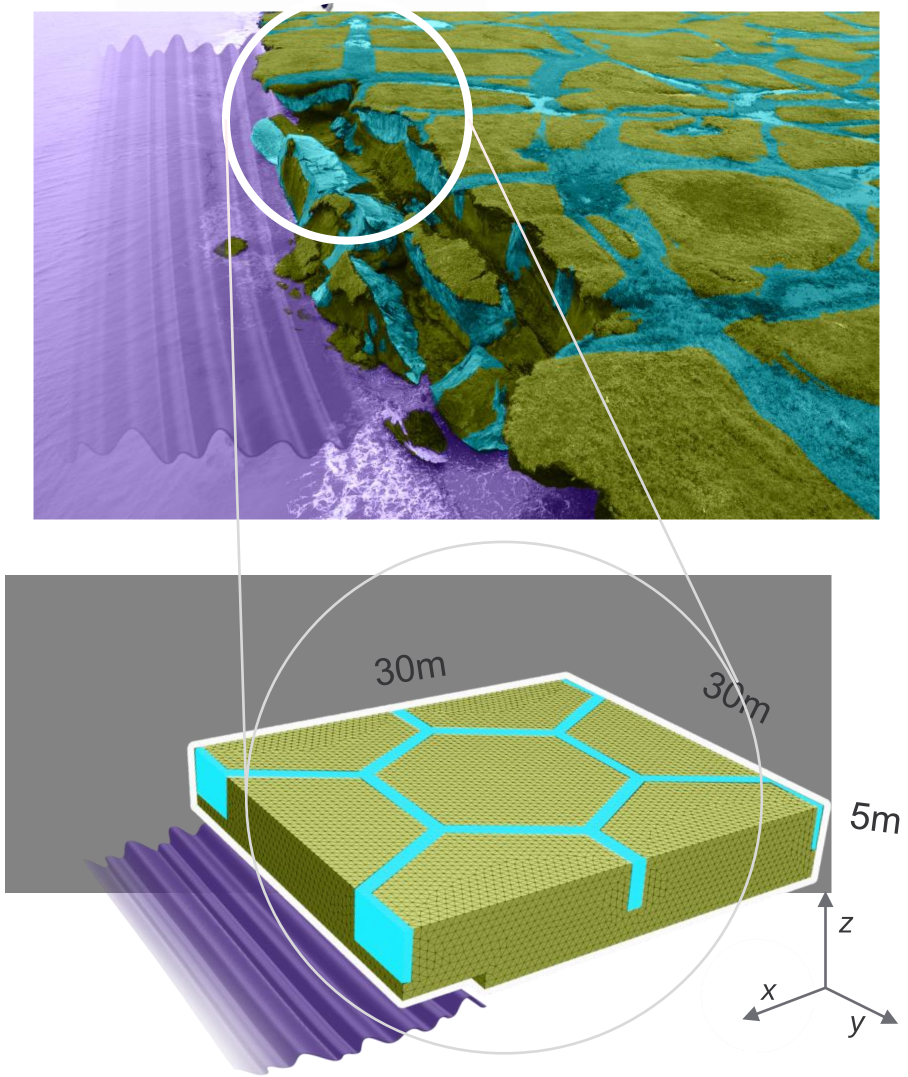
- ***Thermal denudation*** simultaneously with realistic ***niche geometry*** development.



* For details, see: Frederick, Mota, Tezaur, Bull, *J. Comput. Appl. Math*. 2021.

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 Sandia's Geomechanics Laboratory, 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 field campaigns at Drew Point, Alaska.



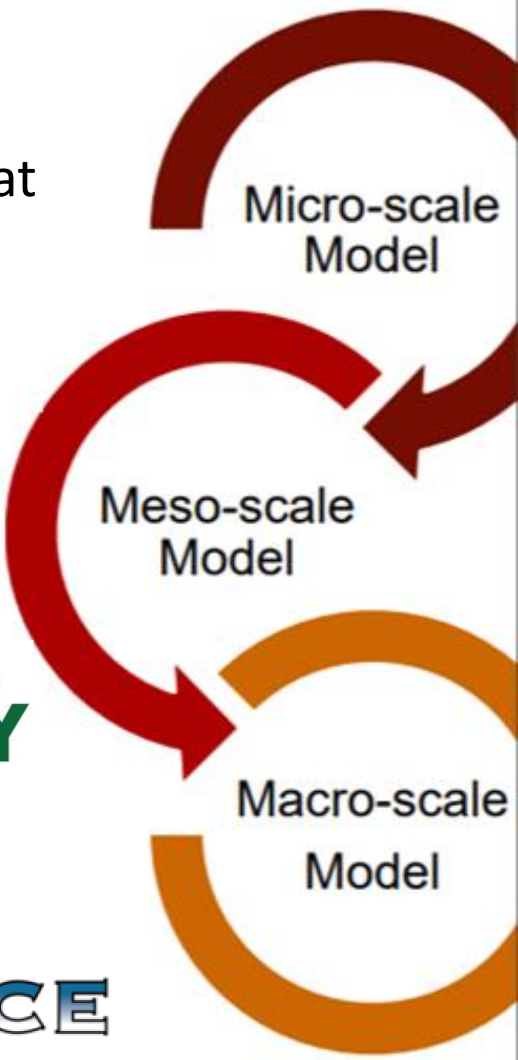
Ongoing/future work

Near term:

- **Quantitative validation study** in which the ACE model predictions are compared to available observational data collected during the 2018-2019 summer seasons at Drew Point, Alaska (2.5D slice + 3D).
- Further **calibration** and **sensitivity studies** using a range of environmental, geomorphological and numerical parameters.

Longer term:

- Integrate **chemical transport** into thermal model.
- Infer **statistical meso-/macro-scale models** 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

References

[1] J. Frederick, M. Thomas, D. Bull, C. Jones, J. Roberts. "The Arctic Coastal Erosion Problem". Sandia National Laboratories Report, SAND2016-9762, 2016.

[2] A. Gibbs, B. Richmond. "National assessment of shoreline change – historical shoreline change along the north coast of Alaska, U.S.-Canadian border to Icy Cape". U.S. Geological Survey Open-File Report, 2015-1048, 2015.

[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.

[5] H. Lantuit, W. Pollard. Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada. Geomorphology, 95, 84-102, 2008.

[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.

[7] C. Koven, J. Riley, A. Stern. "Analysis of permafrost thermal dynamics and response to climate change in the CMPI5 Earth system models". J Climate, 26, 1877-2900, 2009.

[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] J. Frederick, A. Mota, D. Bull, I. Tezaur. "Thermo-chemo-mechanical coupling for Arctic Coastal Erosion", J. Comput. Appl. Math. 2021 (in press).

[10] D. Bull, C. Flanary, C. Jones, J. Frederick, A. Mota, I. Tezaur, J. Kasper, E. Brown, B. Jones, M. Jones, E. Bristol, C. Choens, C. Connoly, J. McClelland. "Arctic Coastal Erosion: Modeling and Experimentation". Sandia National Laboratories report, SAND2020-10223, 2020.

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

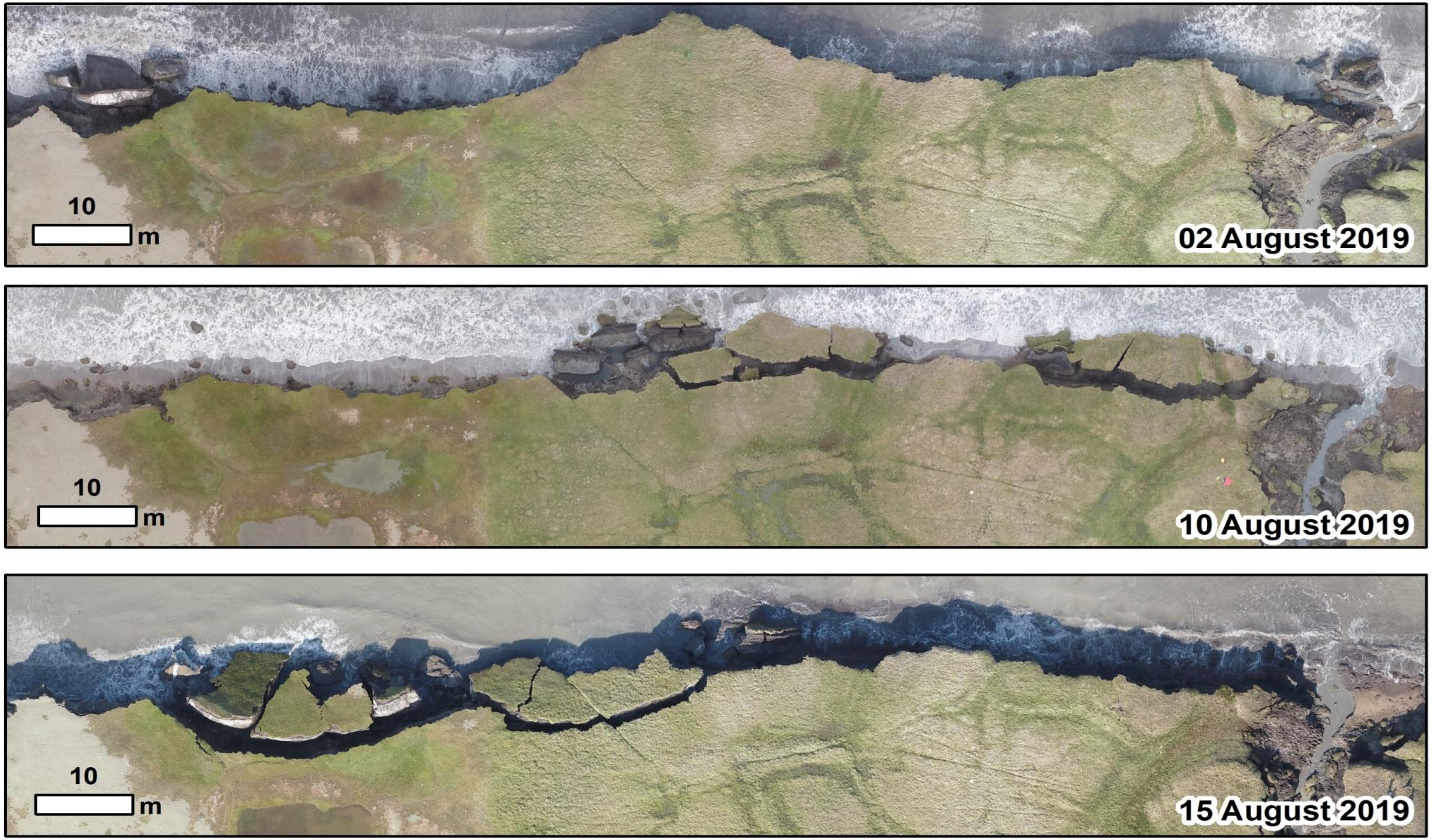
- **3D model** capable of predicting erosion from the material's constitutive relationships capturing all types of **deformation** (**block & denudation**) leading to:
  - **Data-driven** understanding of the characteristics that cause erosion
  - A tool to guide **military** and **civil infrastructure** 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

