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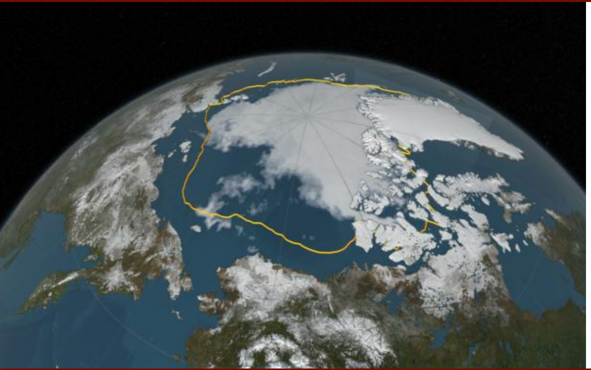
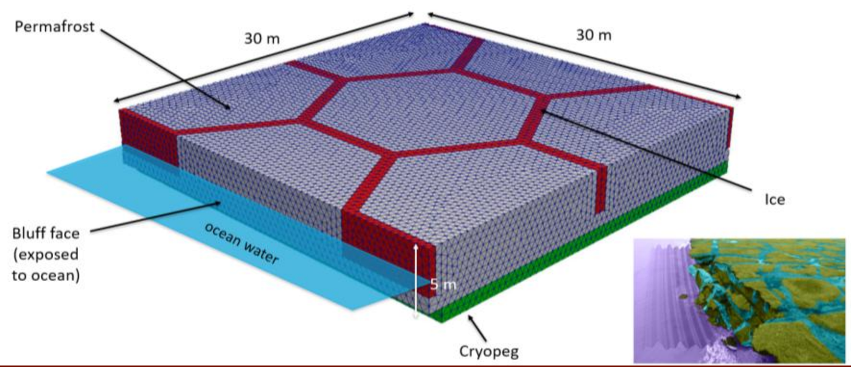


Assessing and anticipating Arctic risks: advanced modeling of permafrost erosion and infrastructure stability

Irina Tezaur

Sandia National Laboratories, USA

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InteRFACE

LDRD Laboratory Directed Research & Development

Nimbus Horizon

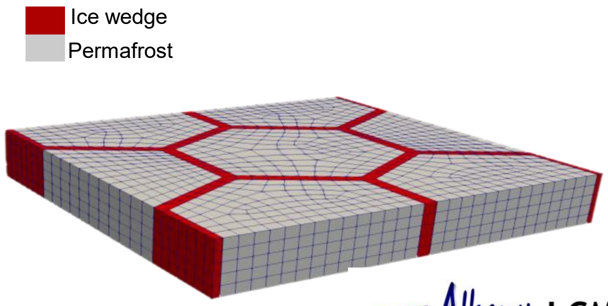
Outline

- Motivation & background
- The Arctic Coastal Erosion (ACE) model

  → *A new mechanistic model for studying Arctic coastal erosion*

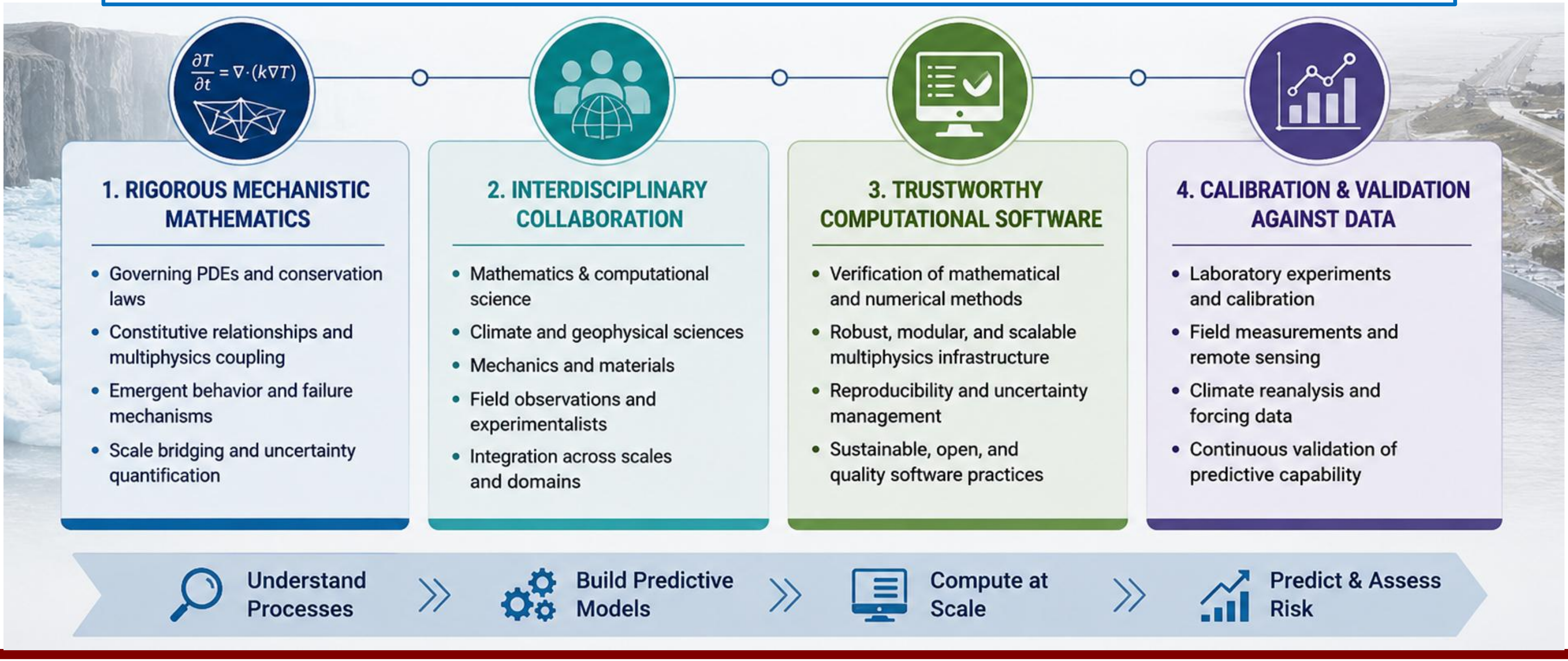
  → ***A case study of the ingredients required to build a credible, predictive mathematical model in Earth science (and beyond)***

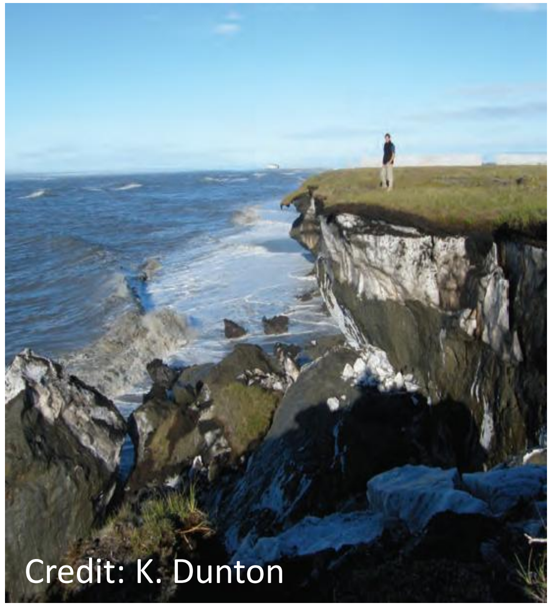
- Conclusions and take-aways



Overarching message

Predictive modeling requires the integration of **mathematics**, **computation**, **domain knowledge**, **experimentation** and **observations**.





Motivation & background: what is permafrost and why do we care?

Motivation

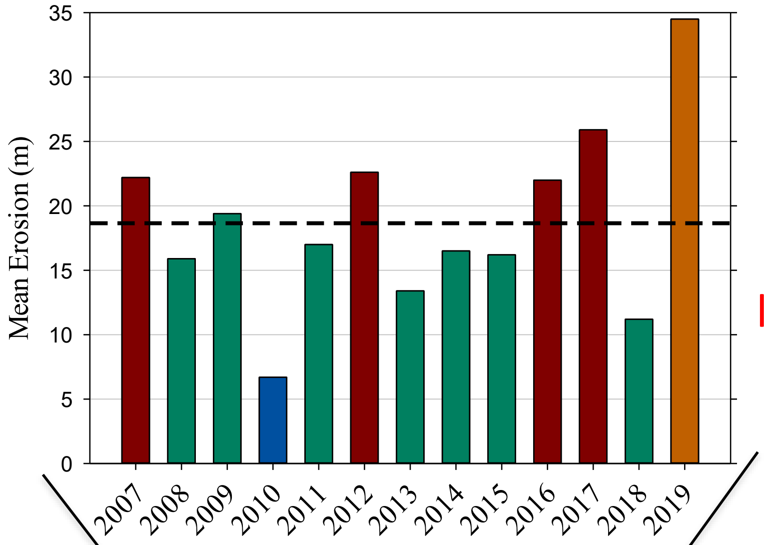
The Arctic is warming at **4×** the rate of the rest of the globe, yielding **accelerated rates of coastal erosion**!

Primary culprit: loss of Arctic sea ice – since 1979 sea ice has lost 51% in area and 75% in volume

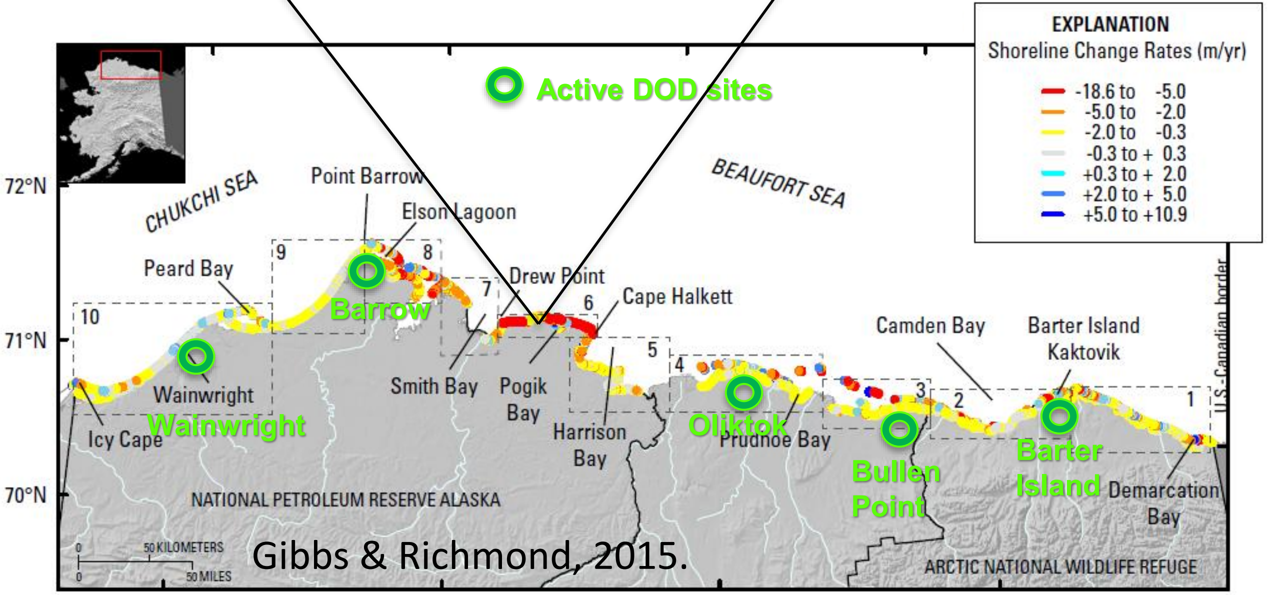
- Increasing **ice-free season**
- Increasing **wave energy** and **storm surge**
- Increasing **sea water** temperatures

Erosion is threatening:

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



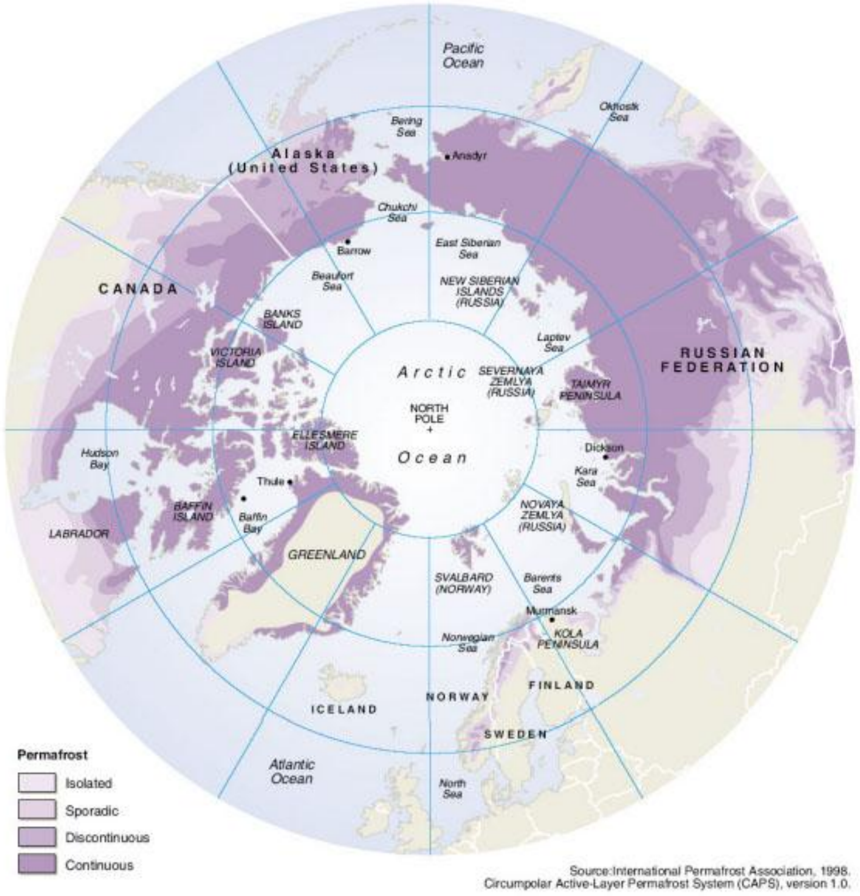
Certain locations lost >250 m (~2 football fields in length) b/w 2007-2019!



Gibbs & Richmond, 2015.

What is permafrost?

- **Permafrost** = ground (soil, rock, silt, clay, sand) held together by ice that remains frozen for 2+ consecutive years.



Map of permafrost distribution in the Arctic (Brown *et al.* 1998)

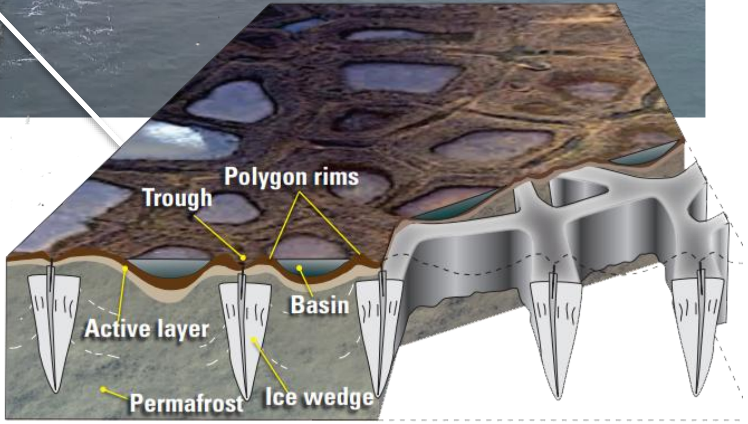
- **24%** of **ice-free land area** in Northern Hemisphere and **85%** of Alaska, Greenland, Canada and Siberia contains **permafrost**.
- 34% of **global coastline** is permafrost.

Arctic coastal permafrost

- Predominant geomorphology: **ice-wedge polygons**
- Ice acts to **bind** unconsolidated soils in permafrost.
- Ice wedges **grow/expand** up to 10s meters wide and deep.
- **Peat/active layer** = organic layer that grows on top of permafrost
- Permafrost thaw can cause **subsidence**, **slumping**, **weakening**.