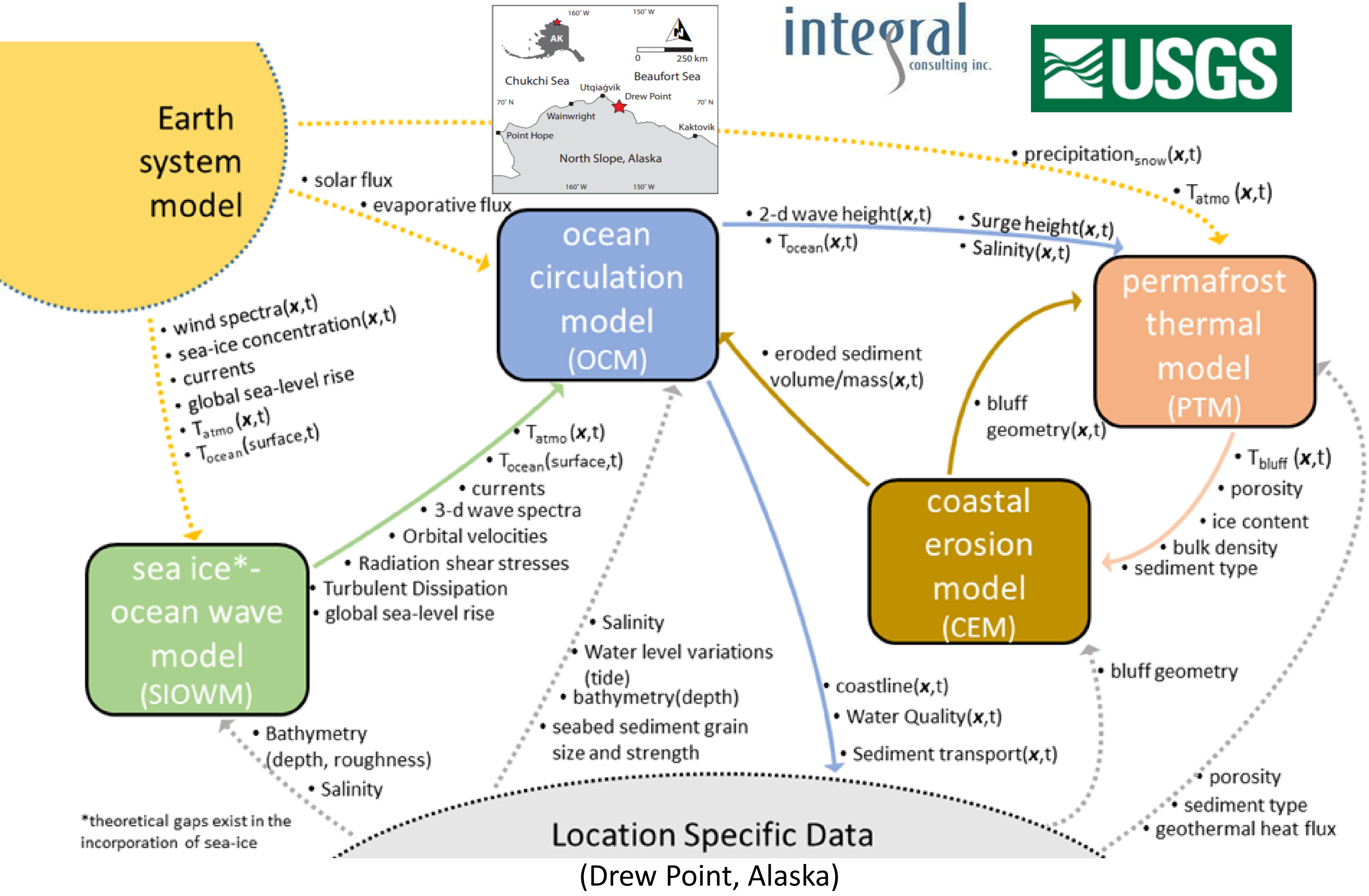
Example of bluff erosion during 2019 UAV surveys*



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

*Images courtesy of Ben Jones, UAF

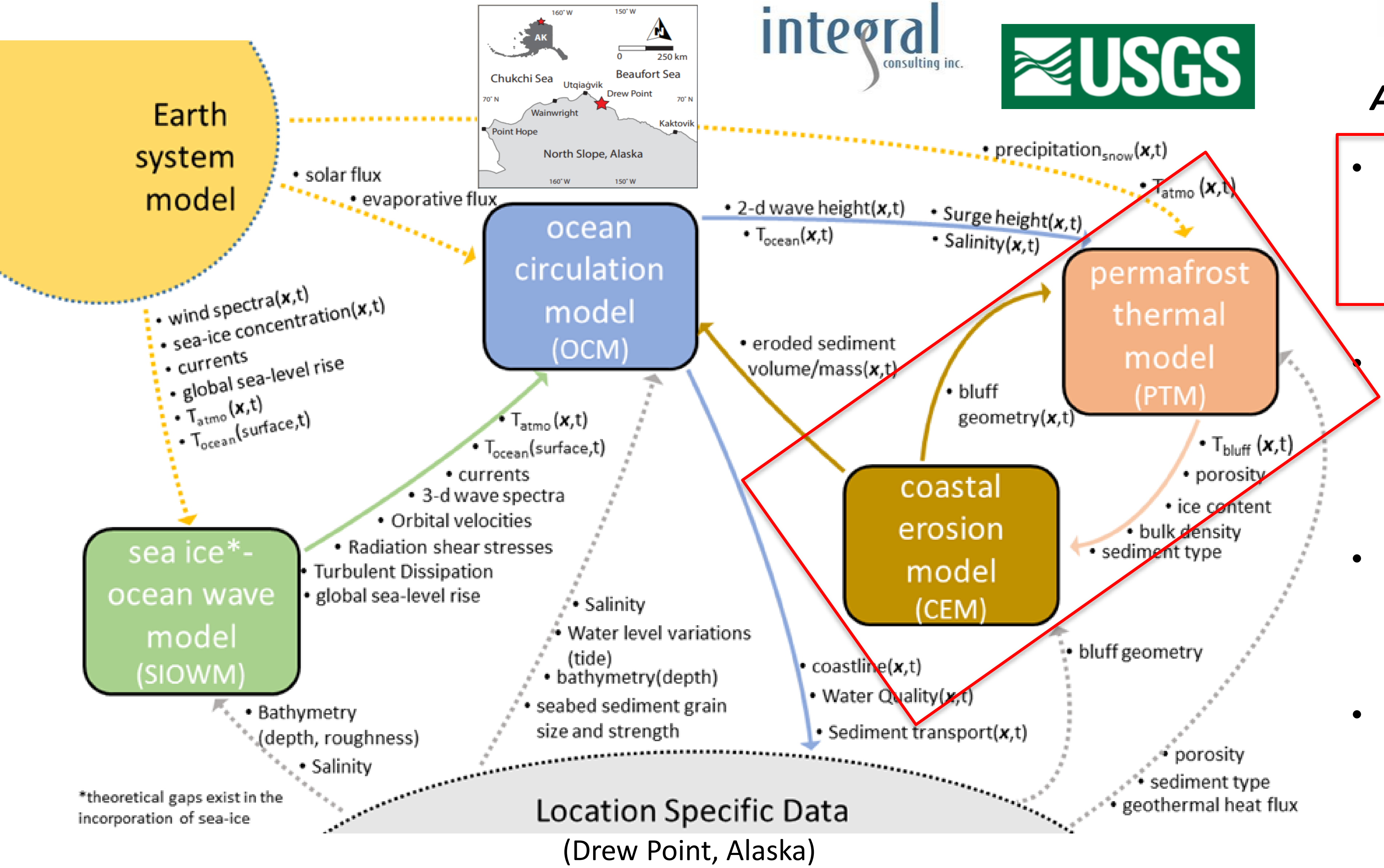
ACE Model Component Coupling



ACE project has many pieces!

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

ACE Model Component Coupling



ACE project has many pieces!

- **Terrestrial model**: thermo-mechanical coupled FEM model that can simulate transient niche development. ***This talk***
- **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.

Oceanography in Mechanistic Model

WW3 — Development of wave field in the Arctic to develop nearshore BCs

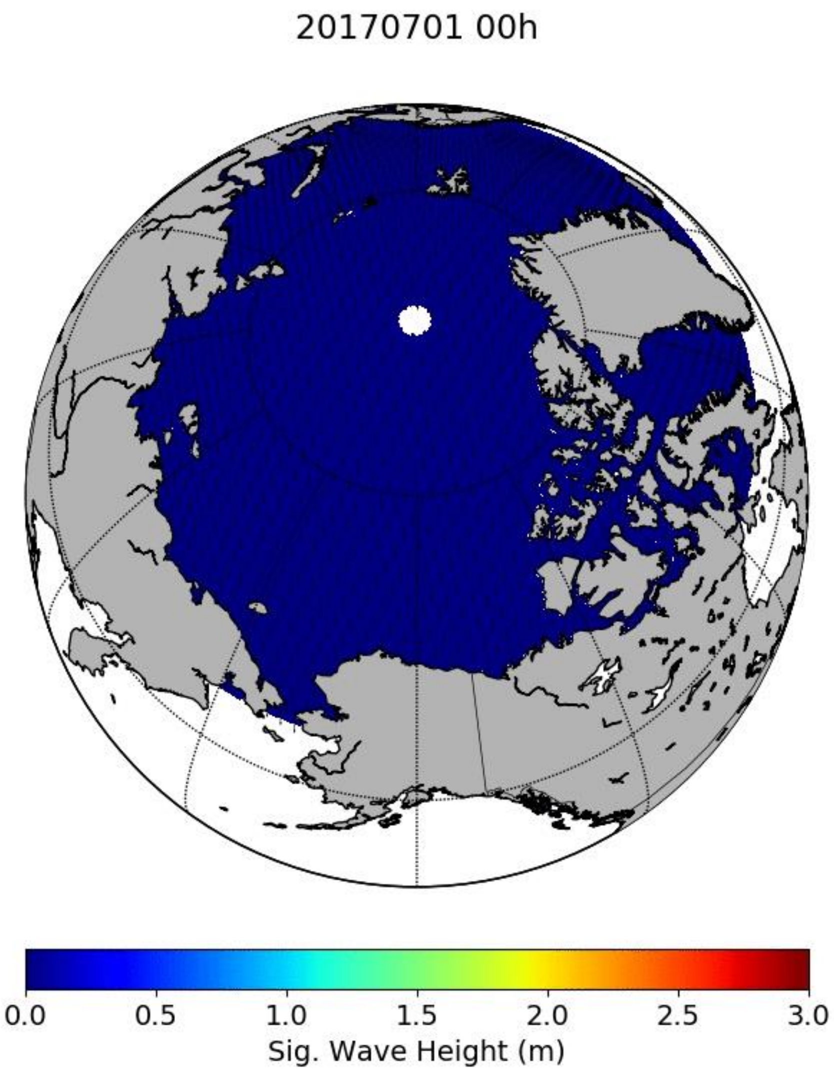
- surface winds
- ice cover
- temperature (surface and ocean)
- solar radiation
- persistent currents

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



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

- 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

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

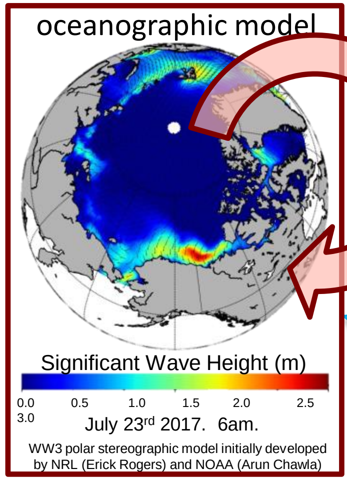
2017-2022

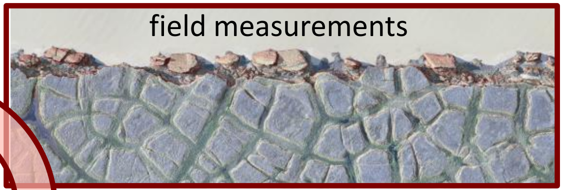
Micro-scale Model

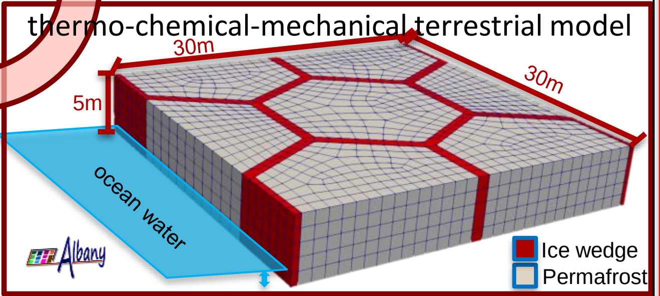
10's of meters & storm duration

- ***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





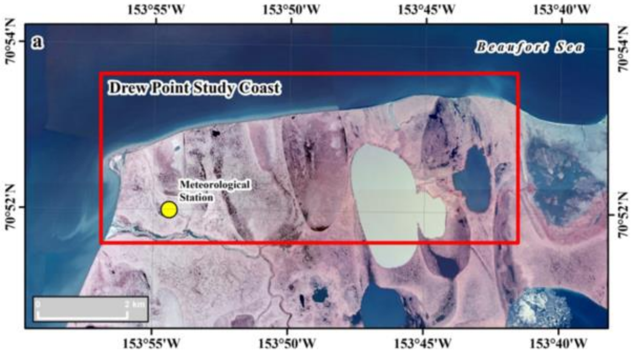


2023+

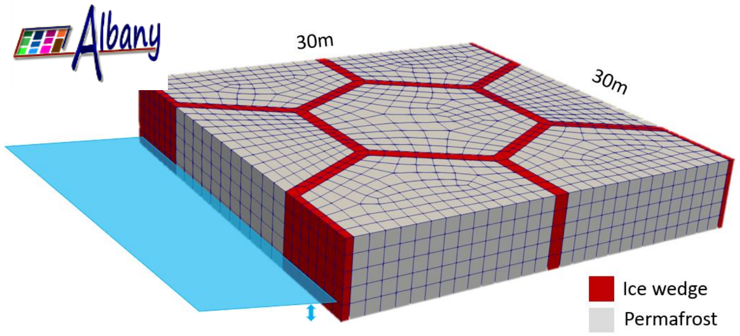
Meso-scale Model

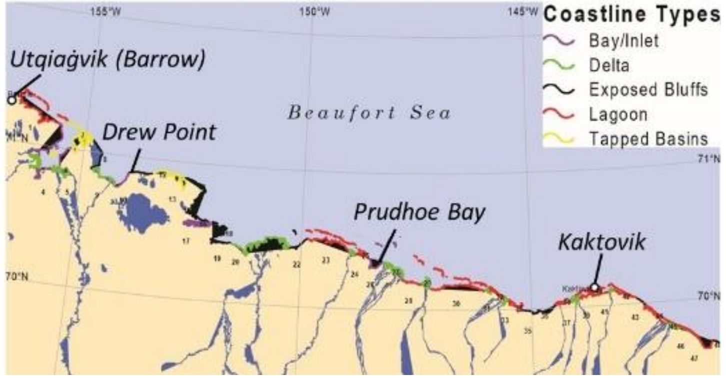
10's of km's & seasonal duration

- 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



Multi-scale approach





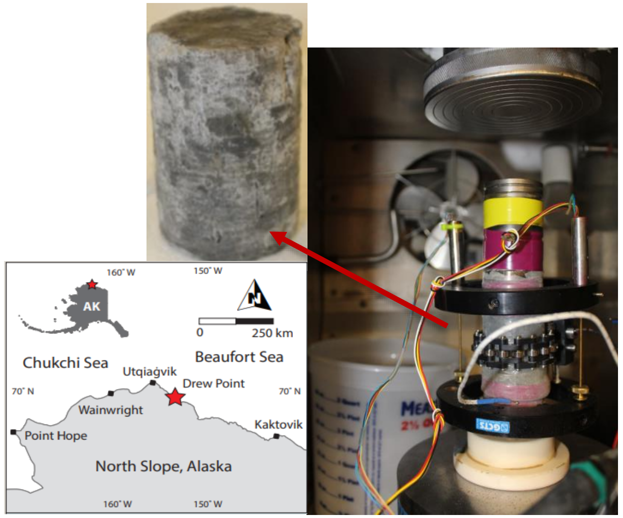
Micro-Scale Model	Meso-Scale Model	Macro-Scale Model
10’s of meters & storm duration	10’s of kilometers & monthly duration	100’s of kilometers & annual (+) durations
One set of input variables defining the geomorphology and geophysics of the terrestrial model.	A number of micro-scale models that represent the stochastic distributions of input variables along a confined coastline.	A number of meso-scale models that represent the diversity of coastline types (delta, exposed bluffs, lagoons, etc.) along the AK coastline.

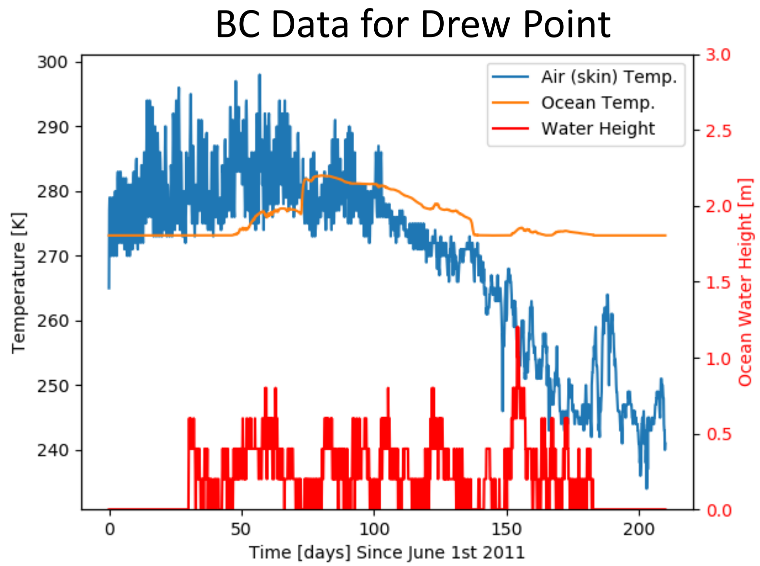
- Working towards a series of fully coupled studies to determine **terrestrial model sensitivities** to:
  - ➢ Height of water on bluff face
  - ➢ Exposure time of bluff face to water
  - ➢ Temperature of water
  - ➢ Salinity of water

Parameters & inputs

Parameters estimated from lab experiments:

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



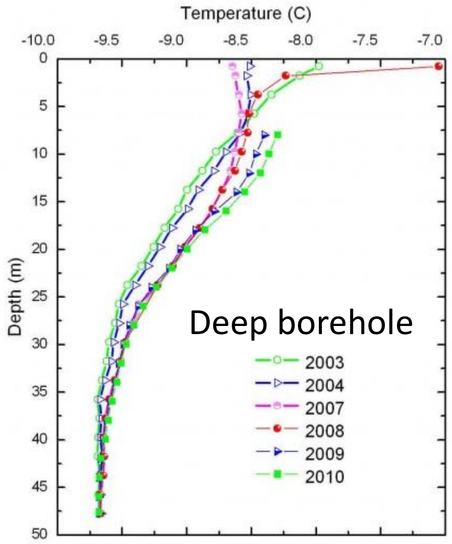


Parameters from literature:

- 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:

- Air 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)

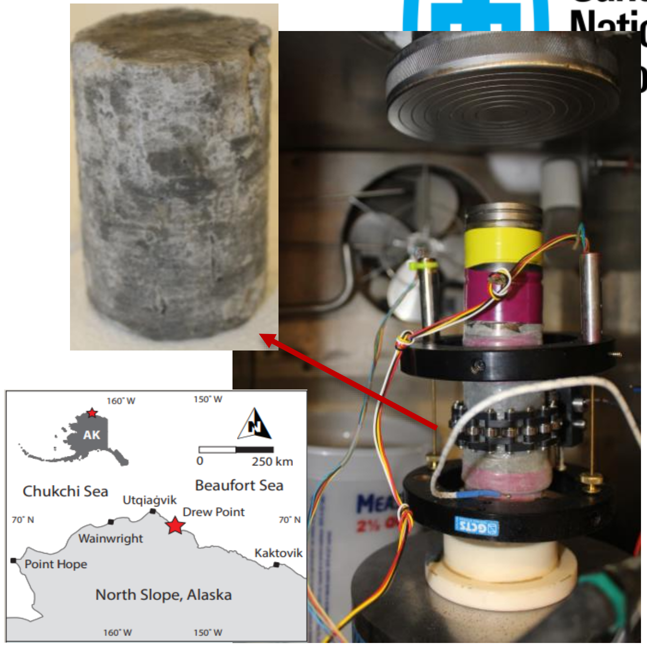


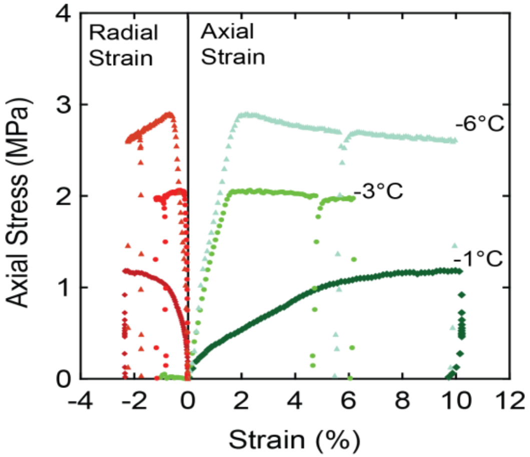
Parameters from wave model (WW3+SWAN+Delft3D):

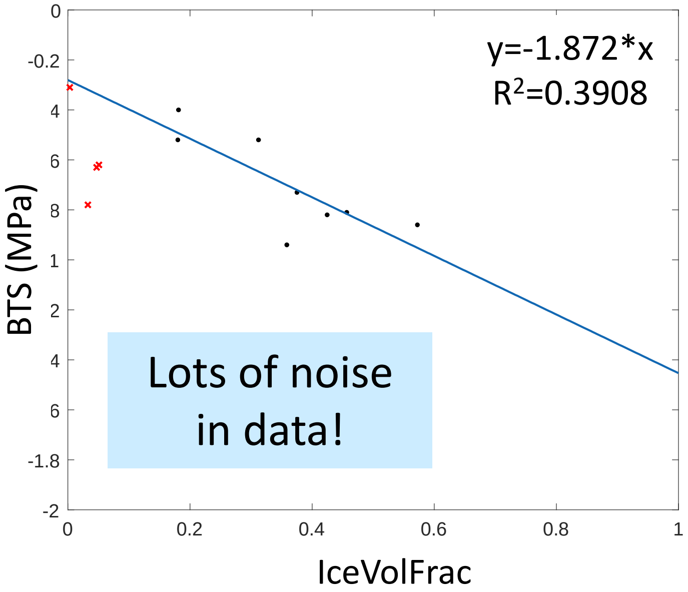
- Ocean temperature, salinity and sea-level w/ time (for thermal and wave pressure mechanical BCs)

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%







[1] Unconfined compressive test. [2] Brazilian tensile tests. [3] Direct tensile tests.