Credit: B. Jones

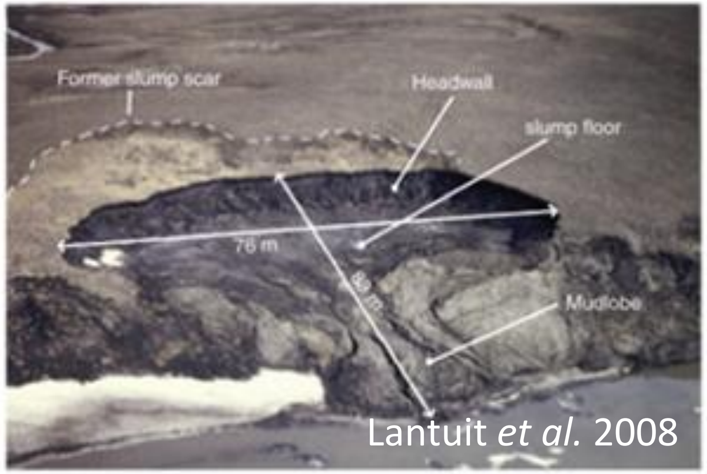
Credit: D. Bull



Polar Media Archive

Coastal 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-denudation**[1].
- **Active layer detachment**: failures are **translational landslides** that occur in summer in thawing soil overlying permafrost, typically caused by **thermo-denudation**[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].
  - **Dominant failure mechanism** in northern Alaska
  - Fallen blocks can disintegrate in the near-shore environment **within 1-2 weeks**!



Retrogressive thaw slumping

Active layer detachment

Thermo-abrasion

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

Coastal permafrost failure mechanisms

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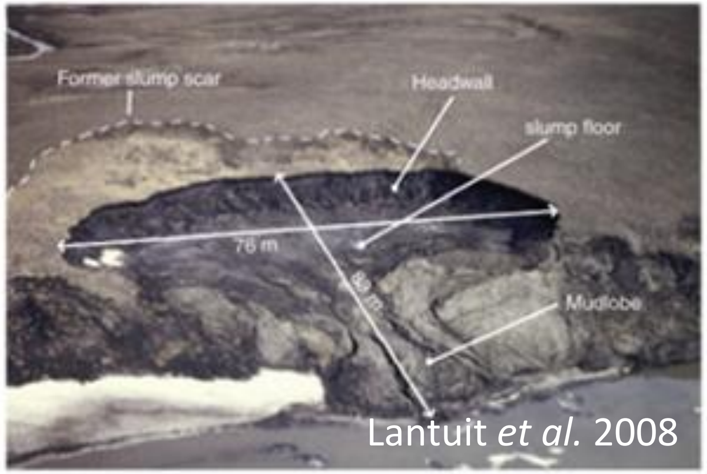


Retrogressive thaw slumping

Active layer detachment

Block failure

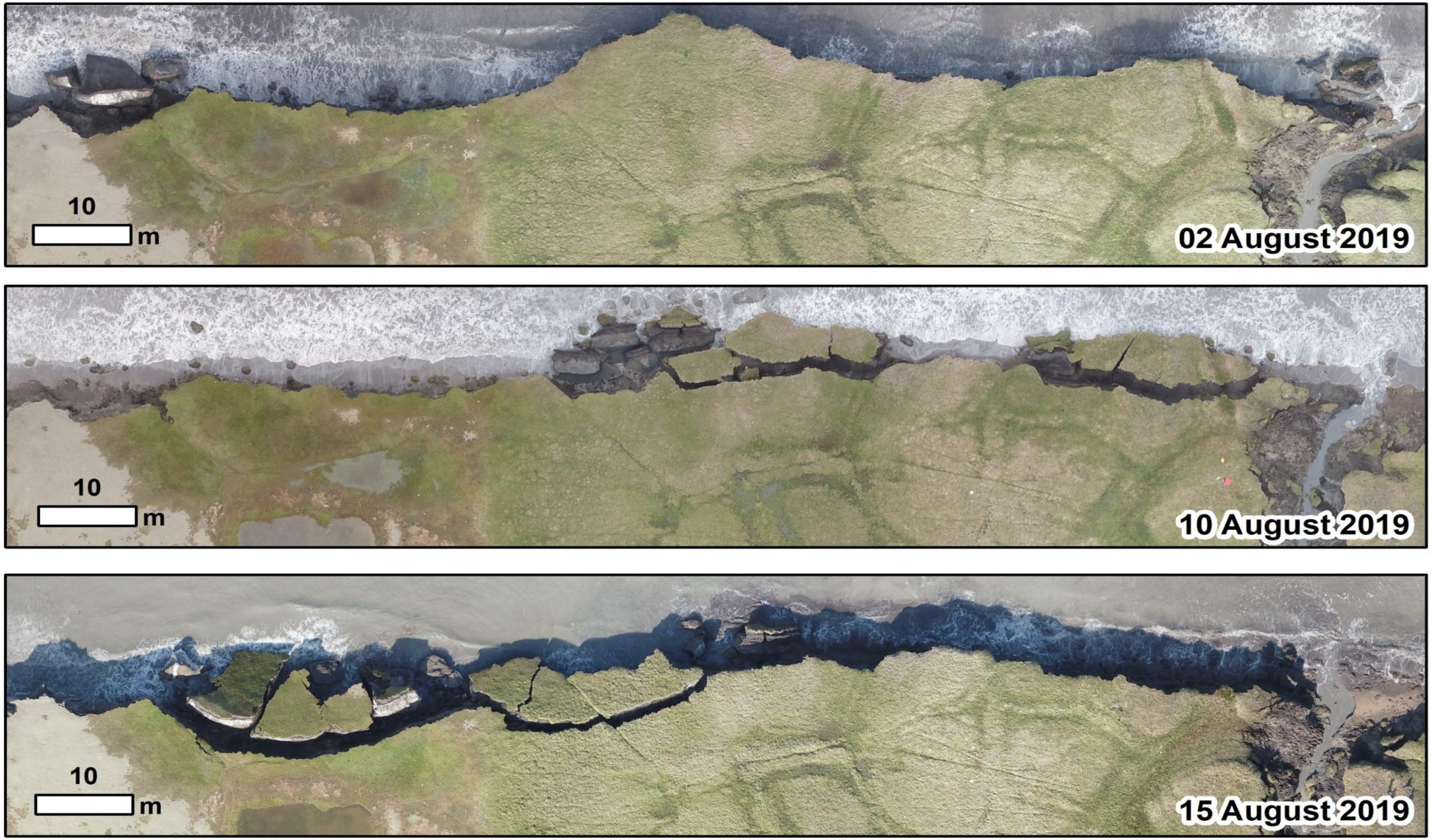
[1]Thawing of permafrost bluffs that proceeds under the influence of gravity. [2]Undercutting of permafrost bluff by warming ocean.

Block failure & block disintegration in action

Drew Point offshore camera showing block failure/disintegration

Fallen block disintegration at Drew Point, Alaska April 13-22, 2010

Bluff erosion in action (from 2019 UAV surveys)



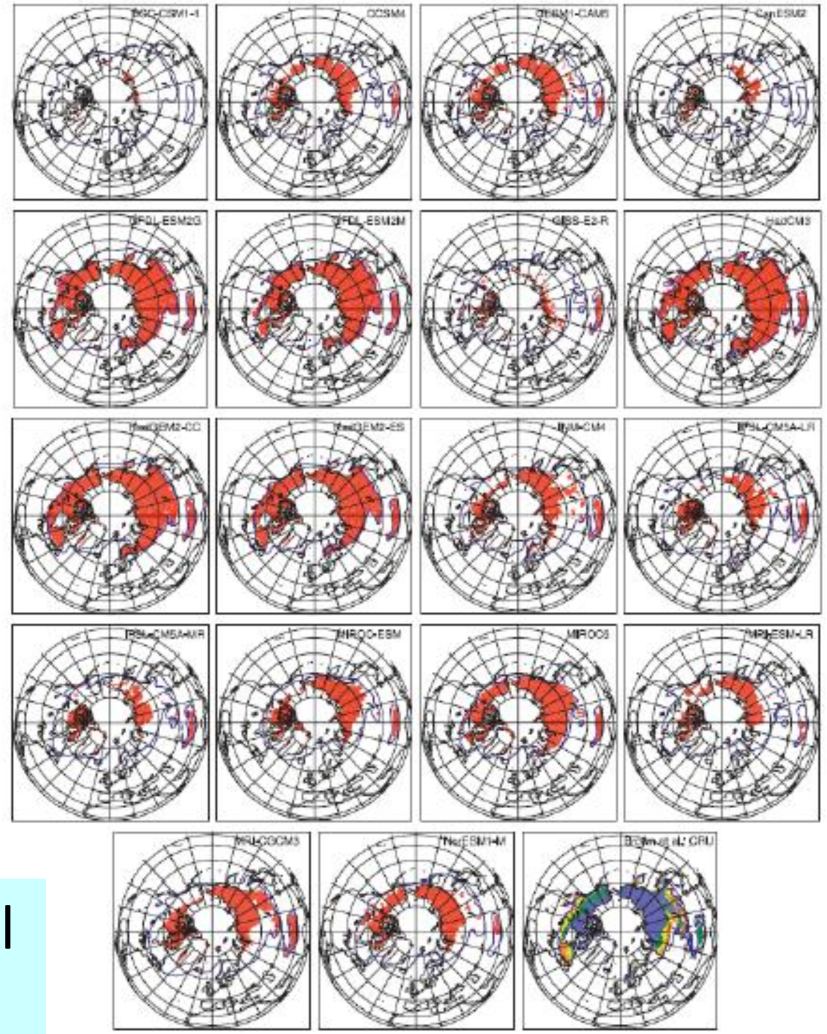
Fallen blocks can disintegrate in near-shore environment **within 1-2 weeks**!

Images courtesy of Ben Jones, UAF

State-of-the-art in permafrost modeling

Most **existing permafrost models*** (including Earth System Model-, or ESM-, coupled models) are fairly **primitive**!

- Most models are 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 assume a **particular type** of **erosion** (e.g., block failure)
- Models **do not** include **realistic boundary conditions** and **do not** account for permafrost **geomorphologies** or **geophysics**.

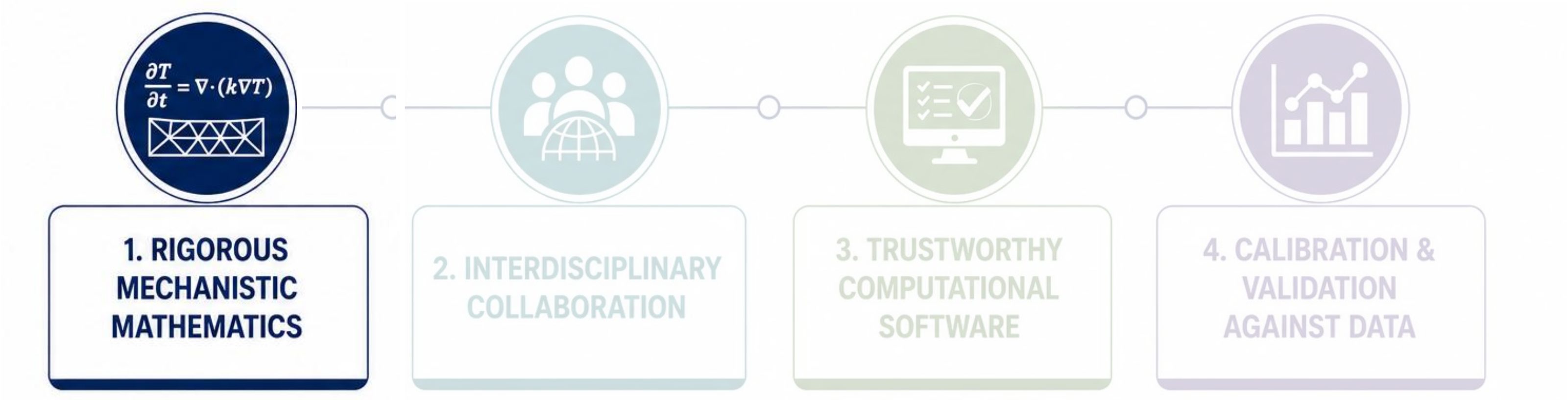


Koven *et al.* 2013

Premise behind ACE: a **predictive** Arctic coastal erosion model must **couple** the influences of evolving **wave dynamics**, **thermodynamics** and **mechanics,** and bring in **real-world data**.

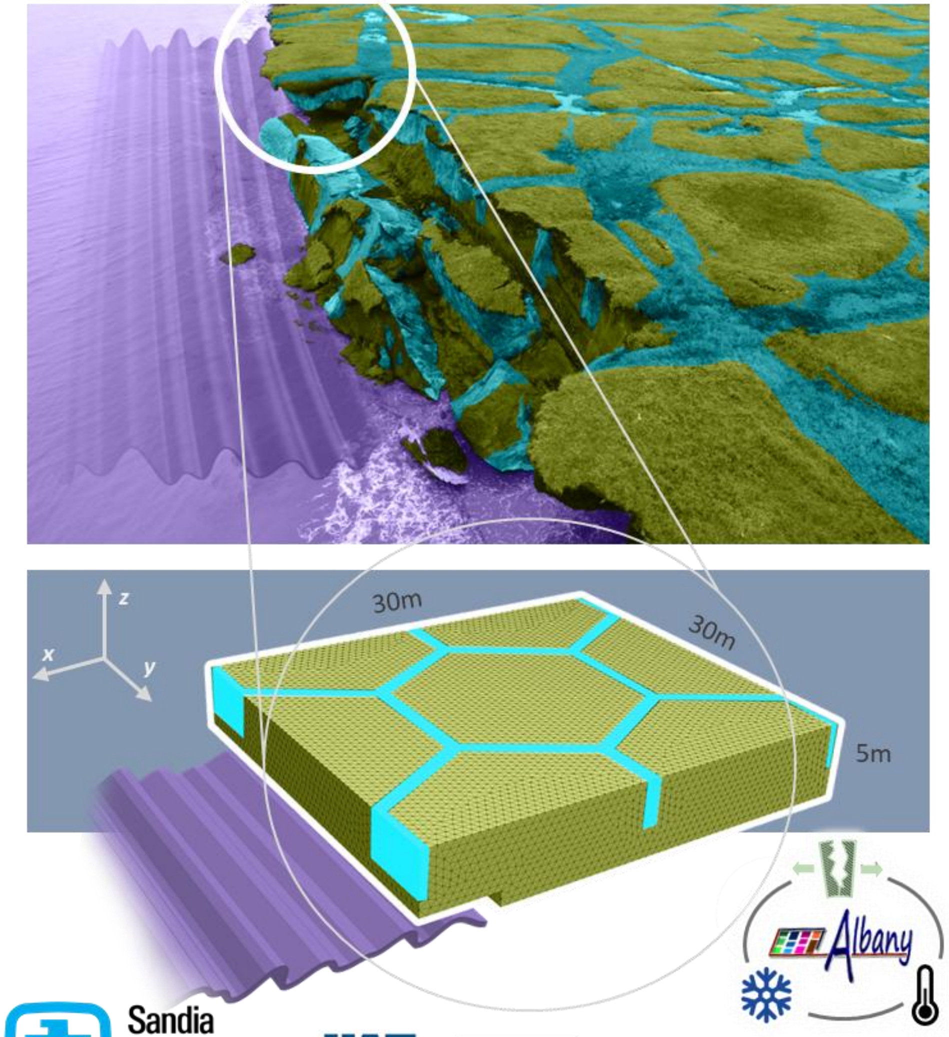
* See [Frederick *et al.* 2016], Chapter 5, for extensive overview.