Mechanics-only simulation*

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ORIGINAL RESEARCH
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Geometric and Material Variability Influences Stress States Relevant to Coastal Permafrost Bluff Failure

Matthew A. Thomas[1*†], *Alejandro Mota*[2], *Benjamin M. Jones*[3], *R. Charles Choens*[2], *Jennifer M. Frederick*[2] and *Diana L. Bull*[2]

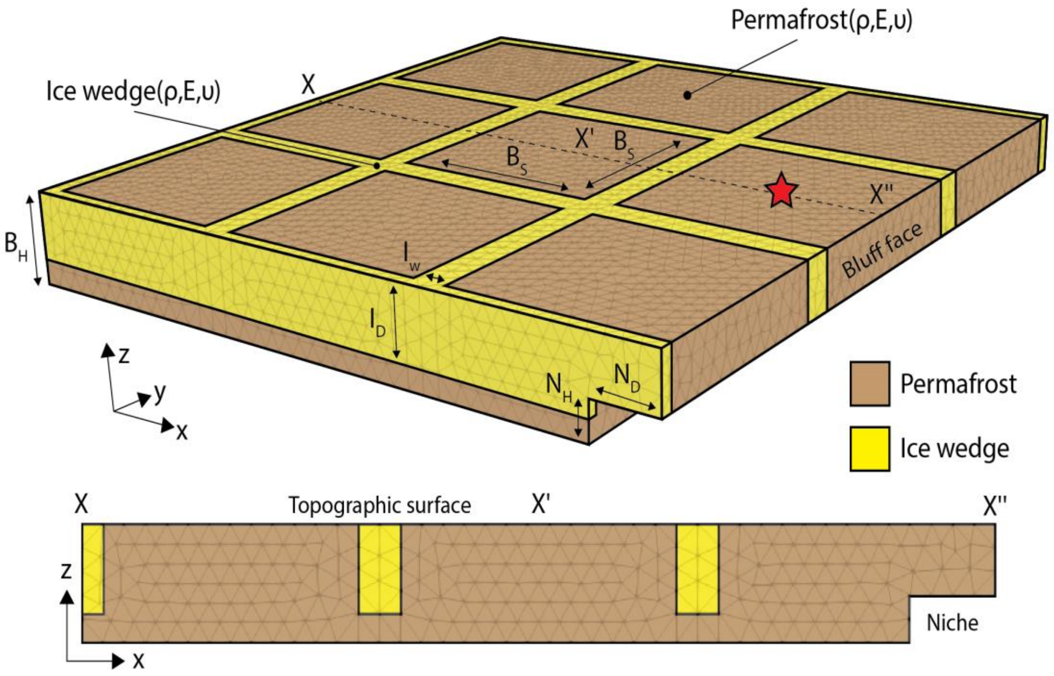
[1] U.S. Geological Survey, Geologic Hazards Science Center, Golden, CO, United States, [2] Sandia National Laboratories, Albuquerque, NM, United States, [3] Institute of Northern Engineering, College of Engineering and Mines, University of Alaska Fairbanks, Fairbanks, AK, United States

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

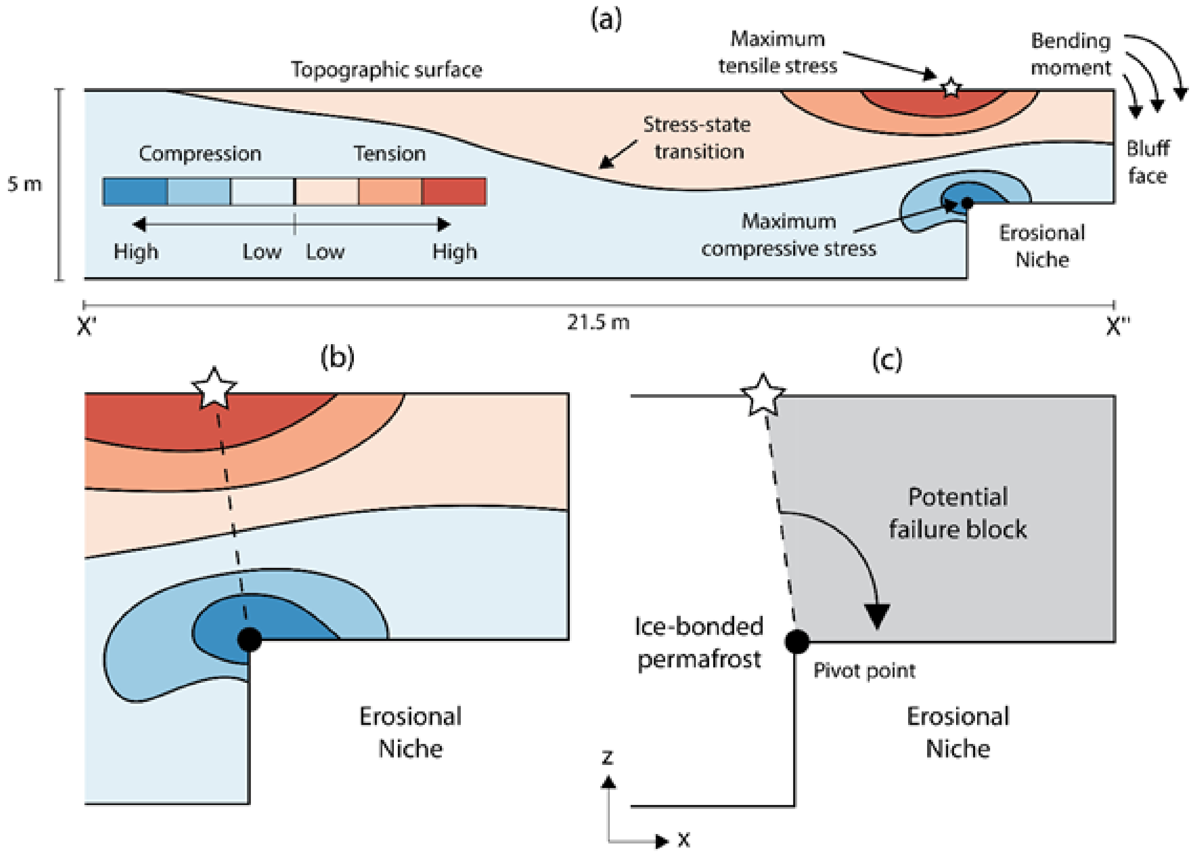
From **2020 article** published in special issue of *Frontiers in Earth Science*.

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

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.

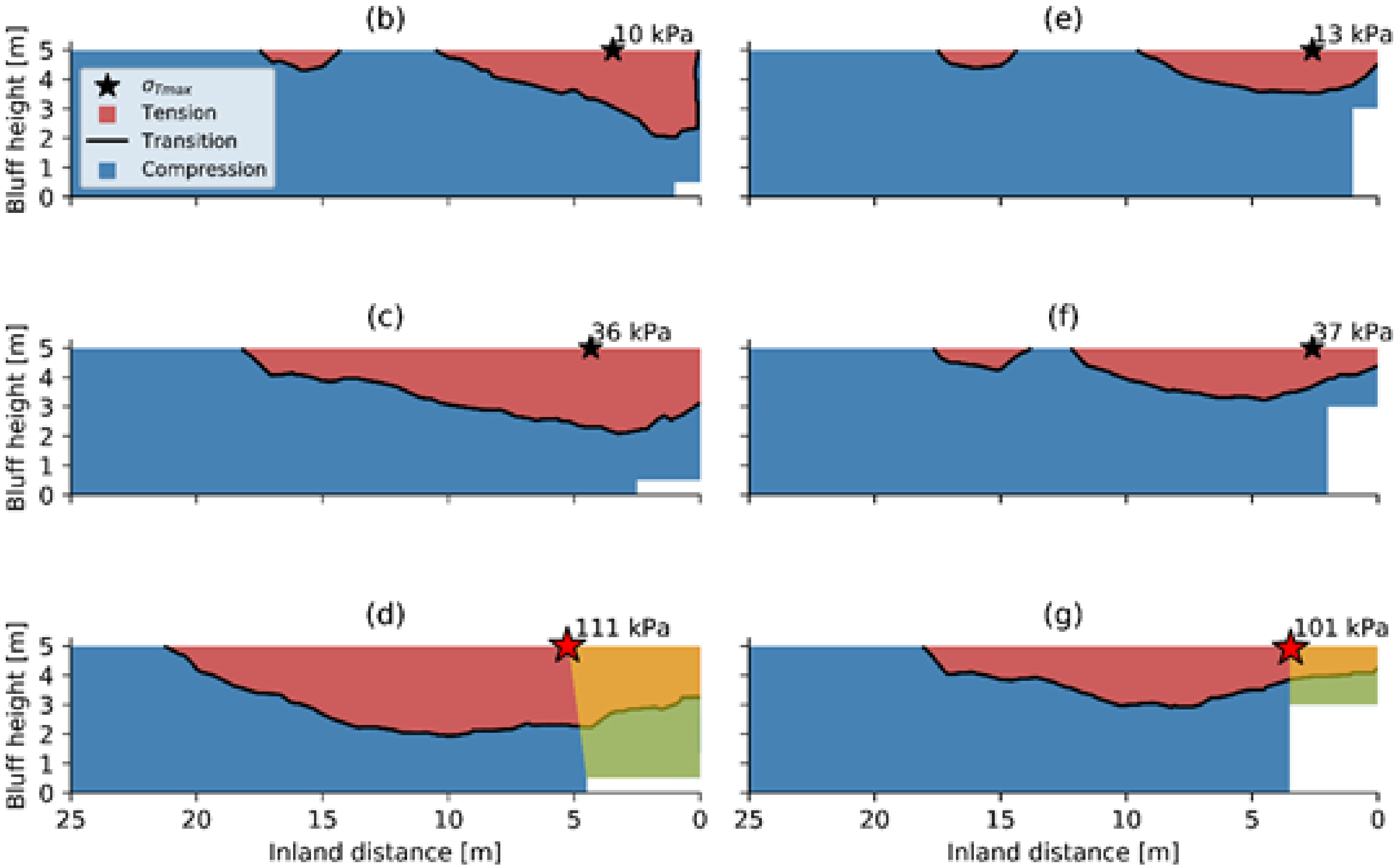


- Simulations facilitated examination of **stress patterns** within bluff and identification of **location** and **magnitude** of **max tensile stress** ($\sigma_{T_{\max}}$)

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

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 strength from lab measurements: 100 kPa
- Orange/green shading highlights potential failure areas.

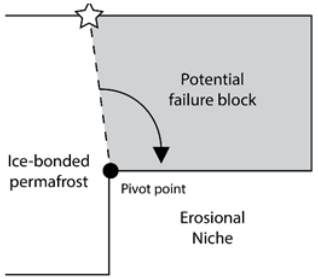
* M. Thomas *et al.* *Frontiers in Earth Science* 8, April 2020.