Rigorous mechanistic mathematical modeling: the Arctic Coastal Erosion (ACE) model



Arctic Coastal Erosion (ACE) model

Ocean | Ice wedge | Permafrost | Boundary Conditions



LOCATION SPECIFIC DATA

BOUNDARY CONDITIONS

Reanalysis (ASR & ERA) *(Historic)*

HYCOM *(Historic)*

SNAP Downscaled RCP 8.5 Earth System Models *(Projections)*

- WIND SPEED / DIRECTION
- ATMOSPHERIC TEMP
- PERMAFROST TEMP
- OCEAN ICE EXTENT
- OCEAN CURRENTS
- OCEAN TEMP

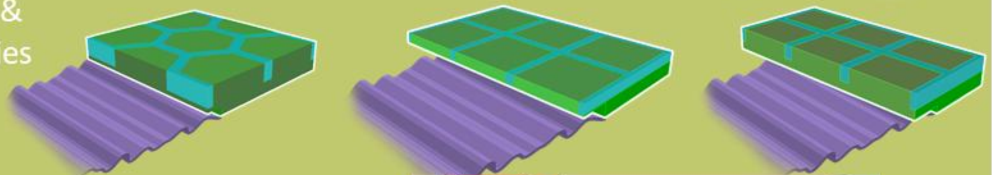
TERRESTRIAL \ TERRESTRIAL

Albany: 3-D multi-physics based finite element model

MECHANICAL: finite deformation plasticity model

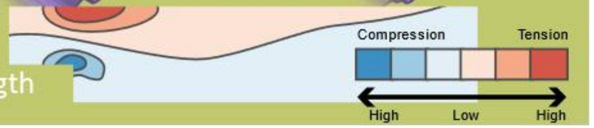
THERMAL: transient temperature and ice saturation evolution

Geomorphology & Material Properties



Strength Properties

MATERIAL: ice content determines strength



OCEAN

Circum-Arctic: wave energy

Nearshore: coupled wave & circulation

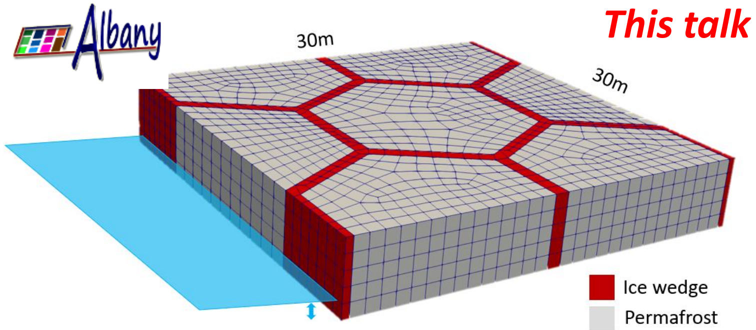
Vision: a multi-scale approach

INTERFACE

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Goal of ACE: 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

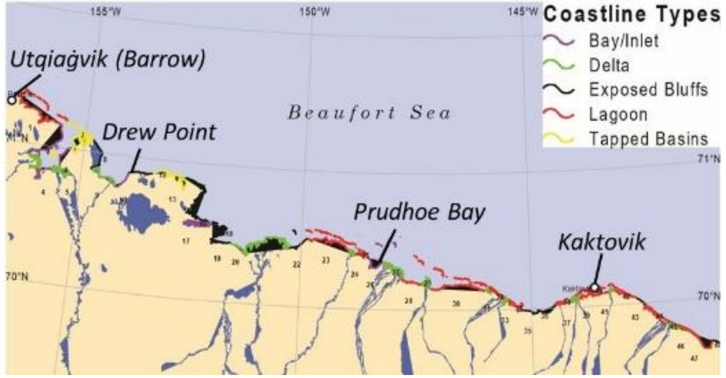
One set of input variables defining the geomorphology and geophysics of the terrestrial model.

- 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

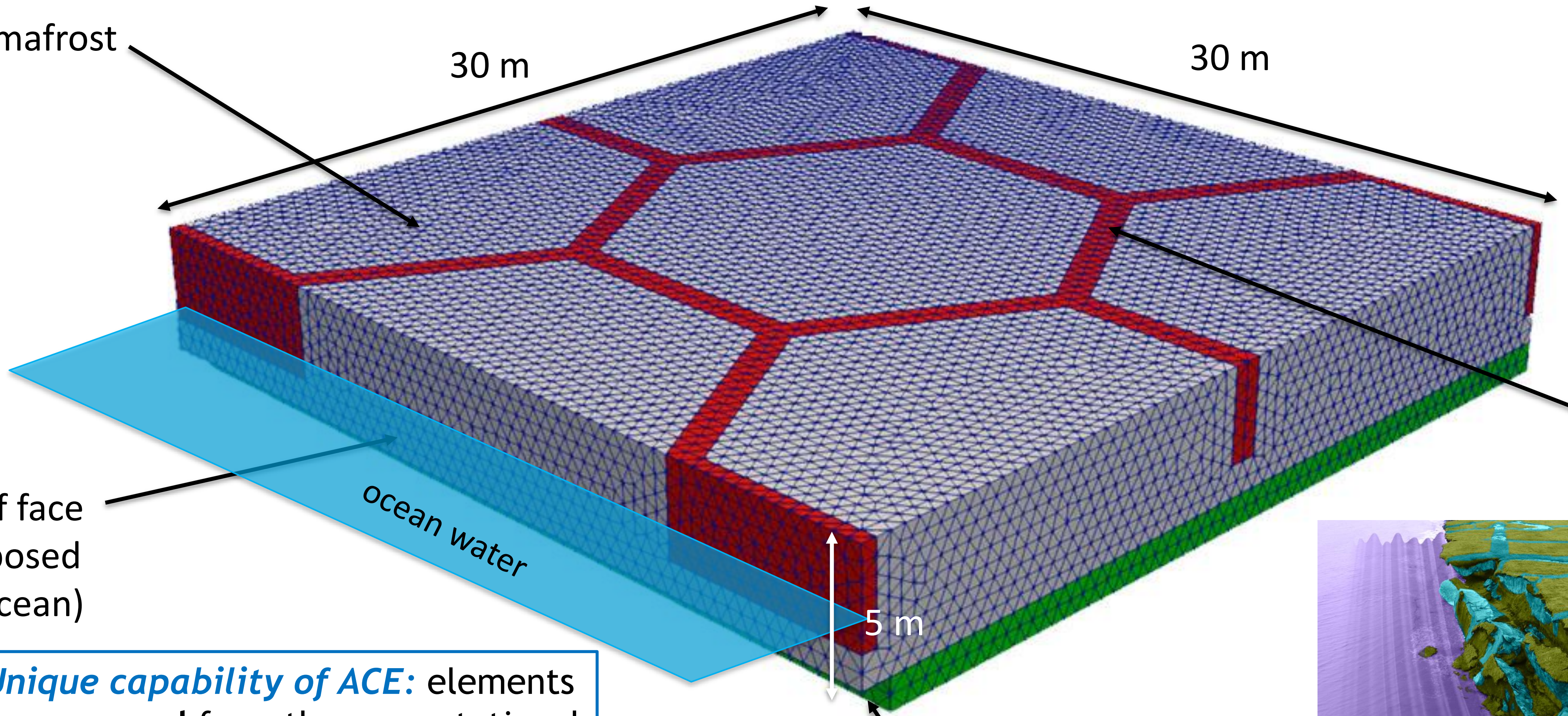
A number of meso-scale models representing different coastline types (delta, exposed bluffs, lagoons, etc.) along the AK coastline.

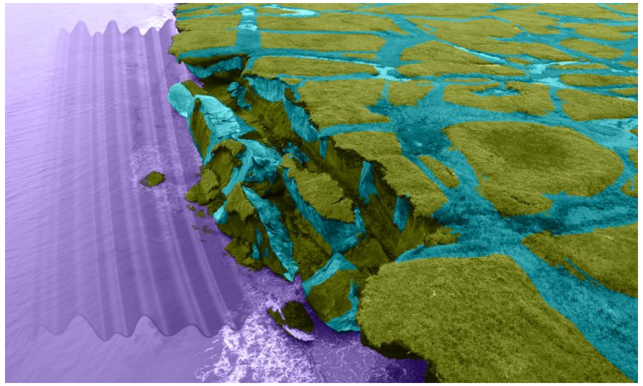
Longer term vision: upscale micro-scale model to meso- and macro-scales

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

There are opportunities for AI/ML here!

Anatomy of a canonical computational domain





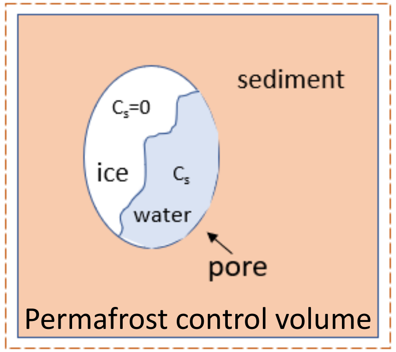
Unique capability of ACE: elements are **removed** from the computational domain based on **failure criteria**.

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

Thermal model

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

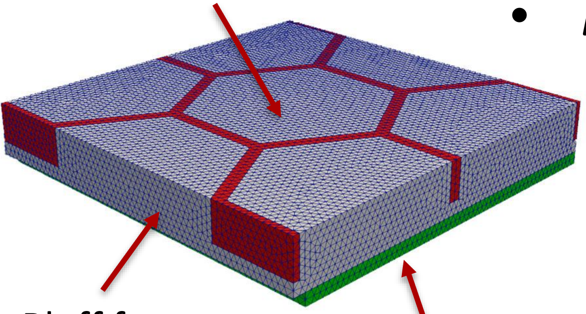
$$(\overline{\rho c_p} + \widetilde{\Theta})\frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{K} \cdot \nabla T)$$



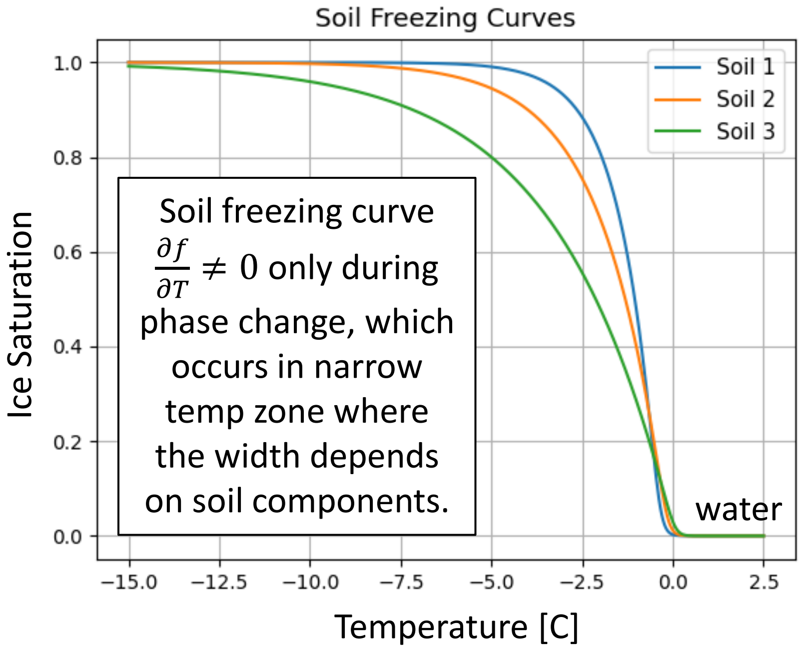
$\bar{\rho}$: density from mixture model
$\overline{c_p}$: specific heat from mixture model
$\boldsymbol{K}$: thermal diffusivity tensor
ρ_f: ice density
L_f: latent heat of water-ice phase change
f: ice saturation ($\in [0,1]$)
$\frac{\partial f}{\partial T}$: soil freezing curve (depends on salinity)

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



- ***Boundary conditions*** (from wave model/data)
  - ➢ Local ***geothermal heat flux*** from below
  - ➢ ***Air temperature**** from above
  - ➢ ***Air/ocean temperature*** at bluff face
  - ➢ ***Ocean salinity*** at bluff face**



* Or, alternatively surface ground temperature (if available). ** Used to modify melting temperature of ice.

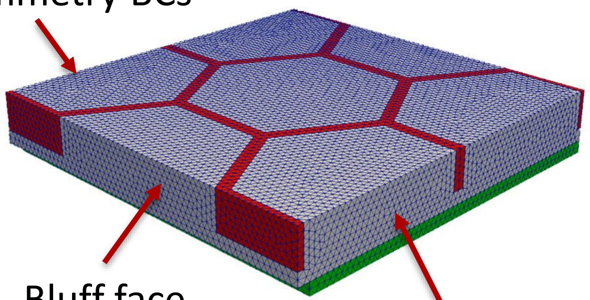
Mechanical model

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

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

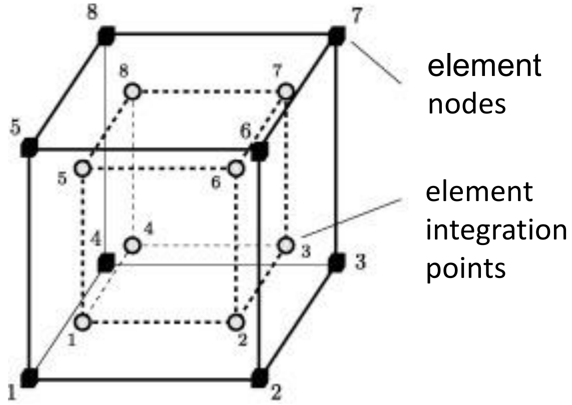
$A(\boldsymbol{F},\boldsymbol{Z})$: Helmholtz free-energy density
$\boldsymbol{Z}$: material variables
$\boldsymbol{F}$: deformation gradient ($\nabla\boldsymbol{\varphi}$)
ρ: density
$\boldsymbol{B}$: body force
$\boldsymbol{T}$: prescribed traction

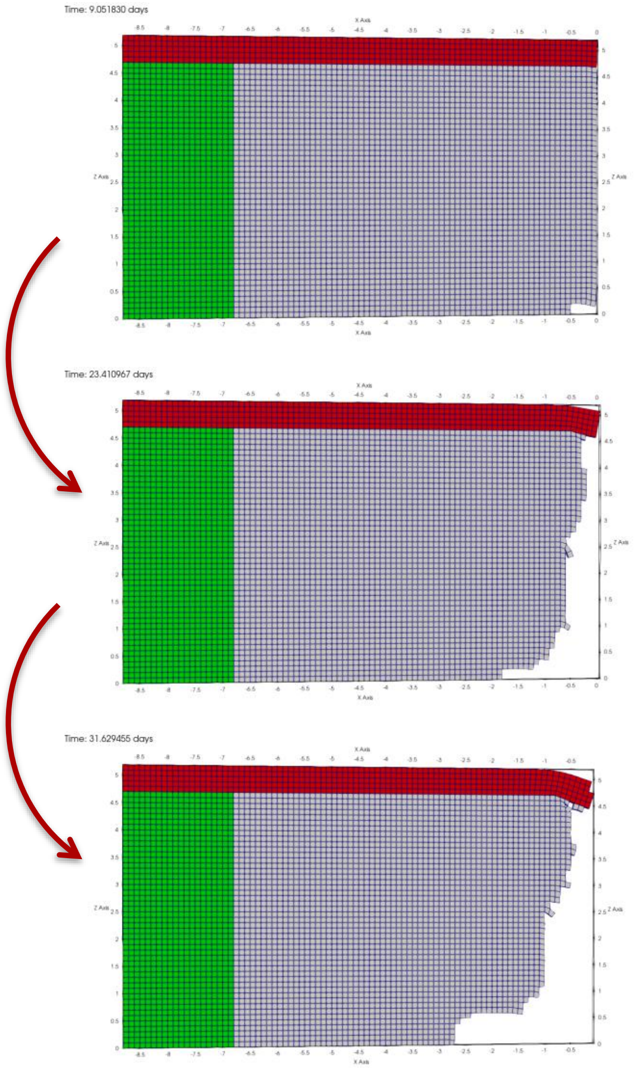
  - Computes ***displacements*** and ***new computational geometry*** (following erosion)
- ***J_2 plasticity*** extended to large-deformation regime ***constitutive model*** for ***ice*** and ***permafrost***
  - ***Incorporates all mechanisms*** that lead to deformation and plastic flow of polycrystalline materials like ice; ***minimal*** calibration ***parameters***; ***simplest*** material model w/ plastic behavior
  - Constitutive model is a function of f, the ***ice saturation****, which comes from the ***thermal problem***
  - Upgrading to ***cap plasticity model***, which incorporates ***volumetric*** (or pressure-sensitive) plasticity
- ***Boundary conditions:***
  - ***Symmetry BCs*** on lateral sides
  - ***Wave pressure Neumann BC*** on bluff face** (from wave model)
  - **Damage variable** on bluff face in contact with ocean (introduces softening due to dissolution by lowering elastic modulus E)



Erosion failure criteria

- **Stress criterion:** when material reaches a critical value of the stress in tension or compression.
- **Strain criterion:** when material reaches a critical strain limit defined as a function of peat content (distortion).
- **Kinematic criterion:** when material has tilted excessively, or exceeded a maximum physical displacement, it is assumed to have fallen as part of block erosion.





When any of the **failure criteria** are reached for all integration points within an element, “failed” elements are **removed** from mesh.

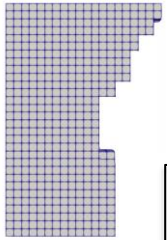
Coupled thermo-mechanical formulation

Sandia National Laboratories

Potential key advantages:

- Failure modes develop from **constitutive relationships** in FEM model (no empirical relationships!)
- **Elements** are actually **removed** from the mesh based on **failure criteria**
- Thermal and mechanical problems can be advanced using **different time-steppers** (e.g., implicit-explicit coupling)
- **Coupled** mechanical + thermal states

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



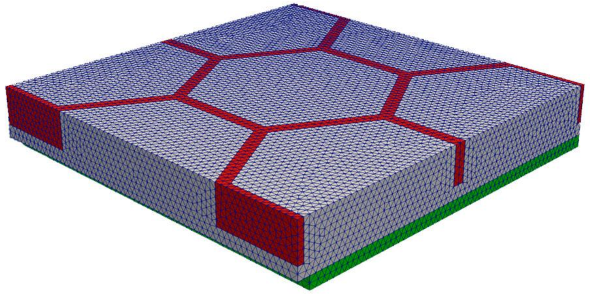
Thermal:

Inputs: geometry, sediment type, porosity, salinity

Outputs: temperature field, ice saturation

Eroded geometry

Ice saturation

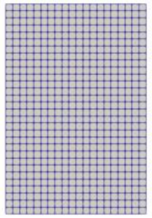


Albany-LCM

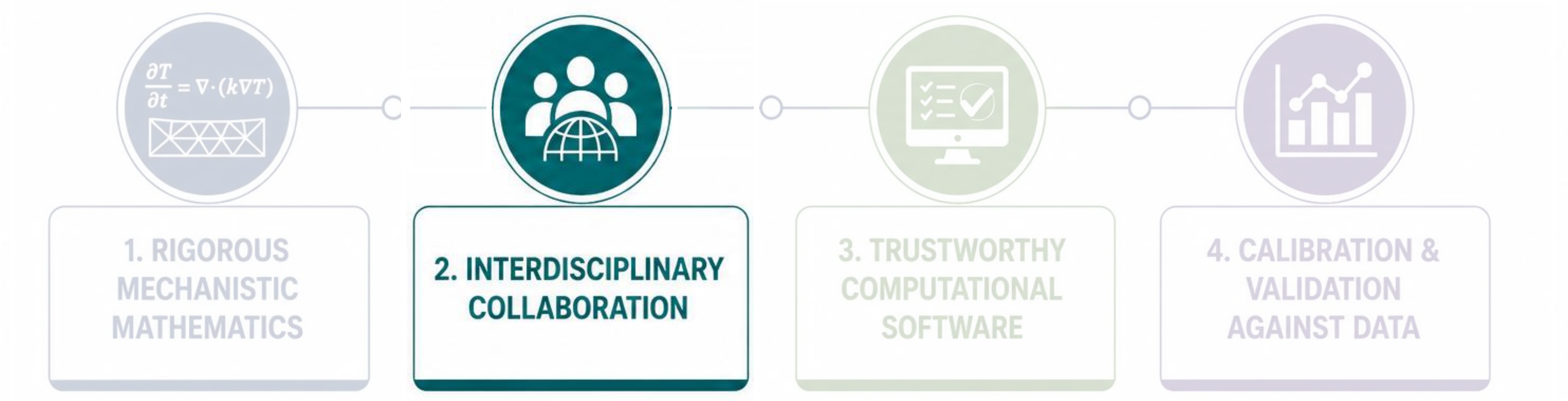
Mechanical:

Inputs: ice saturation, mechanical parameter relationships as function of sediment type and ice saturation

Outputs: displacements, eroded geometry



Interdisciplinary collaboration: inputs to the ACE model



Parameters & inputs to ACE

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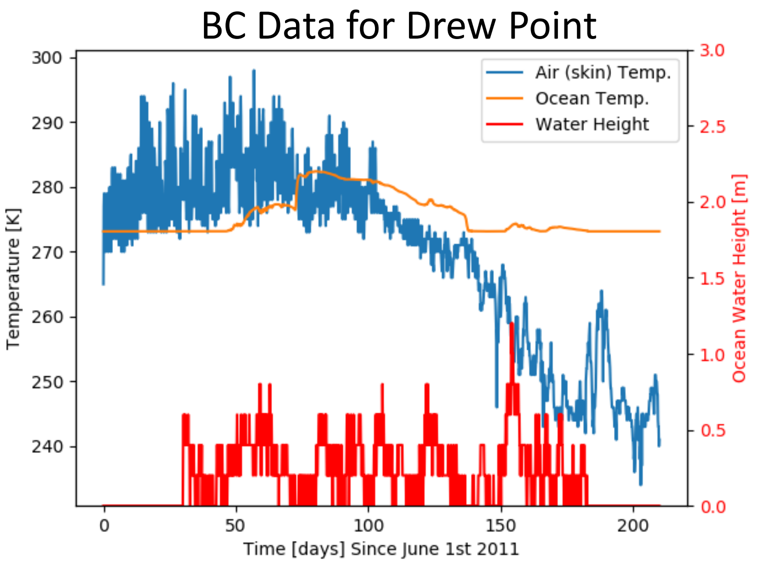
Parameters estimated from core lab experiments:

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

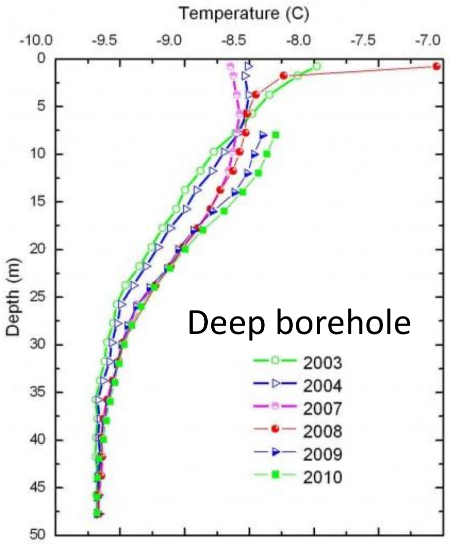


Parameters from literature:

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

Parameters estimated from observational data at Drew Point:

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

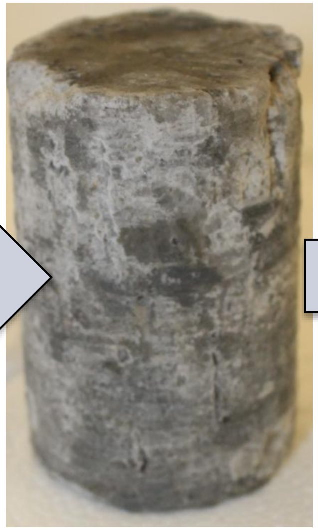


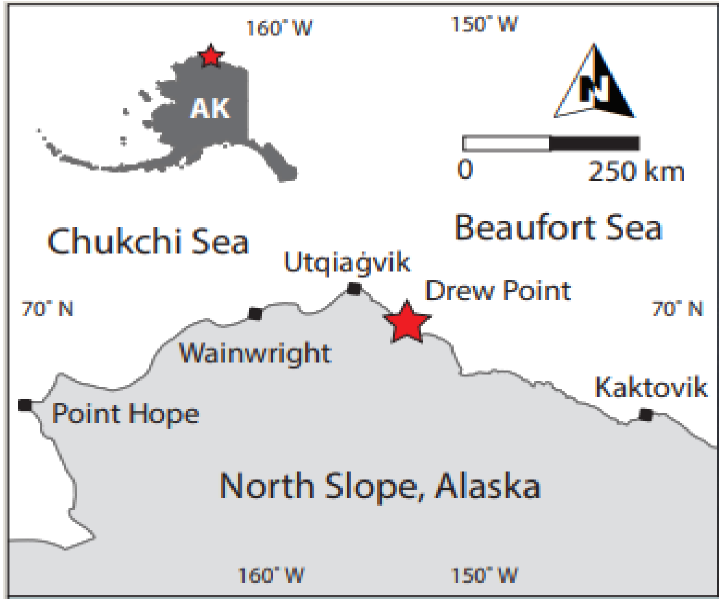
Parameters from wave model (WW3+SWAN+Delft3D):

integral consulting inc.

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

Mechanical testing for material model calibration





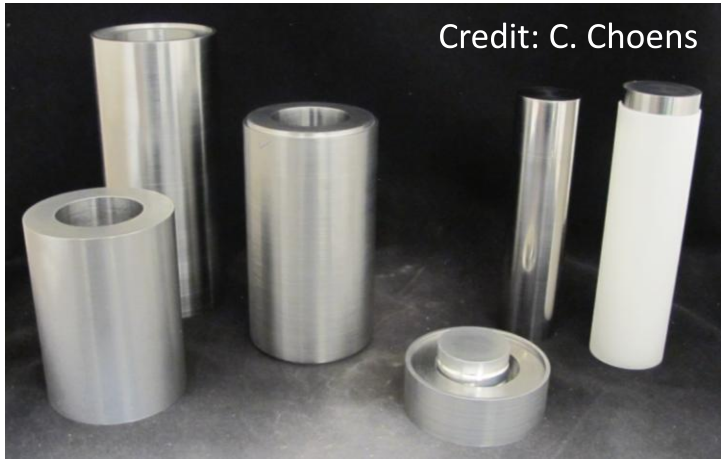
- **Permafrost cores** were drilled at **Drew Point, Alaska** and taken to Sandia's **geomechanics lab**
- **Tensile** and **Unconfined Compressive (UCS) experiments** were performed on samples with **different densities**, **ice contents** and at **different temperatures**
- Experimental tests were used to determine **Elastic modulus** and **yield stress** as a function of ice saturation and porosity

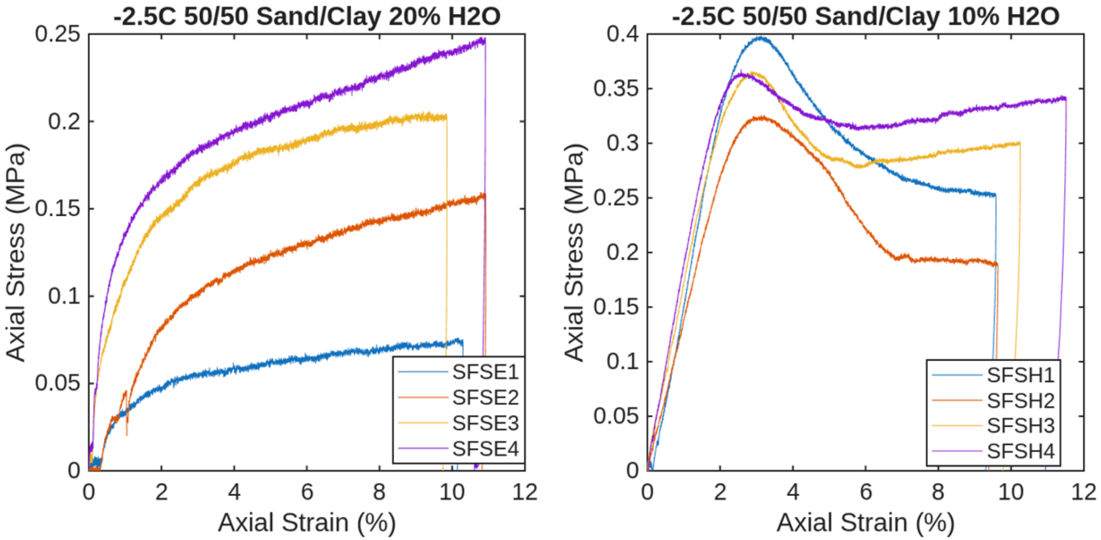
Ongoing work: experiments using synthetic permafrost samples towards universal constitutive model development

<u>Motivation</u>: natural frozen soils are **difficult to work** with and potentially **hazardous**; the **number of experiments** that can be performed is **limited** due to **limited samples**.

Approach:

- Create **synthetic permafrost samples** in the lab
- Perform basic **geomechanical testing** to characterize a broad range of material variations
- Use results to define a **universal constitutive model**
- **Integrate** new model into upgraded **ACE Cap Plasticity model**
- Use experimental data to **calibrate ACE model**
- Use ACE to perform **predictions** of a **natural site**

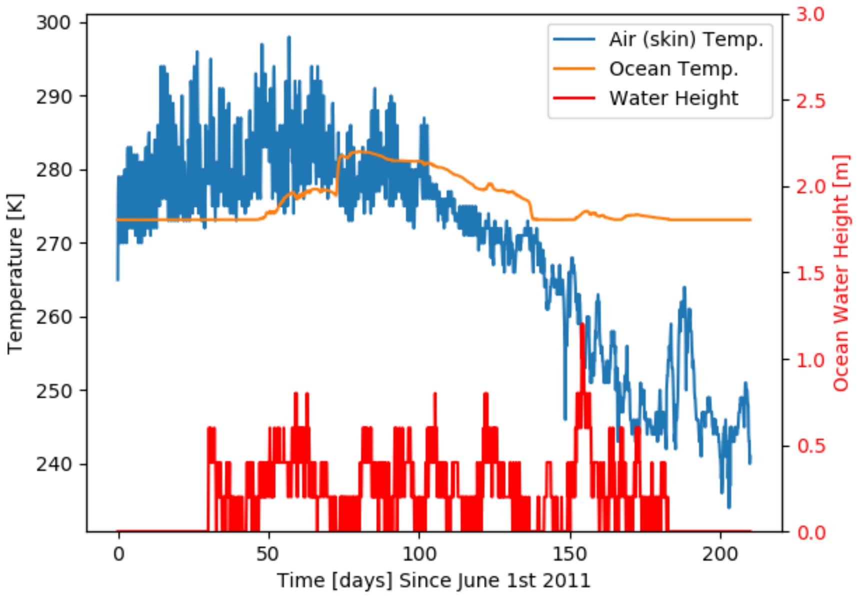




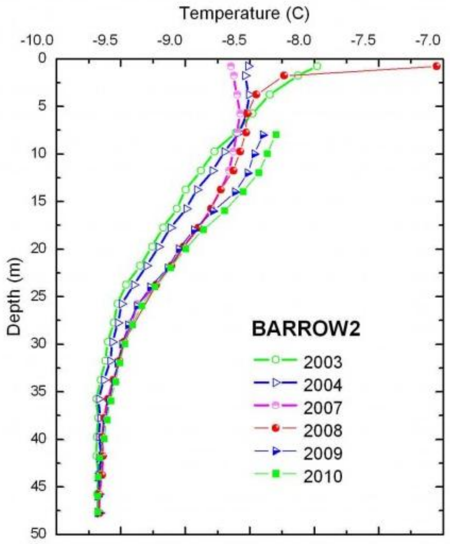
Top right: molds for frozen sample fabrication

Bottom right: stress-strain curves for samples at different temperatures & with different water contents. ***Temperature matters more than water content. Consistency in testing is improving with more testing.***