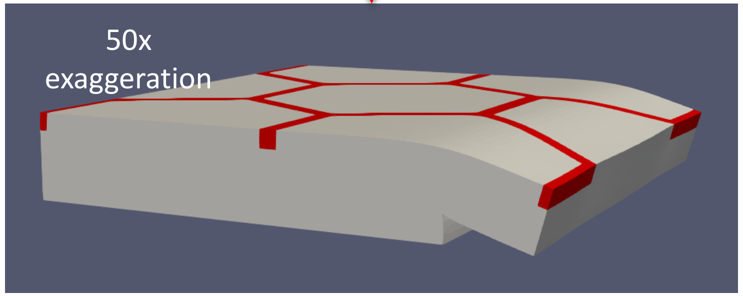
Mechanics-only simulation*: main takeaways

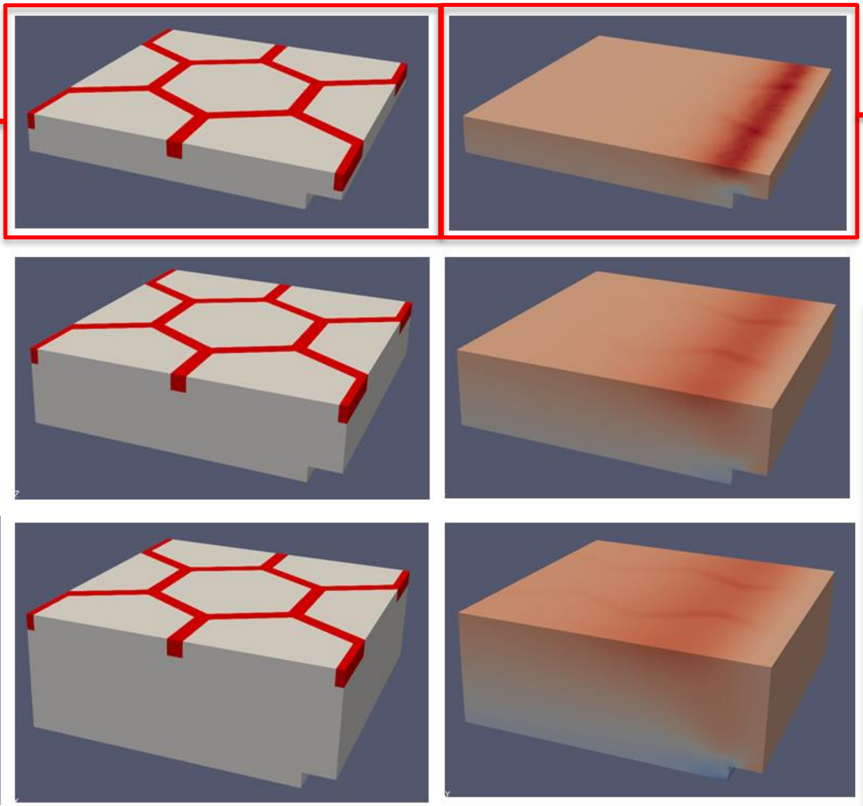
Taller and **narrower** erosional **niches** promote smaller failure masses compared to those with shorter and deeper niches

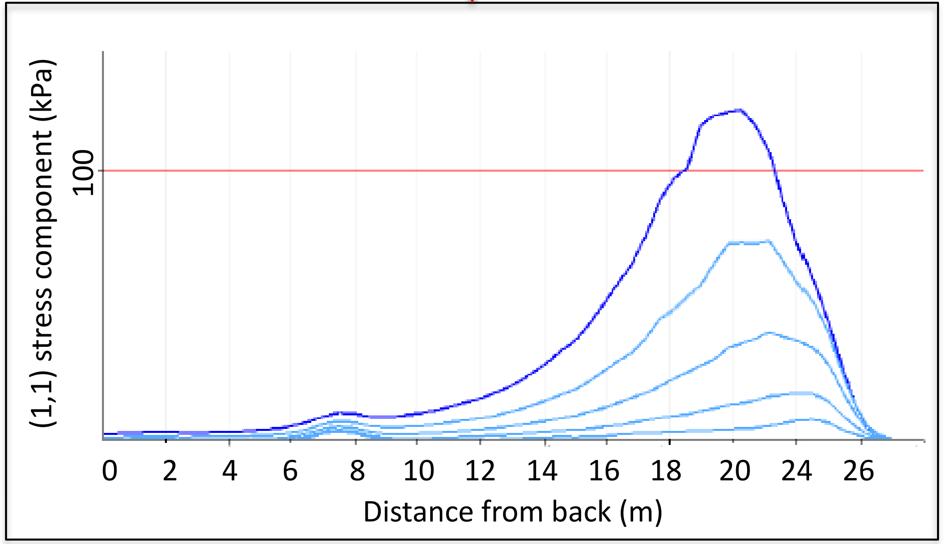
As niche advances into the block, the overhanging section in the block acts as ***cantilever***.

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



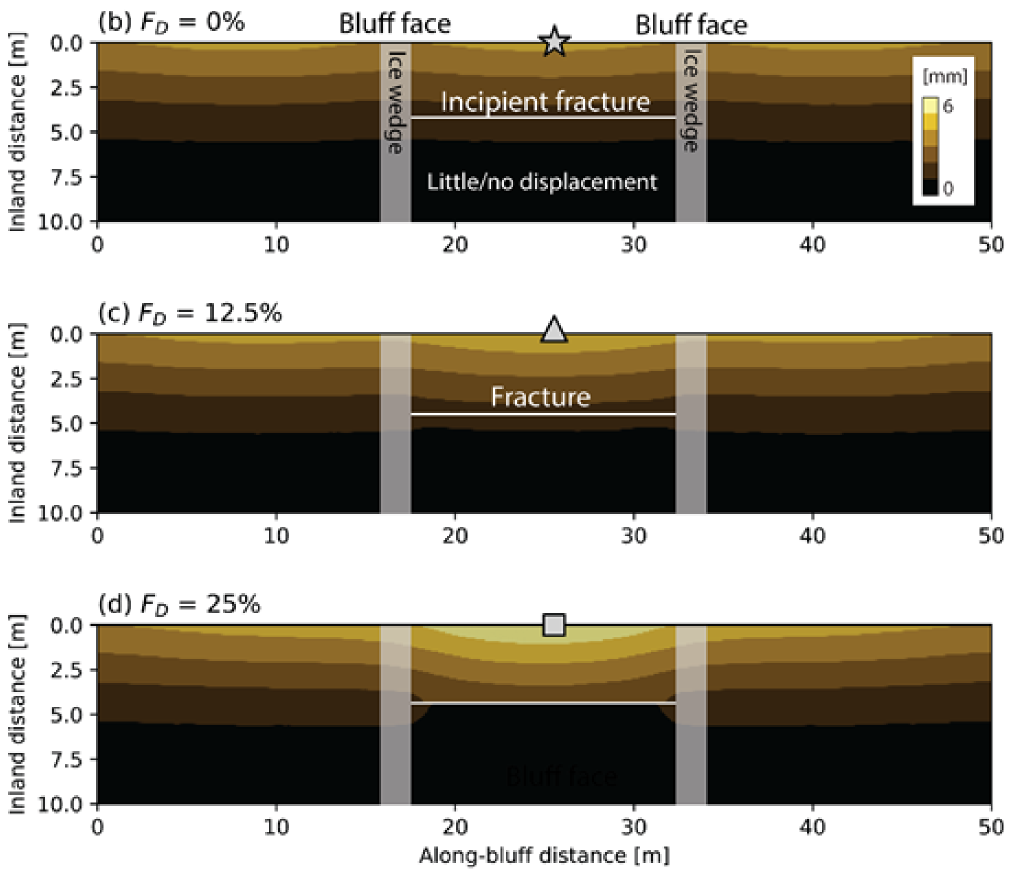






Mechanics-only simulation*: main takeaways

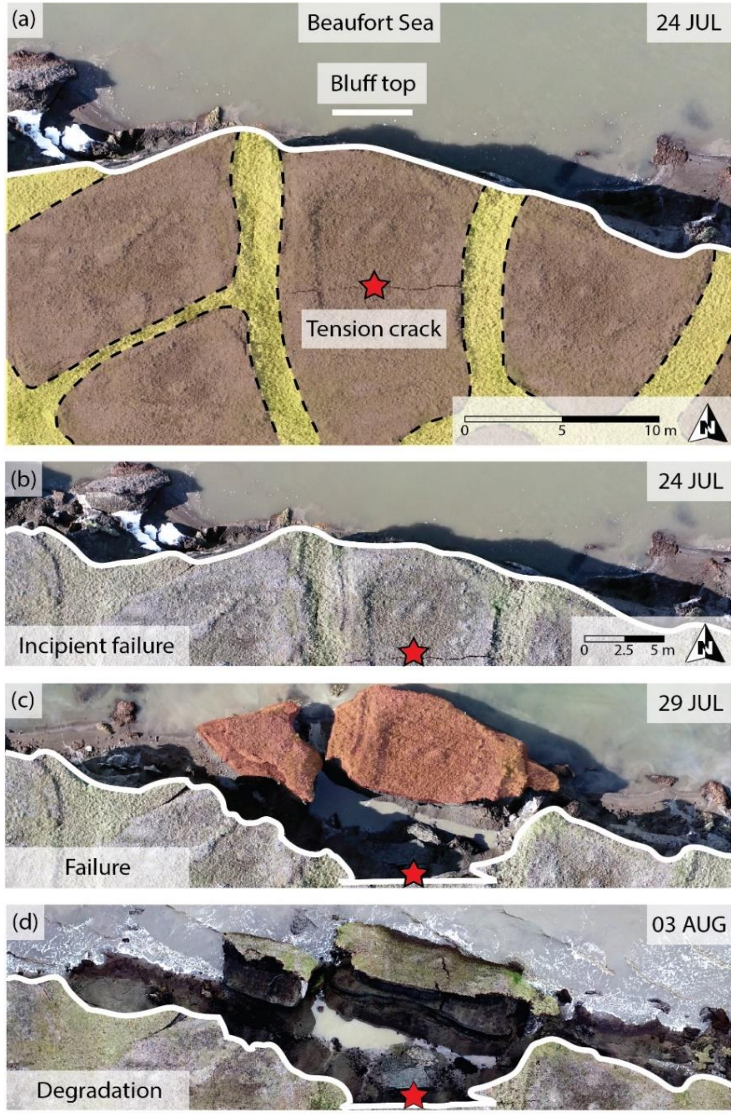
- It has been observed that **failure** can occur along **tension cracks** in ice wedge polygon centers.