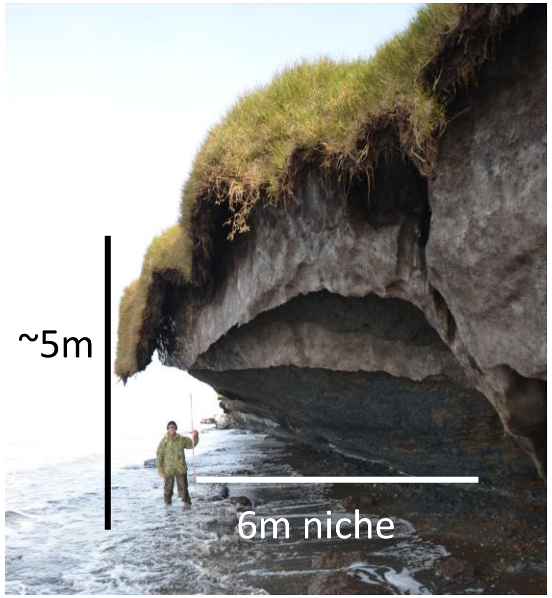
Parameters informed by observation data

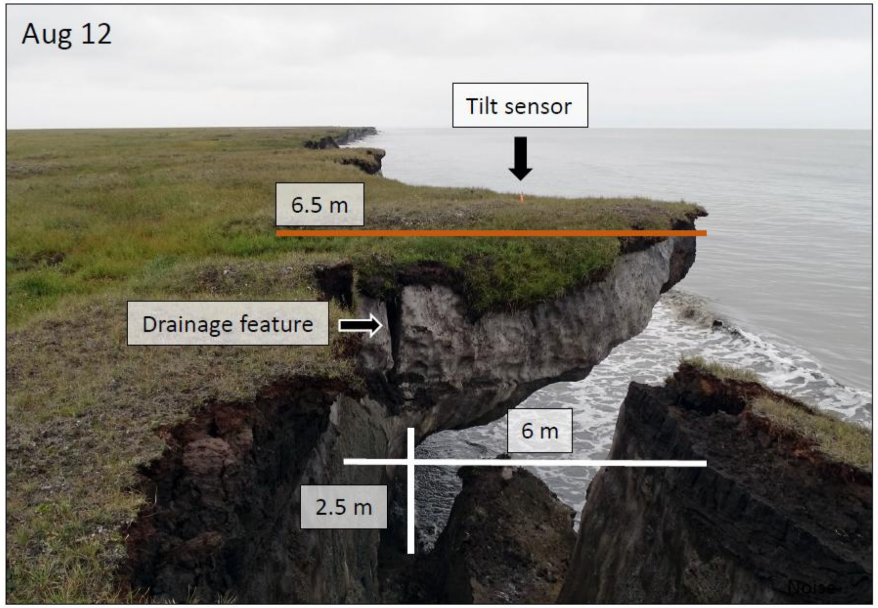


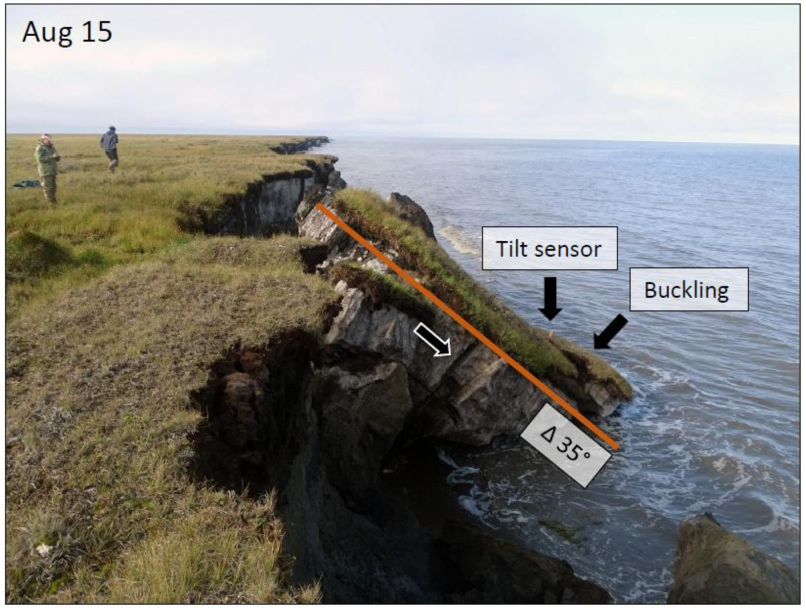
- **Air temperature** with time, initial bluff temperature (***USGS weather station data***)
- **Geothermal heat flux** (***borehole at Utqiagvik, AK***)
- **Polygon dimension, ice wedge thickness** and **depth, bluff height, organic layer (peat) thickness** (***August 2019 field campaign***)

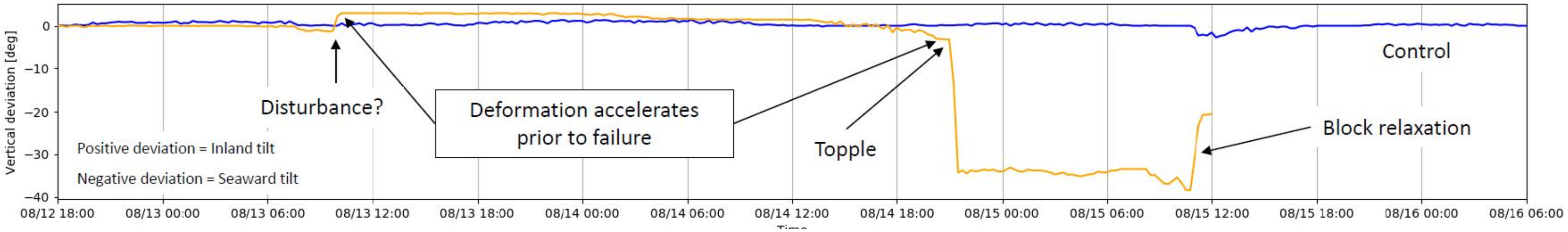


2019 field campaign at Drew Point, Alaska









Goals:

- Measure typical **polygon dimension**, **ice wedge thickness** and **depth**, **bluff height**, **organic layer (peat) thickness**
- Collect data for model **calibration** and **validation**

Credit: B. Jones, D. Bull, J. Frederick

Oceanographic forcing in mechanistic ACE model

WW3 Development of wave field in the Arctic to develop nearshore boundary conditions (BCs)

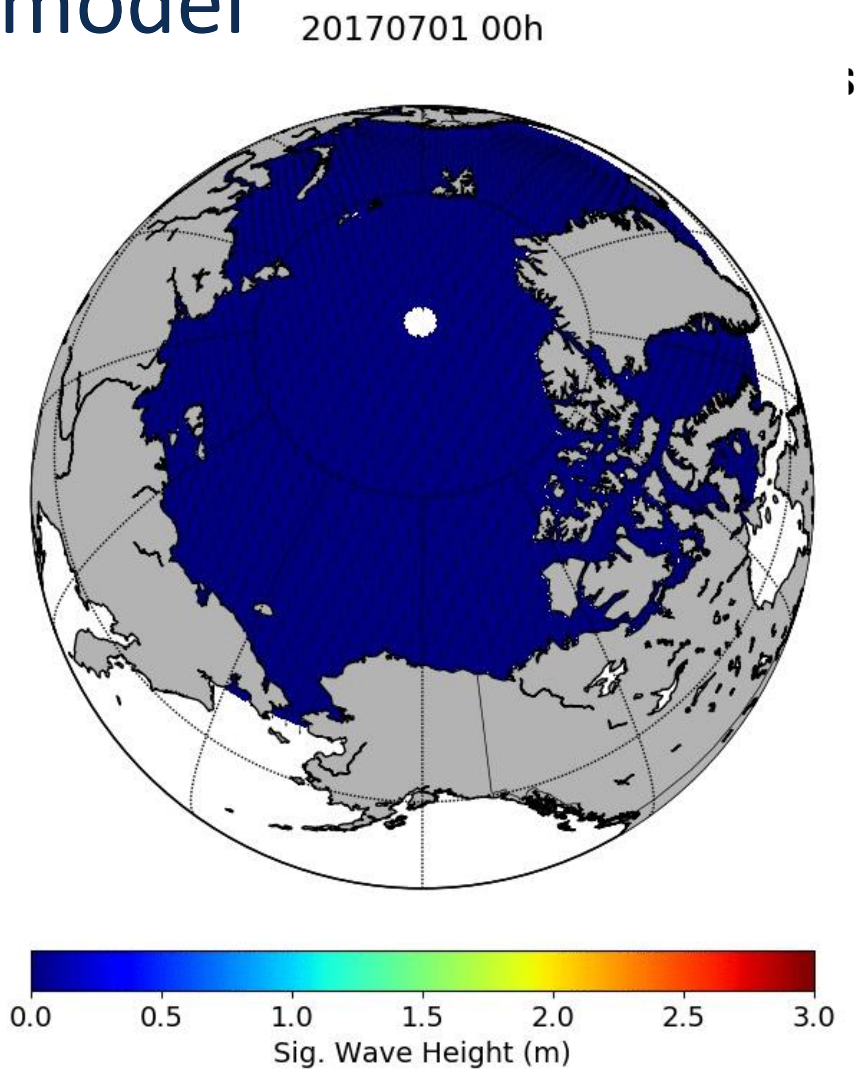
- Surface winds
- Ice cover
- Temperature (surface and ocean)
- Solar radiation
- Persistent currents

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

Wave model is run **offline**, **post-processed** to generate **ocean boundary conditions (BCs)** for **ACE.**

Trustworthy software implementation: the Albany-LCM code

Finite element implementation in Albany-LCM

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.
- All software is available on ***GitHub***.
- ***Mature code*** with implemented ***software quality measures*** (version control, nightly regression & performance testing, etc.)
- ACE model implementation was ***verified*** on simple test cases with known solutions prior to deploying the model on realistic problems

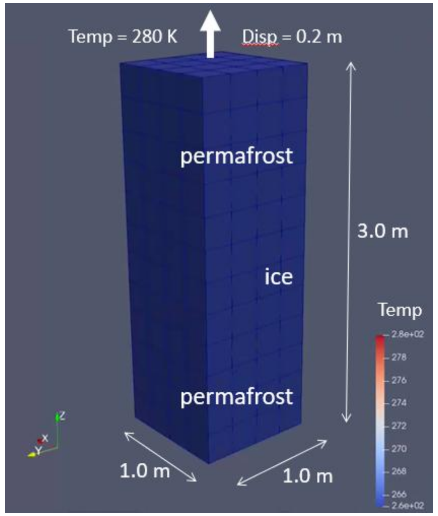
Albany-LCM

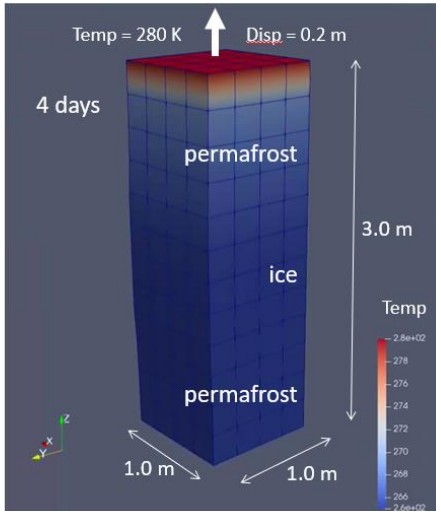
https://github.com/sandialabs/LCM

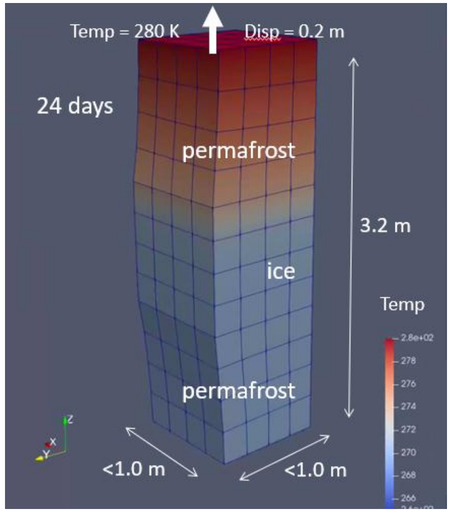
Trilinos

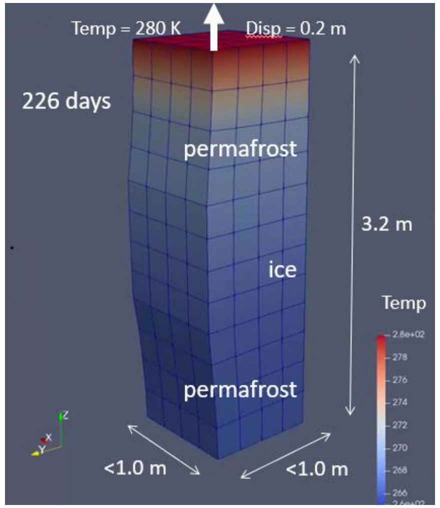
https://github.com/trilinos/trilinos

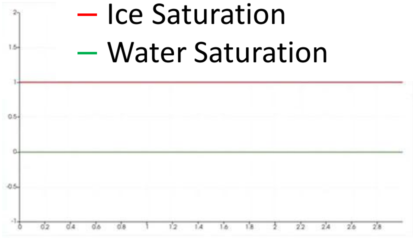
Verification on simple test cases

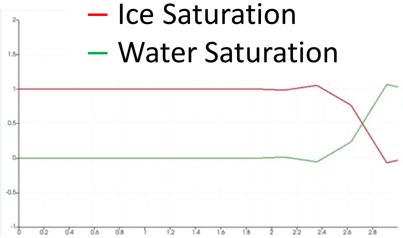


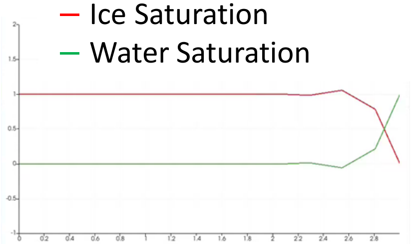


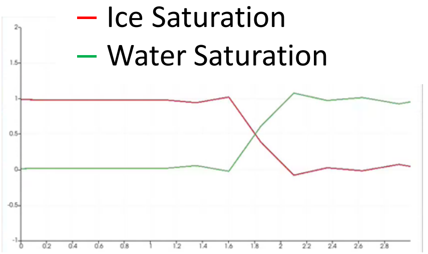


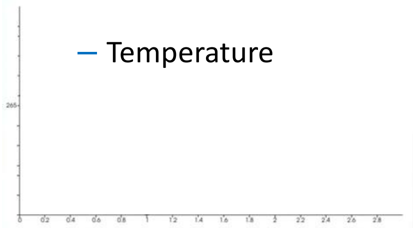


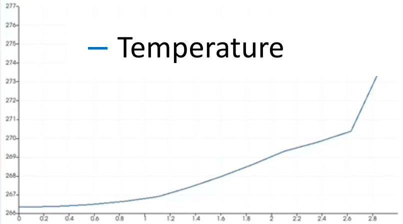


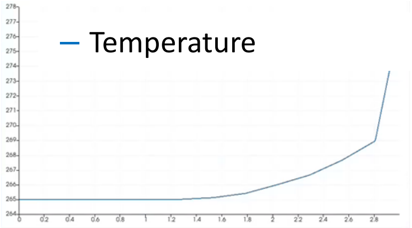


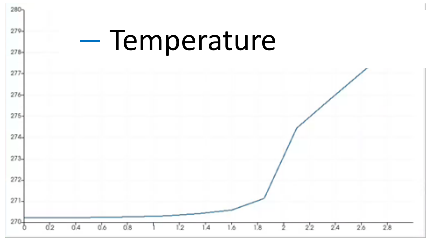


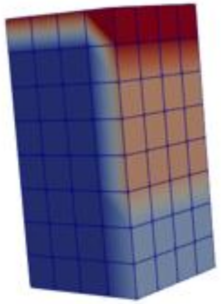












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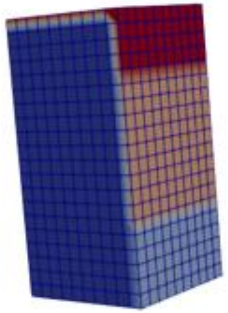

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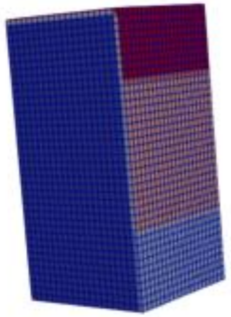

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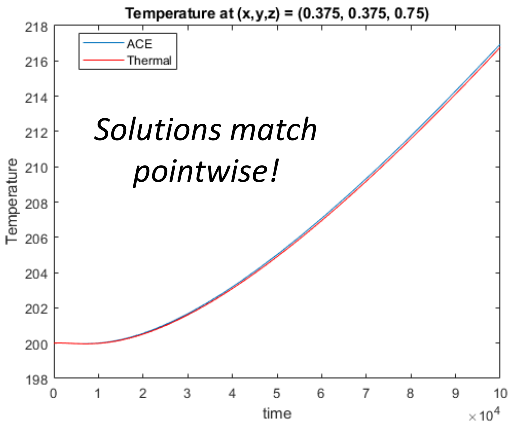


Nightly testing to maintain software quality

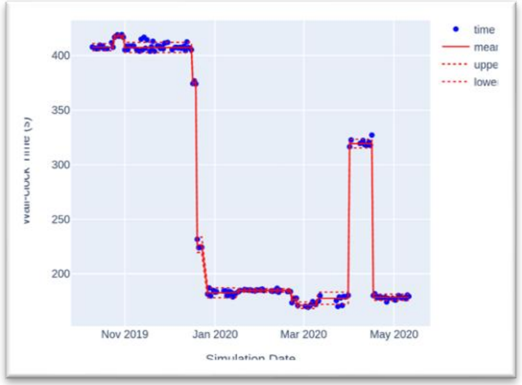
Nightly *13 builds*

View Timeline

Site	Build Name	Configure Error	Configure Warn	Build Error	Build Warn	Test Not Run	Test Fail	Test Pass	Start Time
camobap.ca.sandia.gov	Albany-Linux-4.18.0-553.75.1.el8_10.x86_64-gcc-13.2.0-Release-OpenMP	0	1	0	30	30^{+1}	8^{+1}	136^{+1}	May 06, 2026 - 12:32 UTC
cee-compute033	Albany-Linux-4.18.0-553.115.1.el8_10.x86_64-Intel(R)-18.0.0-Release-Serial	0	25	0	50	0	2^{+1}	199^{+3}	May 06, 2026 - 05:48 UTC
cee-compute030	Albany-Linux-4.18.0-553.115.1.el8_10.x86_64-gcc-11.4.0-Debug-Serial	0	25	0	0	0	1^{+1}_{-3}	195^{+6}	May 06, 2026 - 04:27 UTC
cee-compute031	Albany-Linux-4.18.0-553.115.1.el8_10.x86_64-gcc-11.4.0-Release-Serial	0	25	0	0	0	1^{+1}	200^{+3}	May 06, 2026 - 04:24 UTC
camobap.ca.sandia.gov	Albany-Linux-4.18.0-553.75.1.el8_10.x86_64-gcc-13.2.0-Debug-FPE-Serial	0	2	0	30	0	1	201^{+3}	May 06, 2026 - 02:17 UTC
cee-compute033	Trilinos-Linux-4.18.0-553.115.1.el8_10.x86_64-Intel(R)-18.0.0-Release-Serial	0	29	0	50	0	0	0	May 06, 2026 - 05:35 UTC
cee-compute031	Trilinos-Linux-4.18.0-553.115.1.el8_10.x86_64-gcc-11.4.0-Release-Serial	0	28	0	5	0	0	0	May 06, 2026 - 04:13 UTC
cee-compute030	Trilinos-Linux-4.18.0-553.115.1.el8_10.x86_64-gcc-11.4.0-Debug-Serial	0	28	0	0	0	0	0	May 06, 2026 - 04:18 UTC
attaway.sandia.gov	Albany-Linux-4.18.0-553.92.1.1toss.t4.x86_64-Intel(R)-18.0.0-Release-Serial	0	16	0	50	0	0	174^{+3}	May 06, 2026 - 05:26 UTC
attaway.sandia.gov	Trilinos-Linux-4.18.0-553.92.1.1toss.t4.x86_64-Intel(R)-18.0.0-Release-Serial	0	12	0	50_{-7}	0	0	0	May 06, 2026 - 04:05 UTC
hayka.ca.sandia.gov	Trilinos-Linux-5.14.0-611.49.1.el9_7.x86_64-gcc-11.4.0-Release	0	1	0	11	0	0	0	May 06, 2026 - 06:00 UTC
camobap.ca.sandia.gov	Albany-Linux-4.18.0-553.75.1.el8_10.x86_64-gcc-13.2.0-Release-Serial	0	1	0	0	0	0	150^{+3}	May 06, 2026 - 01:57 UTC
hayka.ca.sandia.gov	Albany-Linux-5.14.0-611.49.1.el9_7.x86_64-gcc-11.4.0-Release	0	0	0	0	0	0	150^{+3}	May 06, 2026 - 06:13 UTC

Items per page All

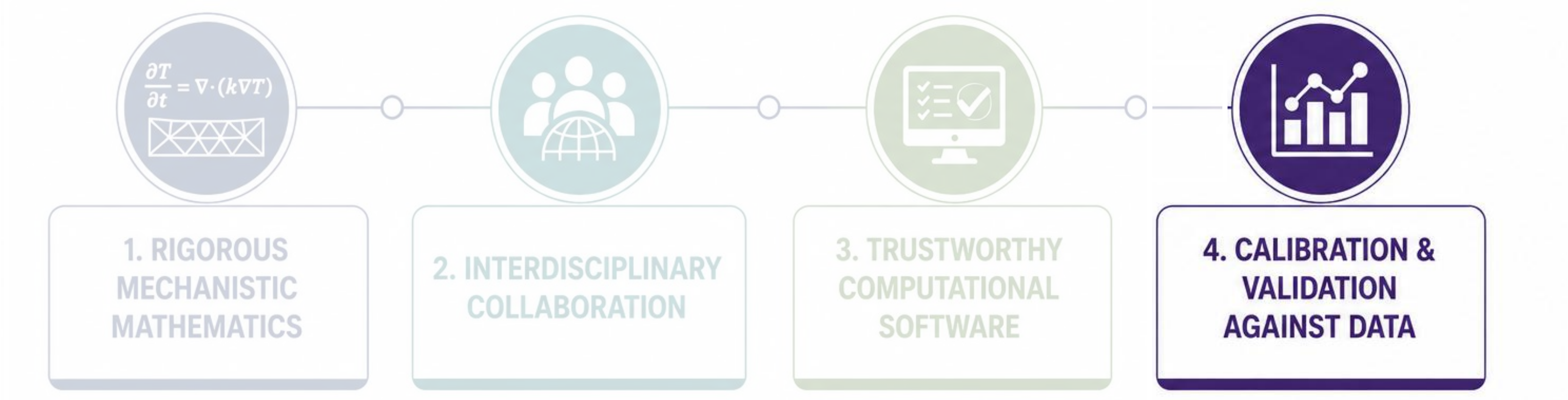
Repository*	Nightly test harness	Mailing lists
Version control	Unit tests	Issue tracking
Build system	Verification tests	Web pages
Config mgmt	Code coverage	Licensing
Regression tests	Performance tests	Release process



Name	Run Test	Performance Tests (Passes/Warnings/Fails)
AIS-8km-l5-np16	Passed	2/0/0
AIS-4km-l10-np64	Passed	0/2/0
AIS-2km-l20-np256	Failed	0/0/0
AIS-1km-l40-np2048	Passed	1/0/1

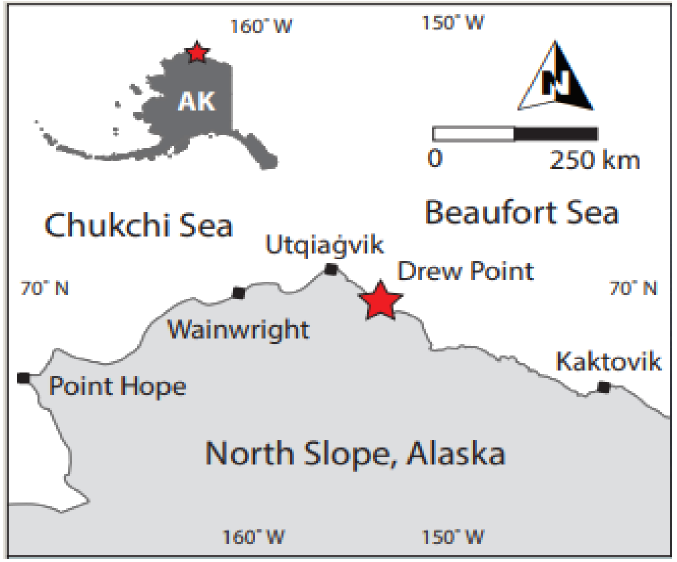
Without **regression** and **performance testing**, it is not a matter of if you will get burned, it is a matter of when!

Calibration & validation against real data: Drew Point, Alaska study



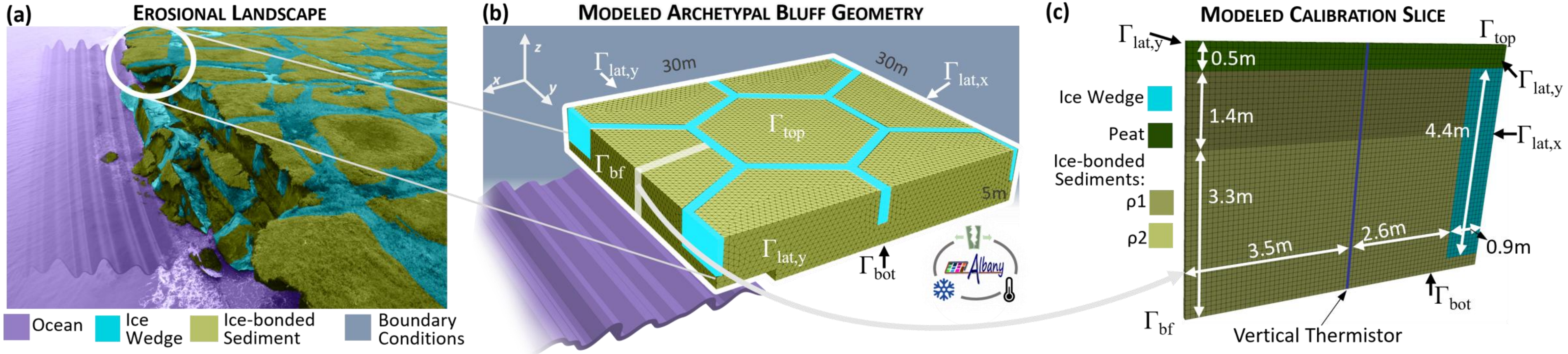
Numerical results: Drew Point 2.5D slice

Sandia National Laboratories



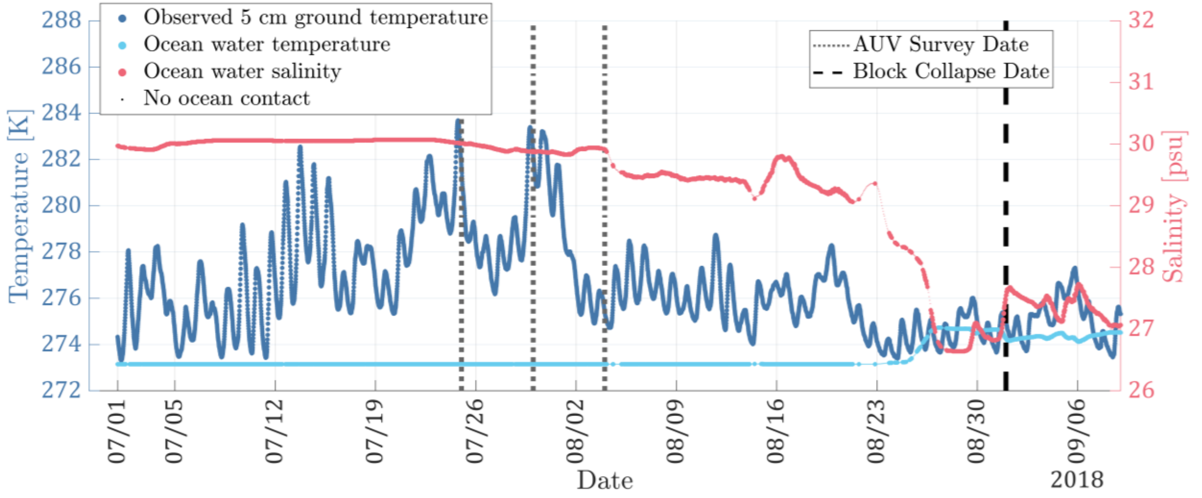
- Computational domain is ***2.5D cross-section*** of archetypal 3D bluff geometry discretized using a uniform hex grid
- ***Pseudo-realistic problem*** with ***realistic oceanic & atmospheric forcing BCs*** from ***Drew Point, AK*** in ***summer 2018.***

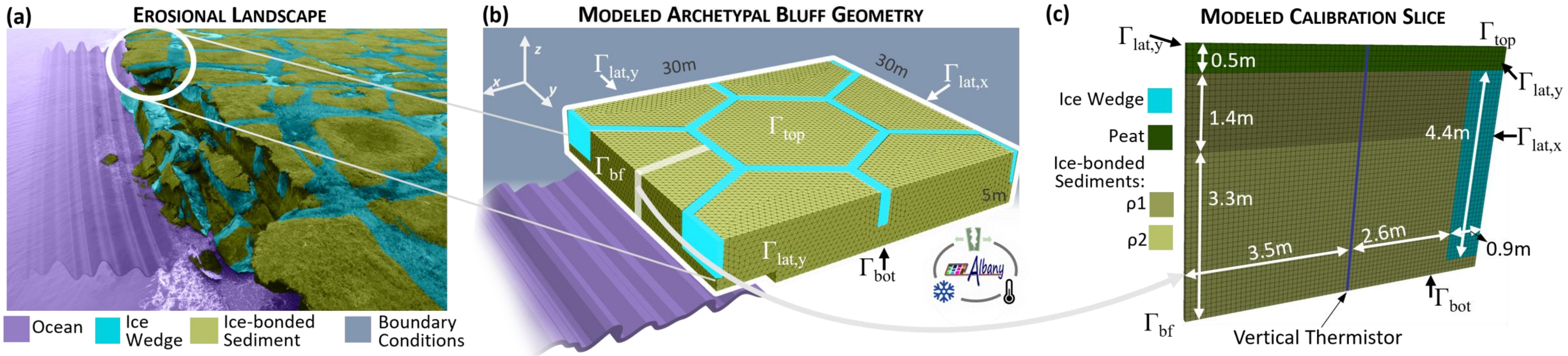
Goal: determine if ACE can simulate ***block failure event*** that occurred on ***Sept. 1, 2018***.



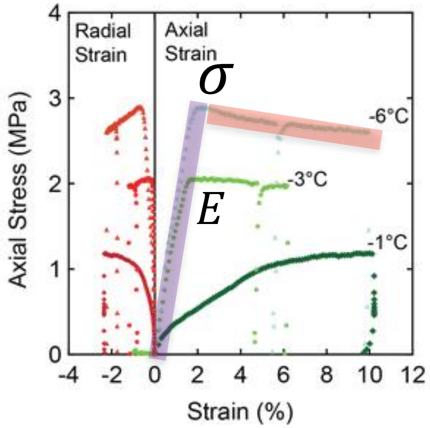
Numerical results: Drew Point 2.5D slice

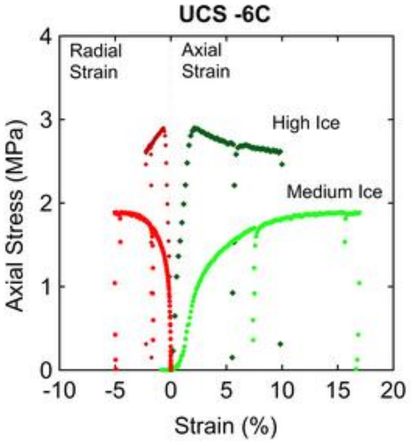
- ***Initial temperature field*** obtained from vertical thermistor string placed into DP1-1 ice core at Drew Point
- ***2.5 month simulation*** starting ***July 1, 2018*** with baseline time-step of 900 s. ***Thermal*** uses ***forward Euler***, ***mechanical*** uses ***implicit Newmark***.