- 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



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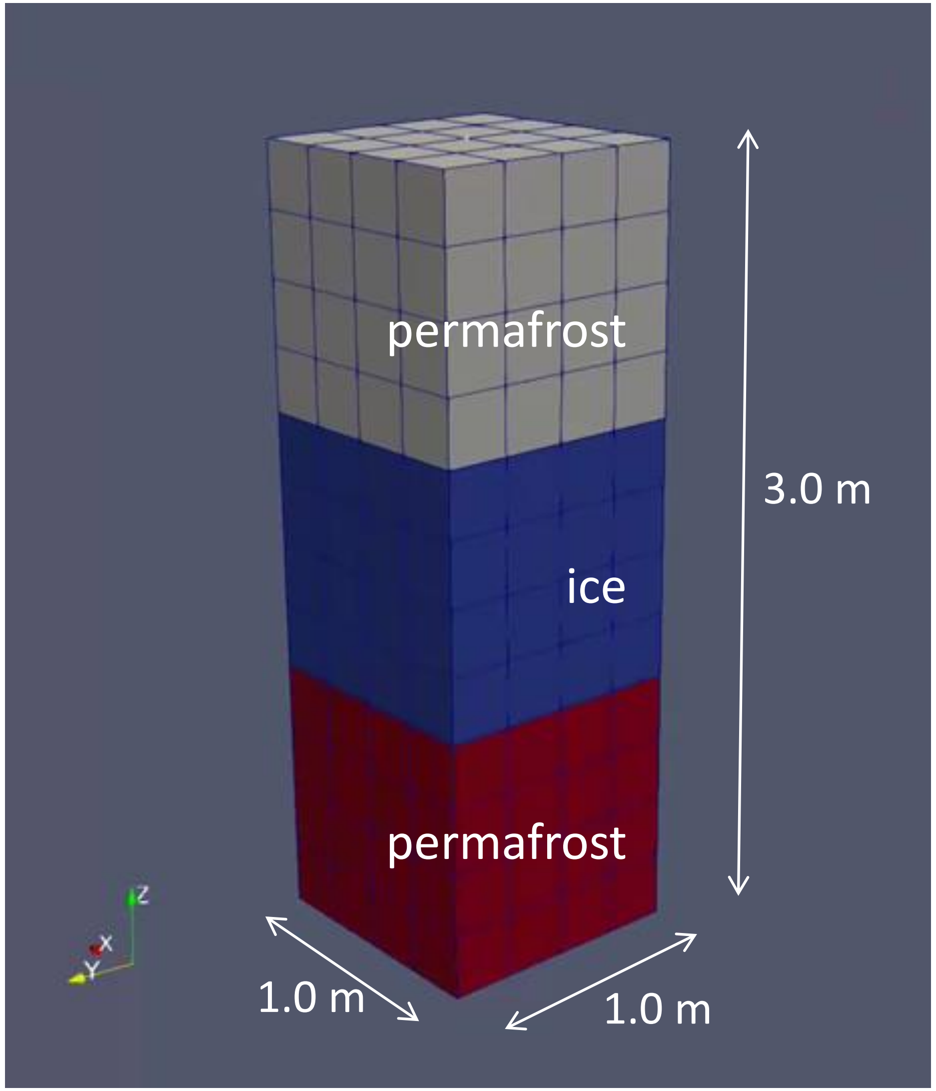
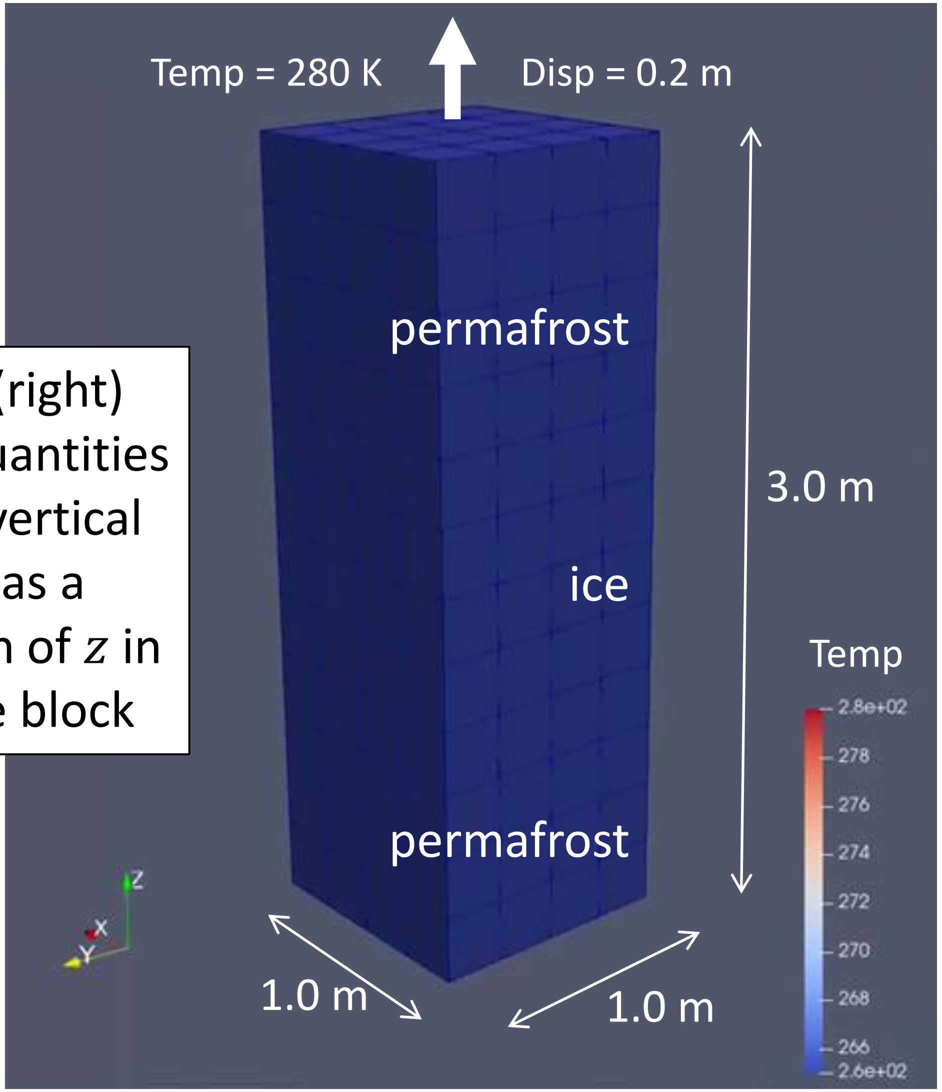
Thermo-mechanical coupling: cuboid problem

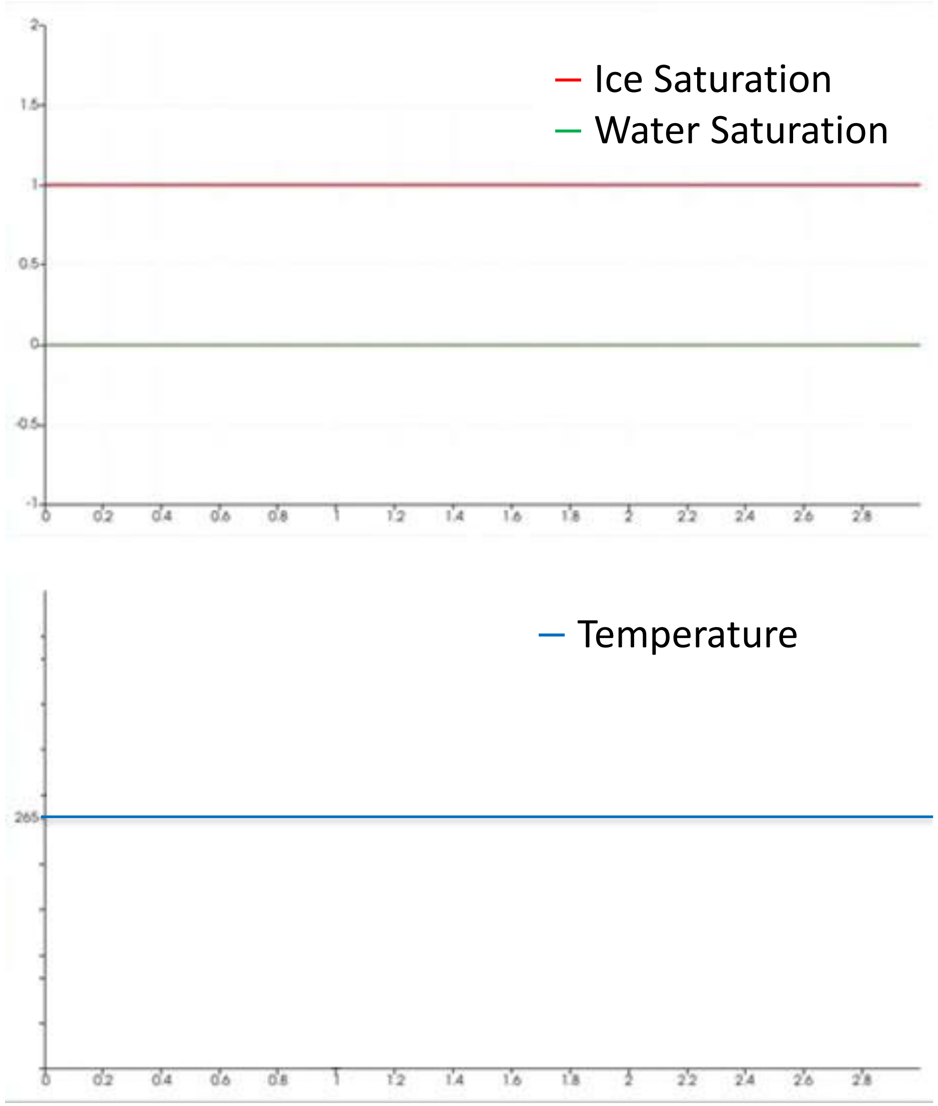


- Cuboid is comprised of block of **ice** material, **wedged** between two blocks of **permafrost** material.
- Cuboid subjected to **simultaneous heating** and **stretching** from the **top**
- Cuboid is **affixed** to the **bottom** and with **symmetry boundary conditions** on the **sides**.
- **Temperature**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

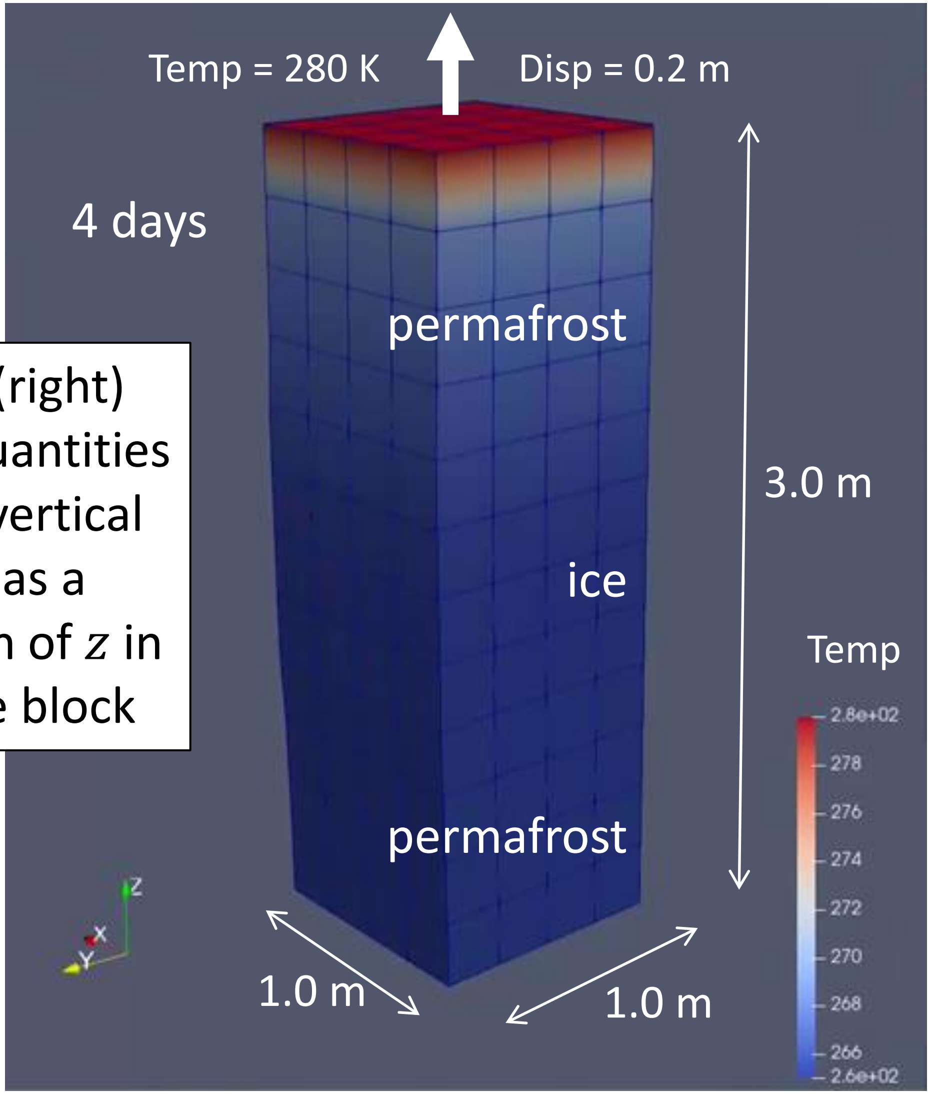
Thermo-mechanical coupling: cuboid problem

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

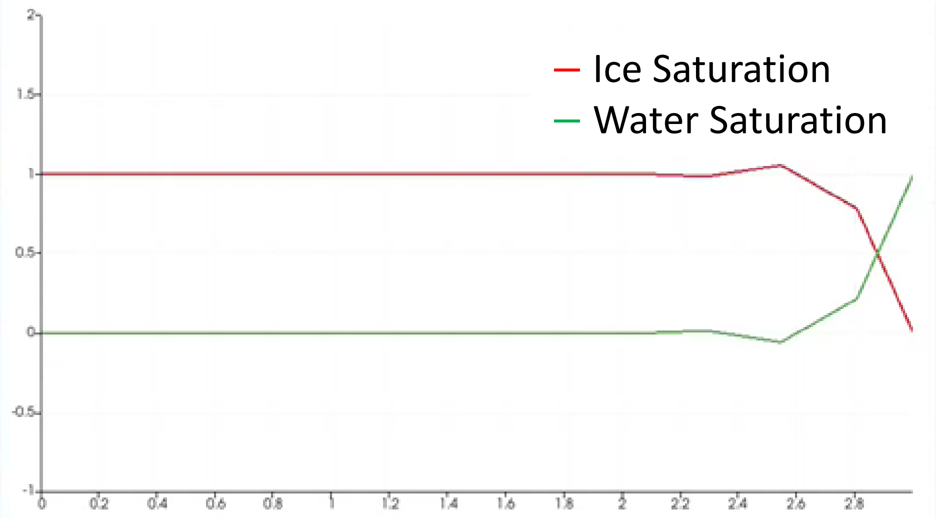


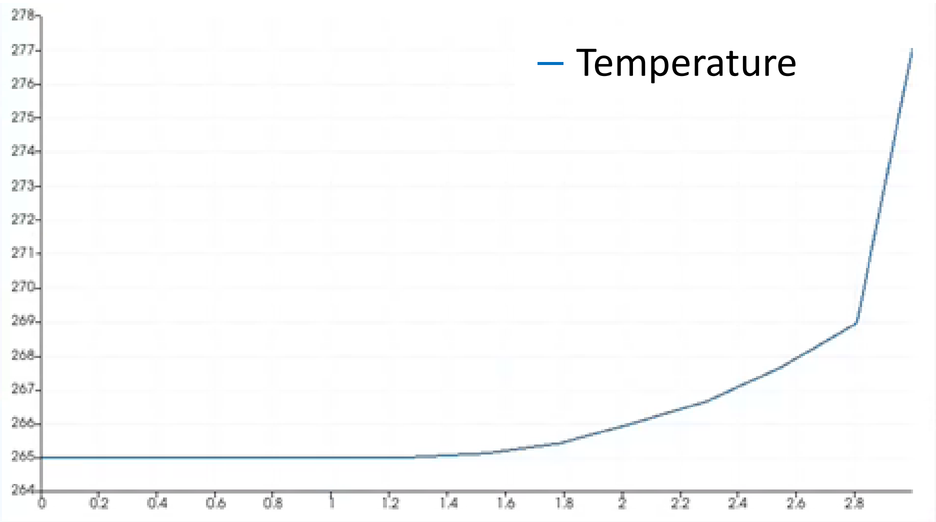


Thermo-mechanical coupling: cuboid problem

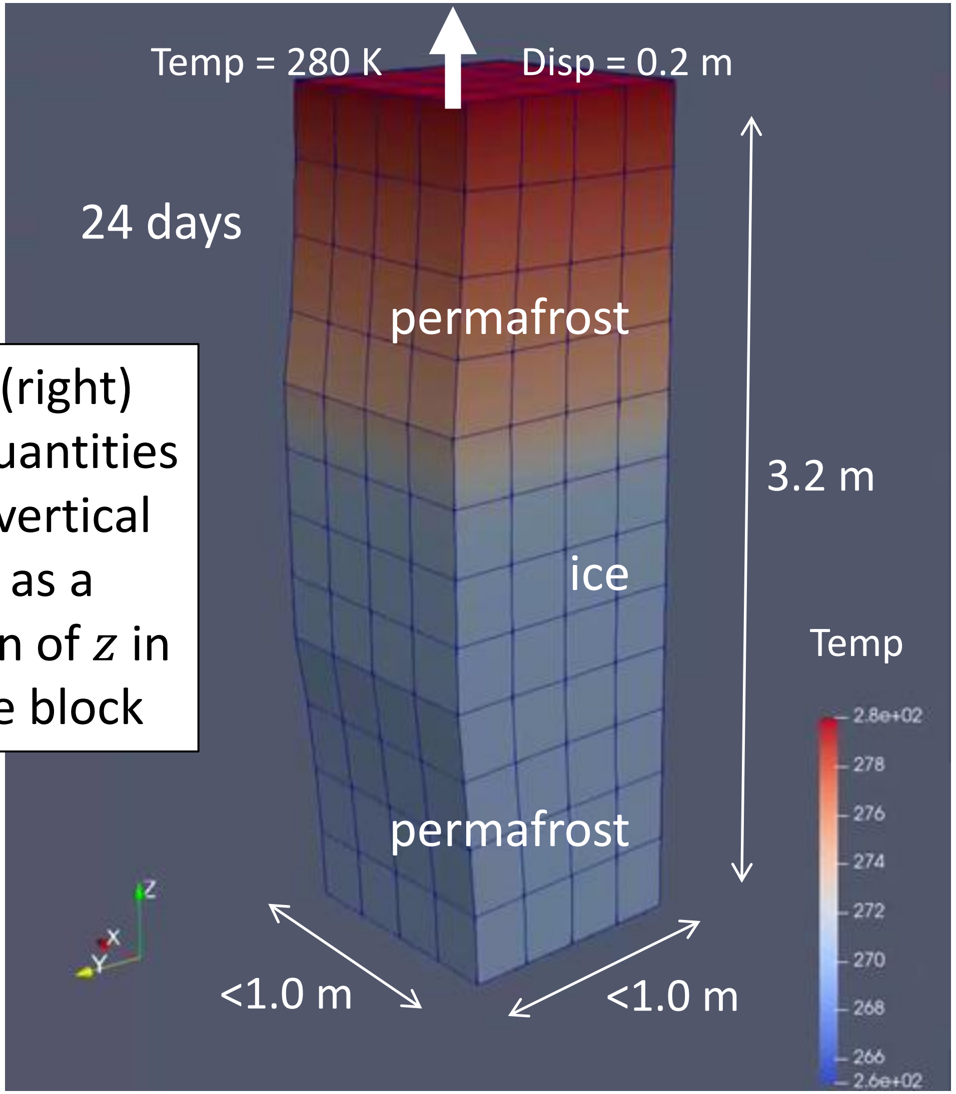


Plots (right) show quantities along vertical line as a function of z in the ice block