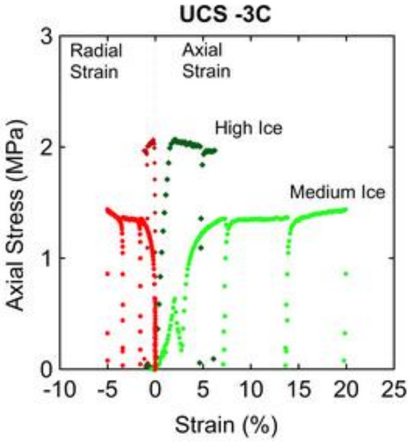




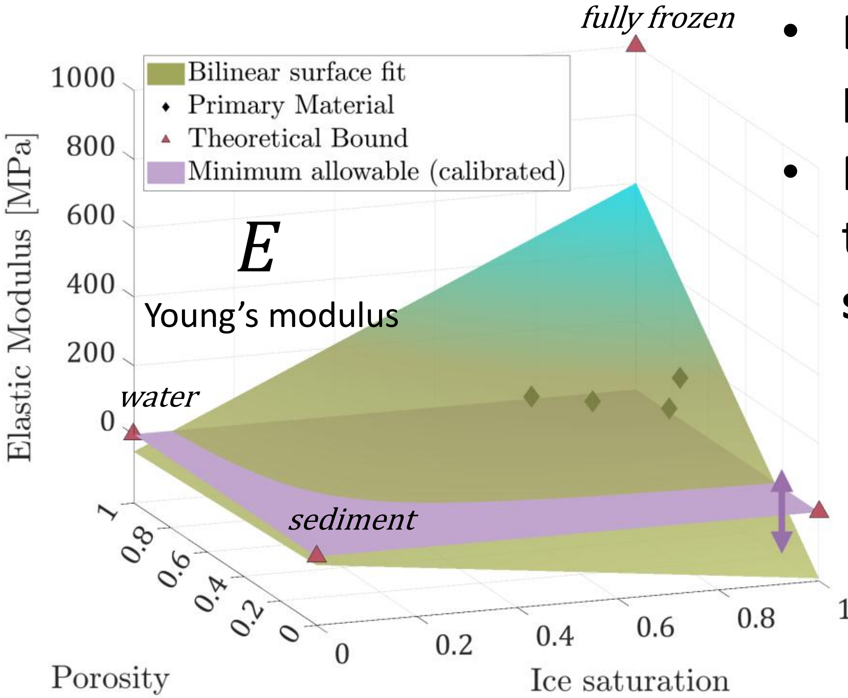
Material model calibration to experimental data





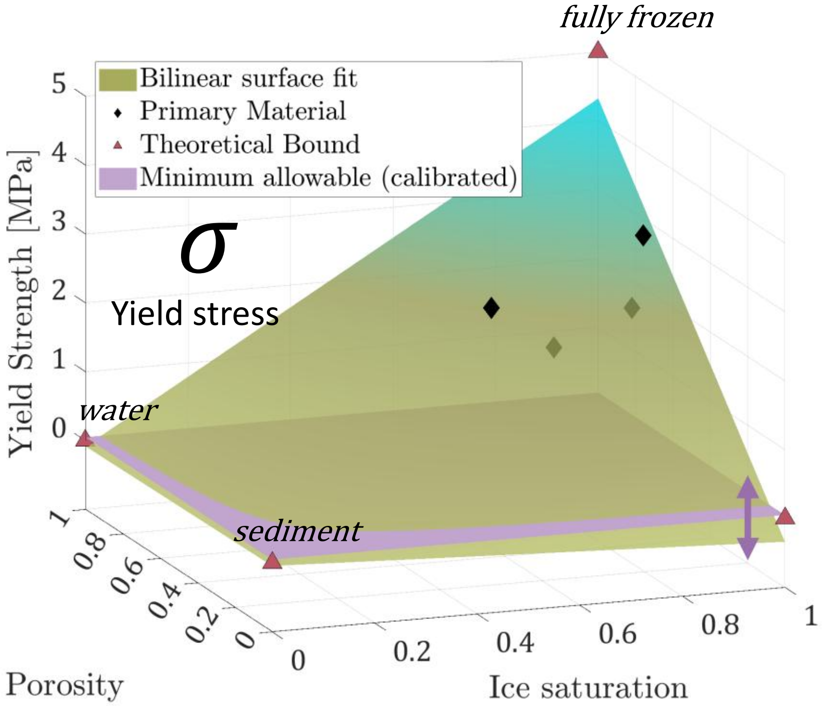


Experimental results on permafrost core samples used to create fits for E & σ as a function of **ice saturation** and **porosity**.

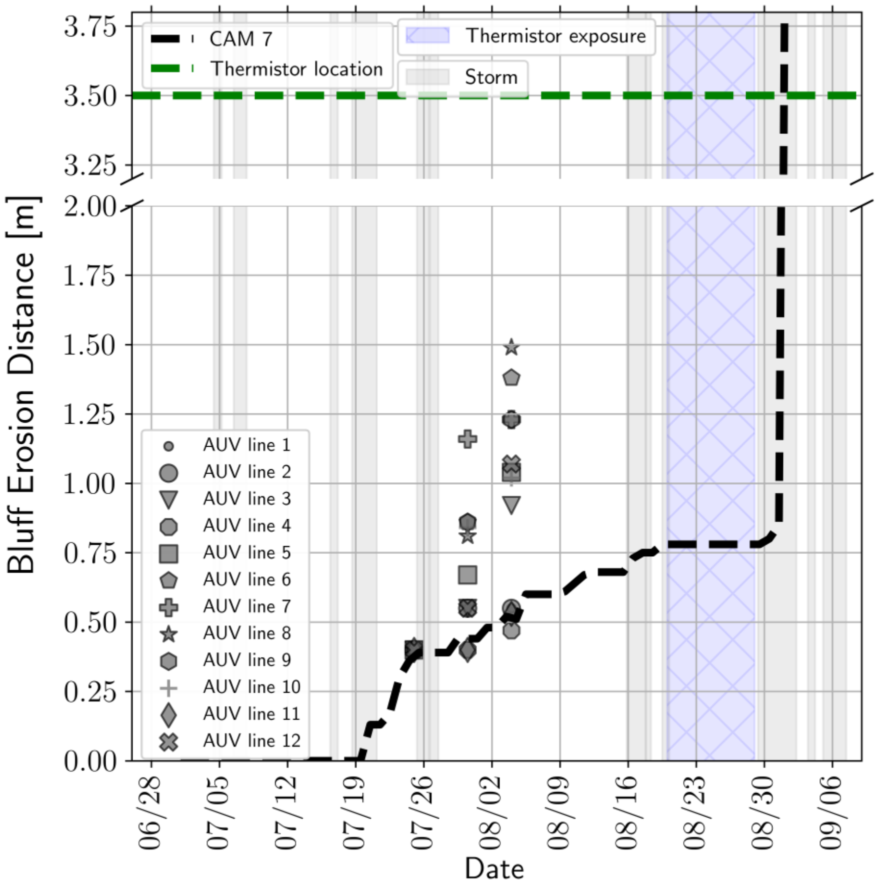


- Experiments were very **challenging** to perform and provide **limited data**!
- Material properties become **difficult** to define as **porosity** and **ice saturation** → 0.

⟹ we defined and **calibrated "minimum allowable" values** to bound the bilinear fits for both E and σ.

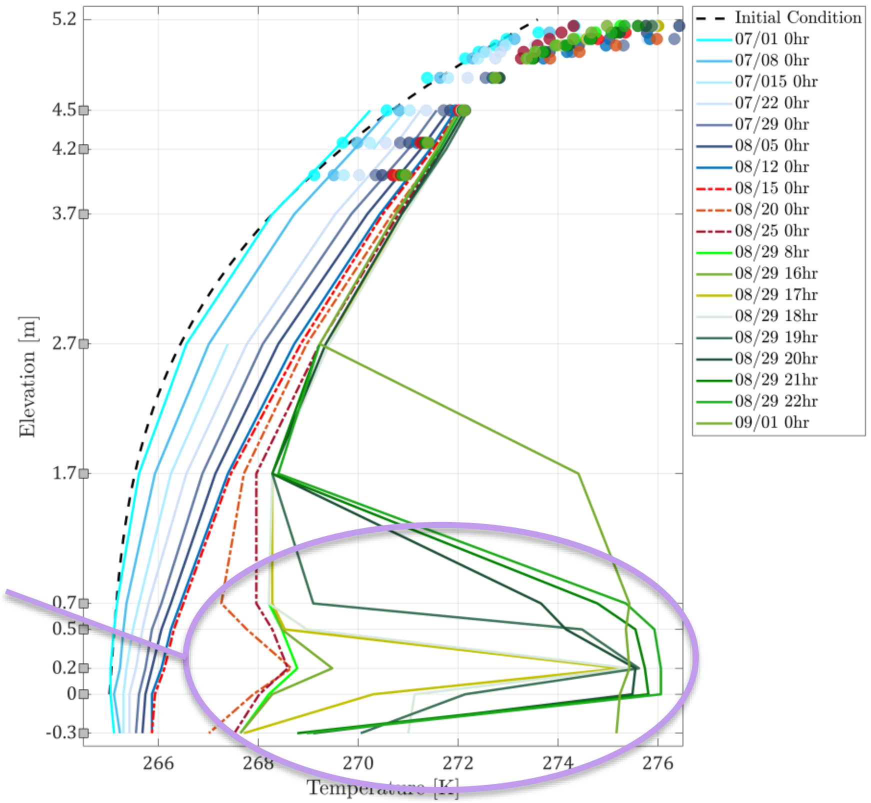


Calibration of minimum allowable E to observations



High-quality observational data provides targets for both **upper bluff erosion** and **niche formation.**

Change to ocean temperature implies formation of a niche

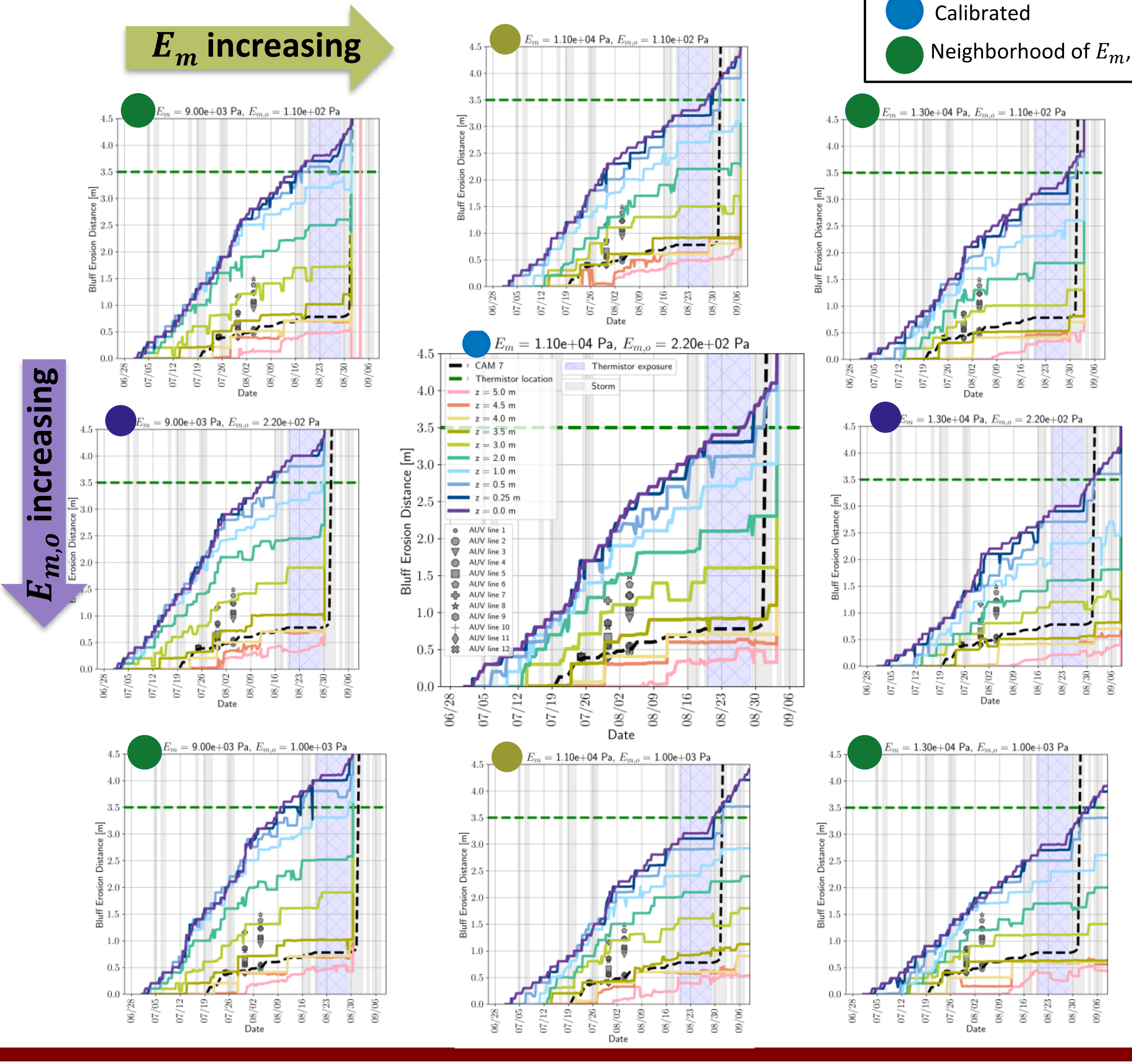


Time-lapse camera and UAV surveys provide **daily** measurements of **bluff erosion**

Vertical thermistor string 3.5 m back from bluff face enabled **detection** of timing/shape of **niche formation**

Calibration of minimum allowable E to observations

Legend
- Calibrated
- Neighborhood of E_m, $E_{m,o}$ near calibrated
- Same E_m as calibrated
- Same $E_{m,o}$ as calibrated



Minimum allowable elastic moduli ***calibrated*** through sensitivity studies s.t. ***upper bluff denudation***, ***niche growth*** and ***day/time of collapse*** match ***observations***

General, E_m (residual elastic modulus): lowest value the elastic modulus, $E = f(\textit{ice saturation}, \textit{porosity})$, can take

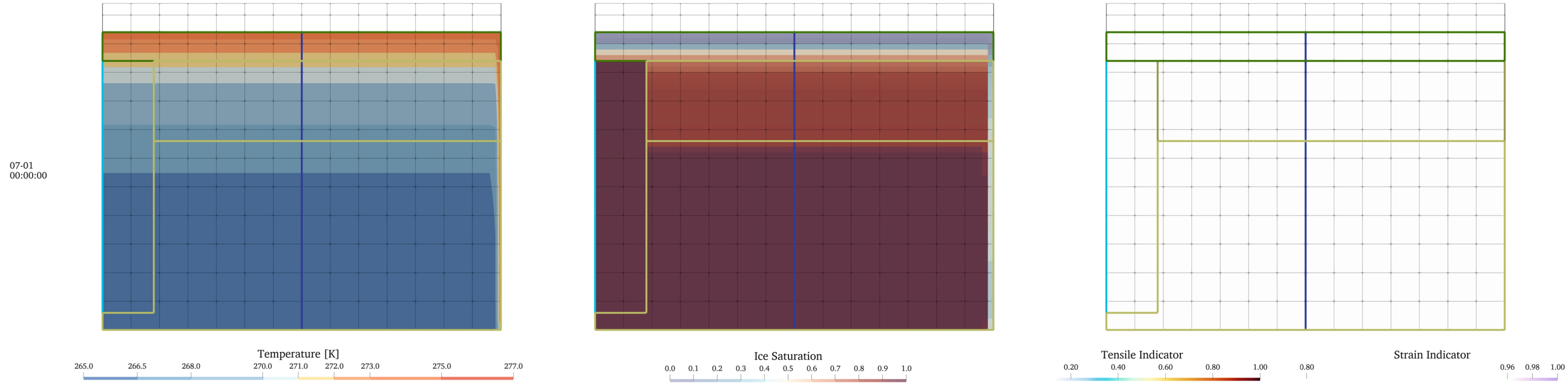
- Represents **softening** of material as it thaws
- **Increasing value** → less deformation/unit stress
- **Decreasing value** → more deformation/unit stress → material more likely to fail in strain
- Plays strong role in **rate of denudation**

Ocean-contacted material, $E_{m,o}$ (E weakening factor): distinct and lowered elastic modulus for material in contact with ocean

- Accounts for permafrost transitioning into a **slurry-like state** when in contact with **ocean**
- Reflects **localized adjustment** in material properties from material dissolution due to ocean-bluff contact
- **Decreasing value** → more deformation/unit stress → material more likely to fail in strain
- Plays strong role in **niche formation**