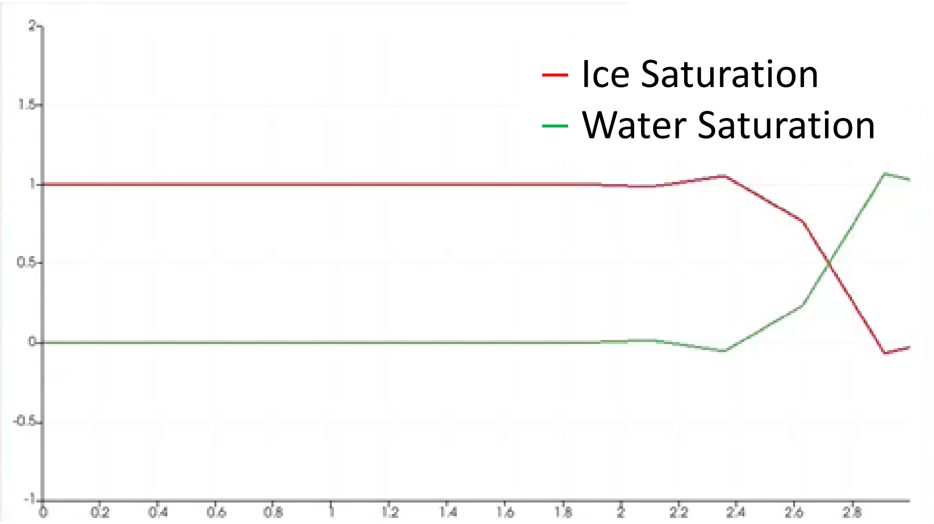


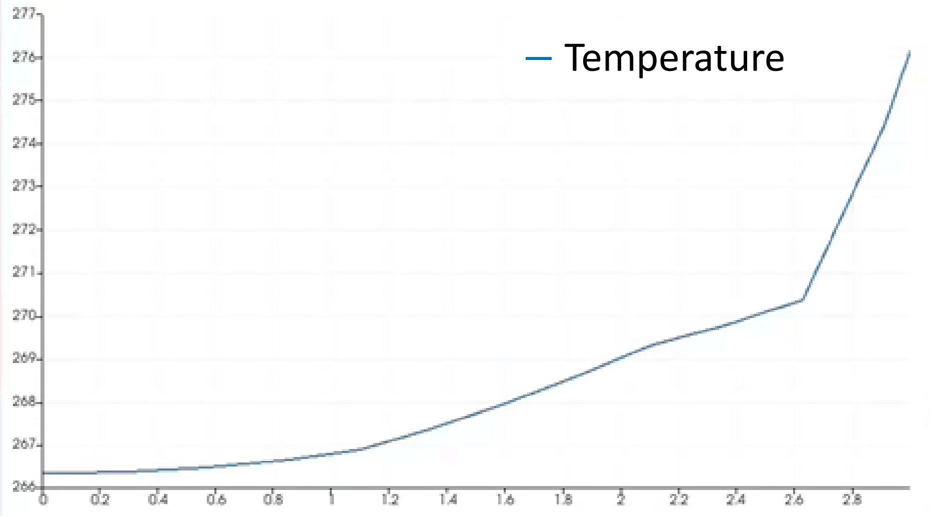


Thermo-mechanical coupling: cuboid problem



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





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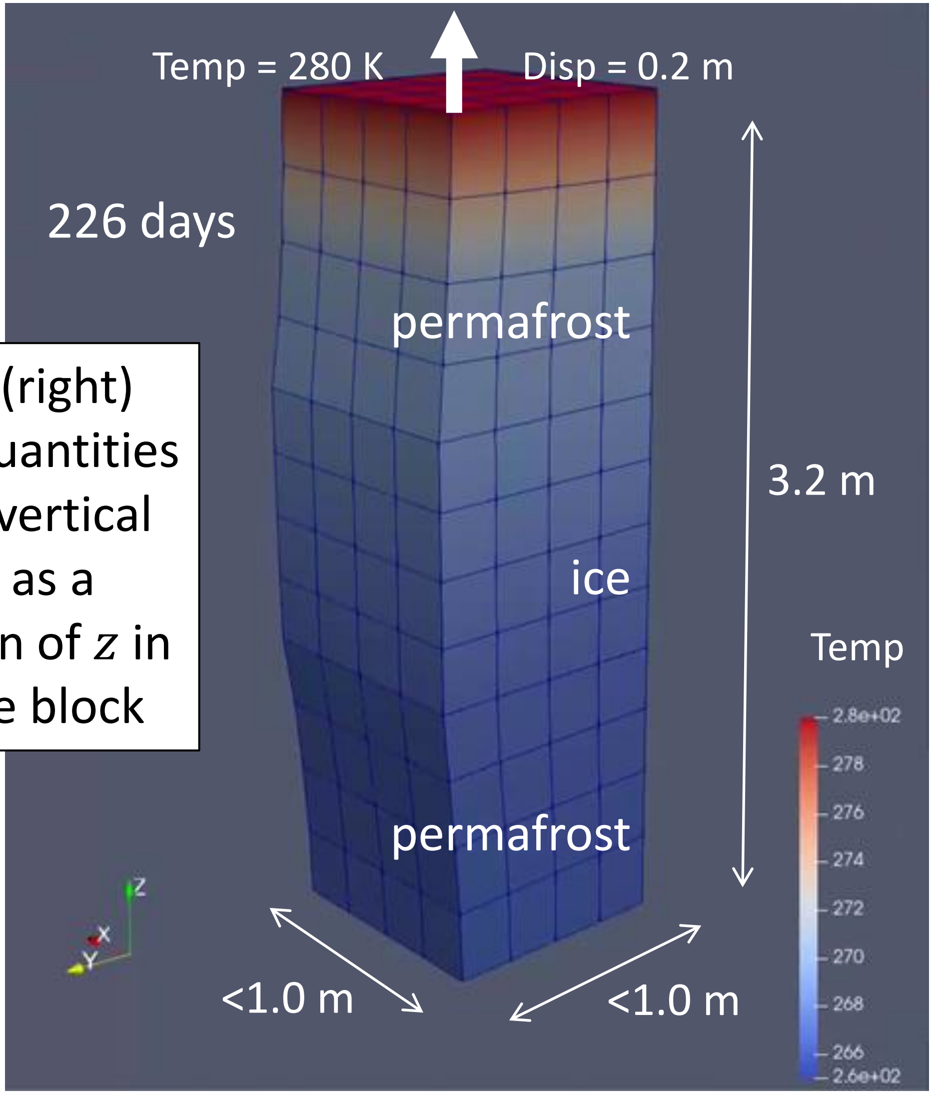
Thermo-mechanical coupling: cuboid problem



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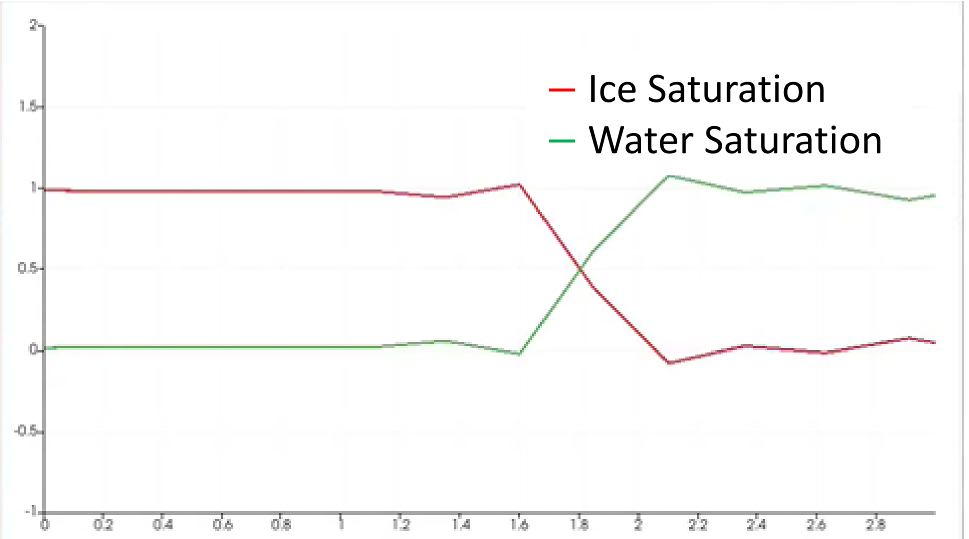
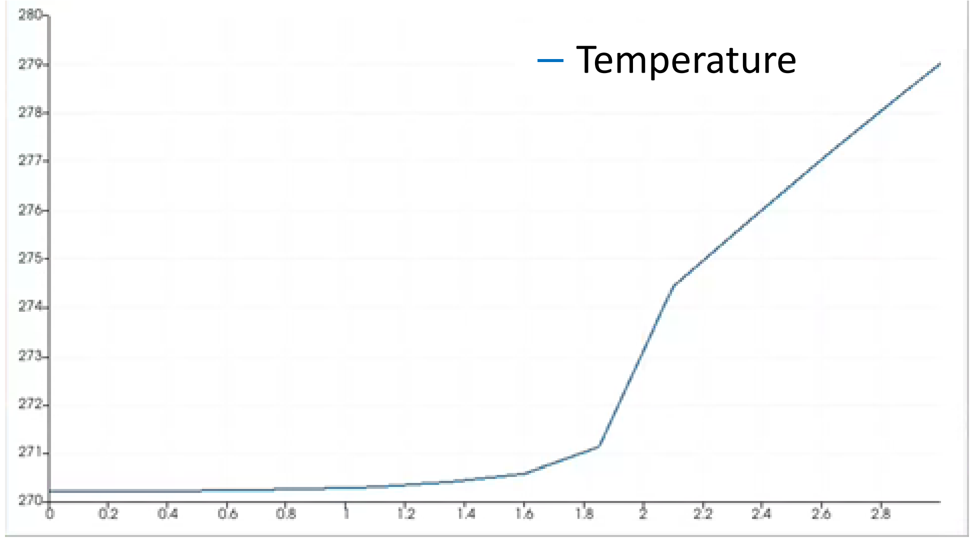
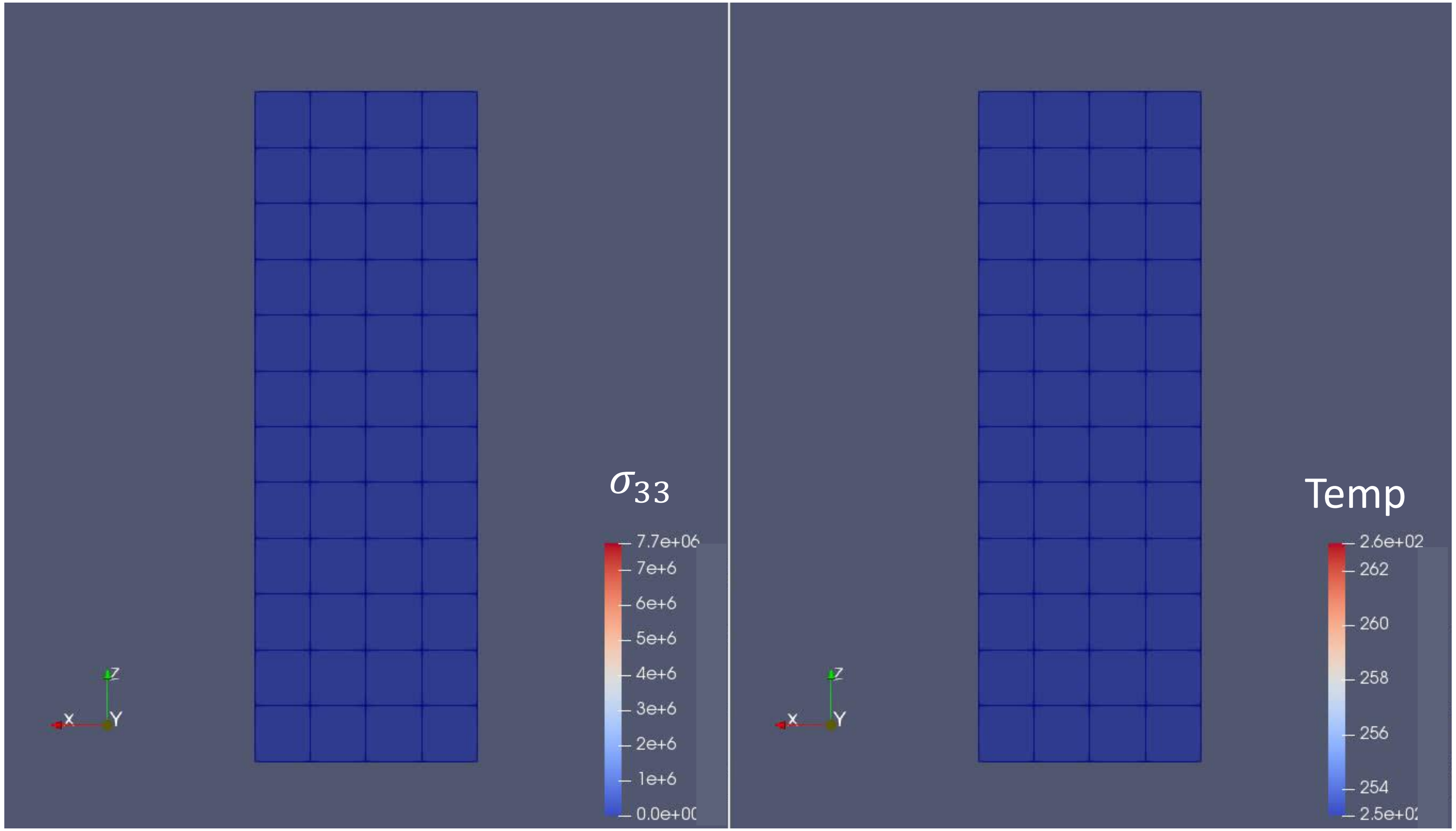
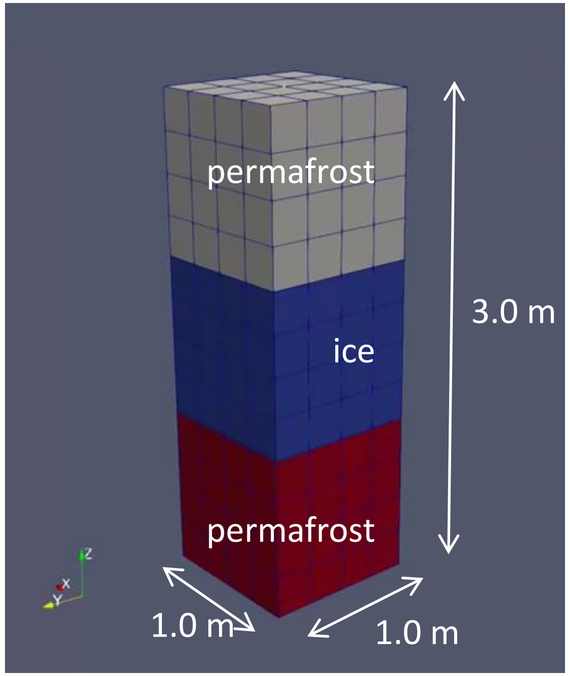




Thermo-mechanical coupling: cuboid problem





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