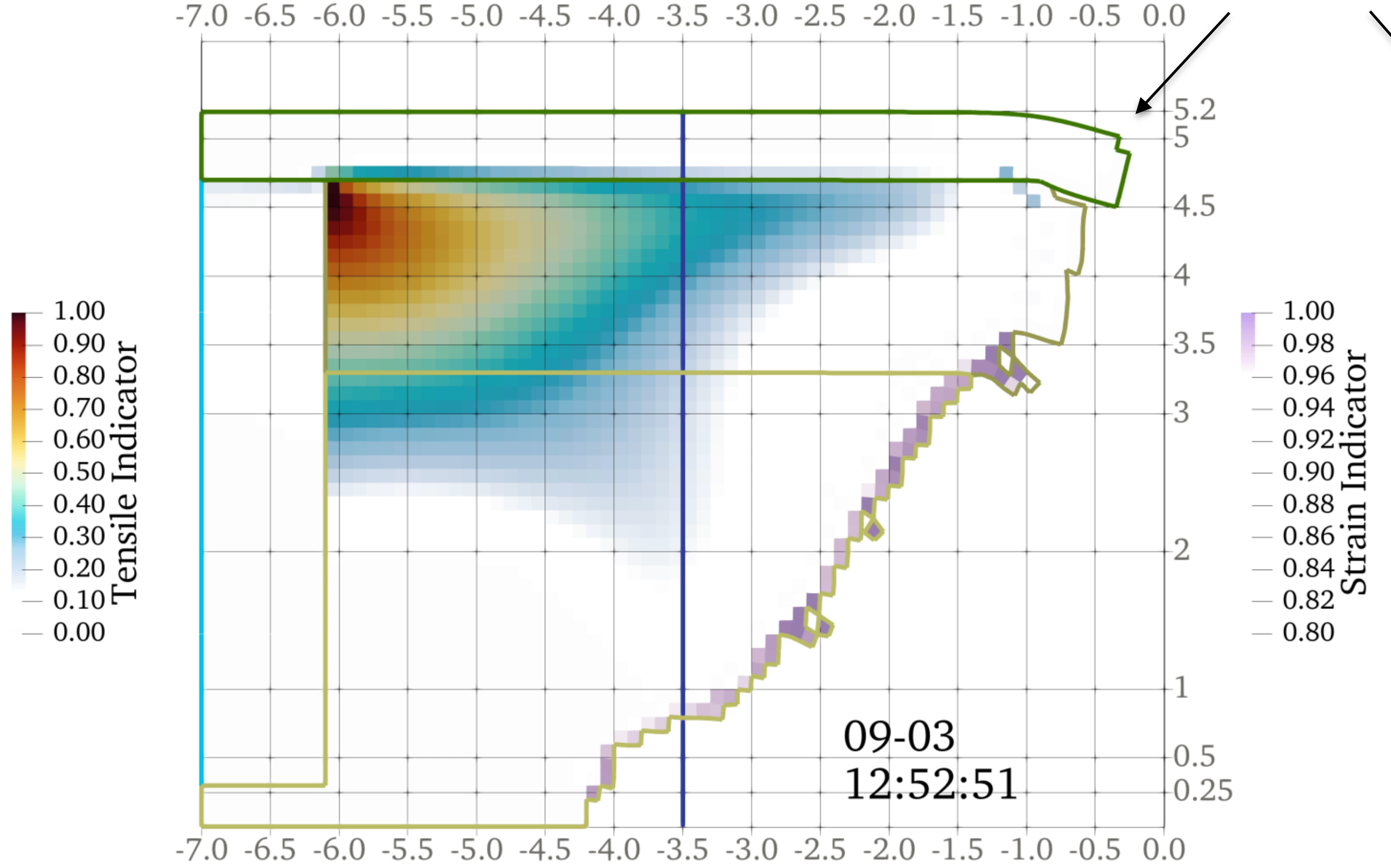
Simulated 2.5D slice: July 1 - Sept 3

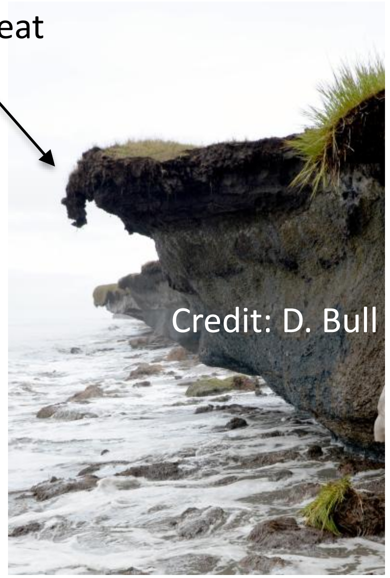
Thermal drivers (ground temp, ocean temp & salinity, etc.) → Temperature —*Freezing curve*→ Ice saturation —*Mechanical material property fits*→ Mechanical state (stress/strain) —*Erosion criteria*→ Erosion



Strain failure occurs at **upper bluff** (thaw-dominant softening) and in **niche** (ocean-dominant, material weakening).

Simulated 2.5D slice: simulated block collapse event (Sept. 3)



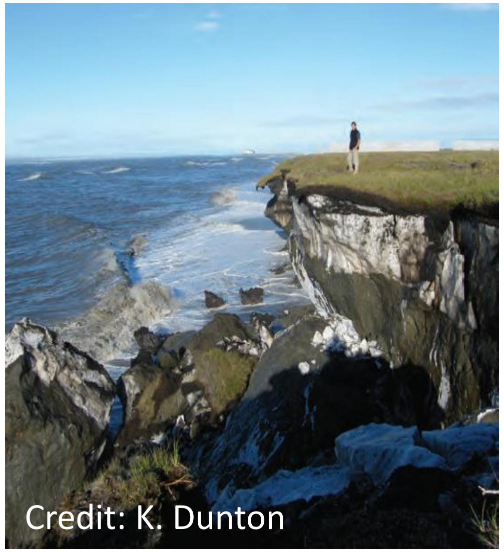


Failure in **tensile stress** leads to **block collapse.**

Calibrated ACE model ***capable of simulating block collapse event*** at Drew Point within 2 days of observation!

E. Bayat *et al.*, 2026

Extension & proof-of-concept: from Arctic coastal erosion to Arctic critical infrastructure



Extension to Arctic Critical Infrastructure (ACI) modeling

Motivation: "Nearly **4 million people** and **70%** of current **infrastructure**" [Hjort, 2018] situated on **Arctic permafrost** is **at risk** as permafrost continues to thaw!

The presence of infrastructure can cause acceleration of permafrost thaw.

- Accumulation of **snow drifts**
- Disruption of natural **water drainage**
- **Albedo** alternation (infrastructure absorbs solar radiation)
- **Heat leaks** (radiative or warm water leaks)
- **Insulation** of ground from cold air (winter refreeze limited)

ACE can be used to explore a variety of **infrastructure-permafrost combinations**, their **failure mechanisms** and possible solutions to **decrease risk** ⇒ **ACI**

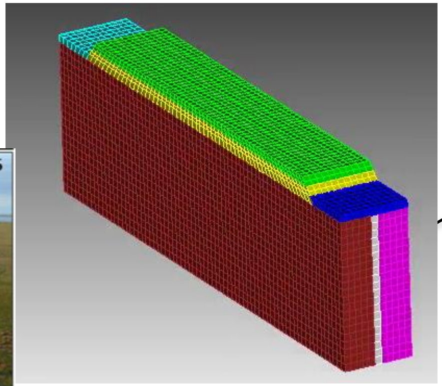

Credit: R.A. Winfree

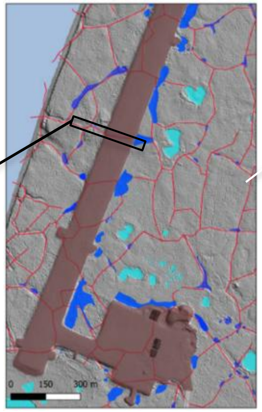

Credit: USGS

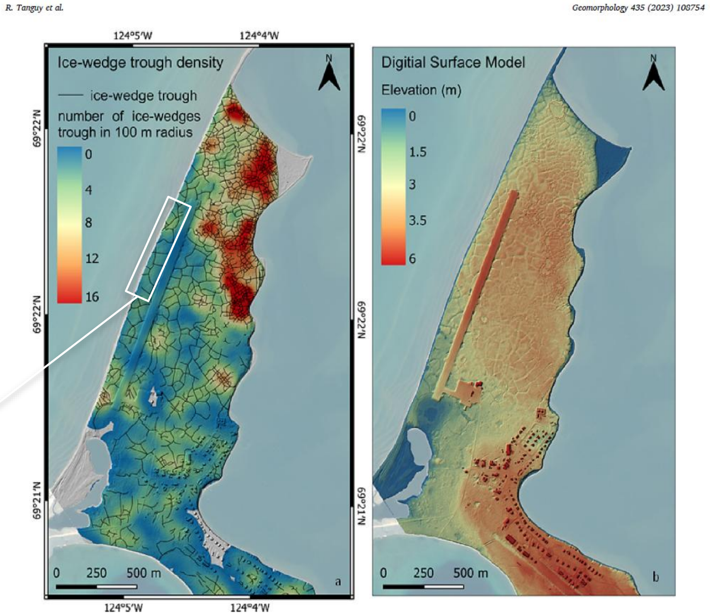
ACI demonstration: Paulatuk peninsula airstrip

Photograph of Paulatuky airstrip (R. Tanguy et al.)

Tanguy, R. et al. (2023) Permafrost degradation in the ice-wedge tundra terrace of Paulatuk Peninsula (Darnley Bay, Canada), Geomorphology, 435, 108754.



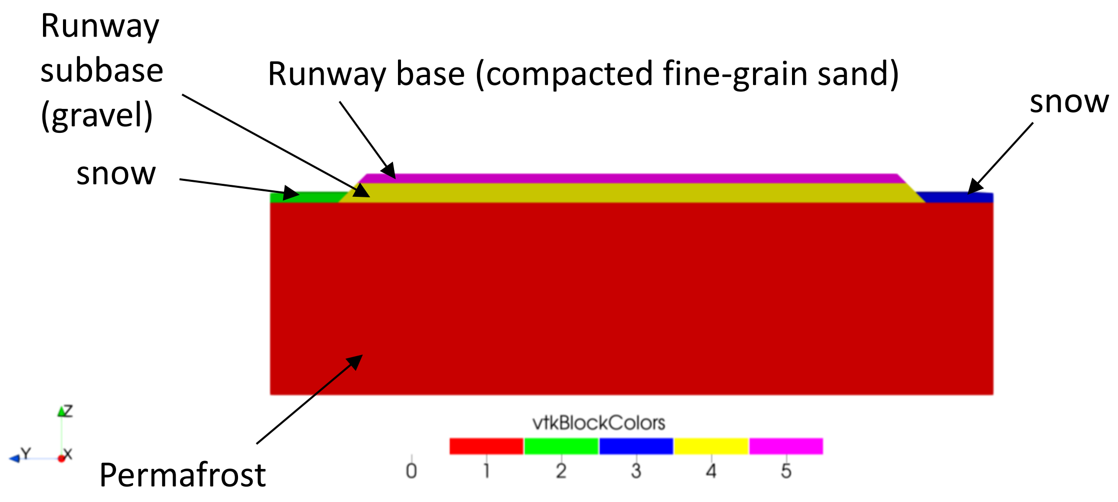


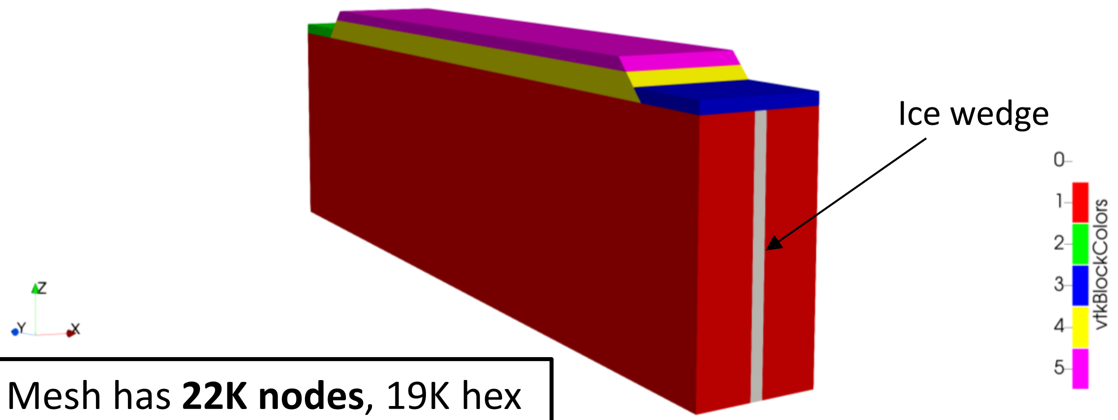


- Located in the Inuvialuit Settlement Region of the Amundsen Gulf in **northern Canada**.
- Permafrost characteristics are **similar** to those from **Drew Point, Alaska**.
- Airstrip overlays tundra and **numerous ice-wedge troughs**.
- Airstrip slopes towards a depression with a maximum angle of 0.37°, suggesting that **subsidence** is occurring
- **Snow accumulation** at side of airstrip acts as insulator and prevents ground from

Geometry of the airstrip cross-section

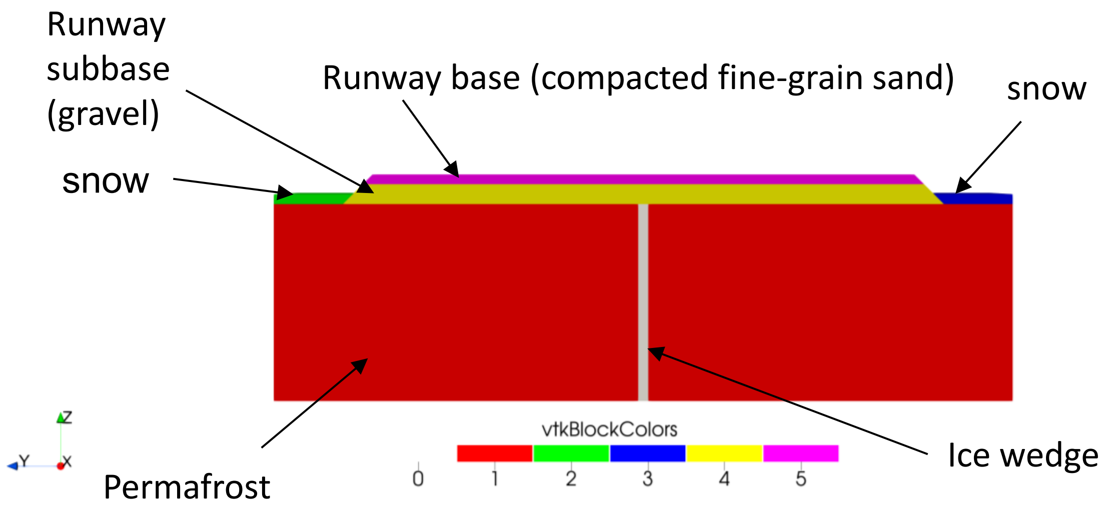
Ice wedge parallel to runway



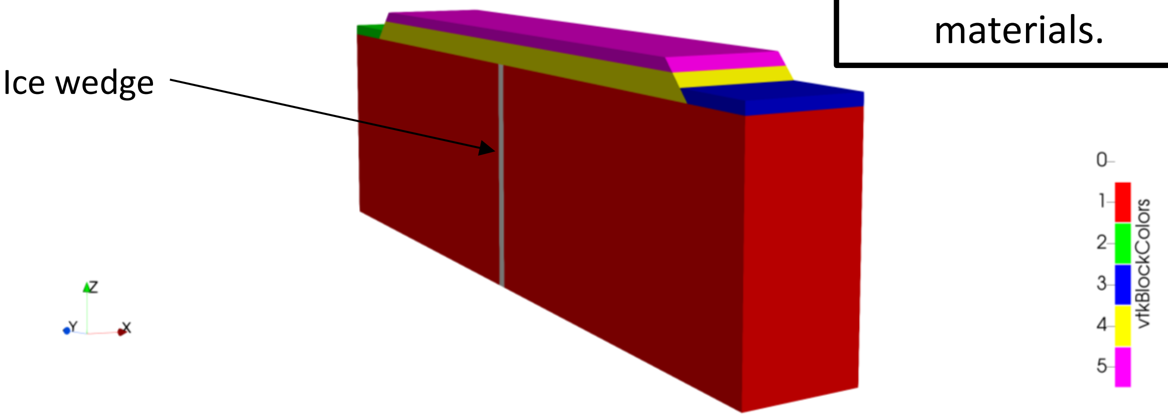


Mesh has **22K nodes**, 19K hex elements. Time-step: **8 hrs**

Ice wedge perpendicular to runway



J_2 plasticity model employed for all materials.



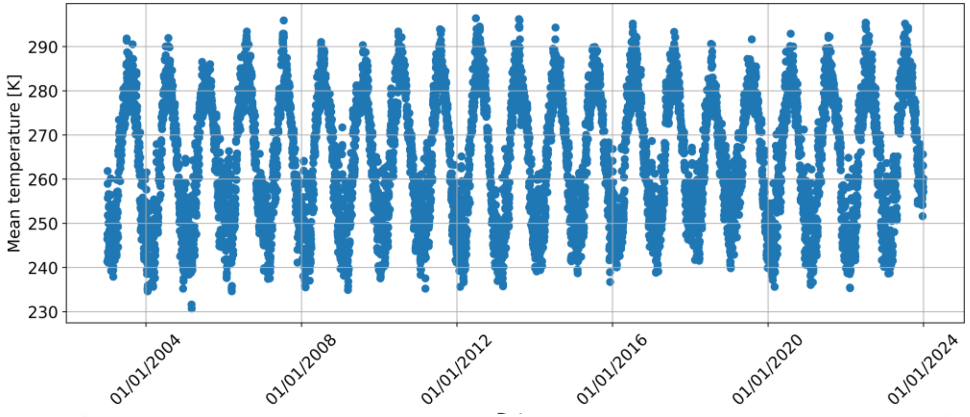
Simulation setup

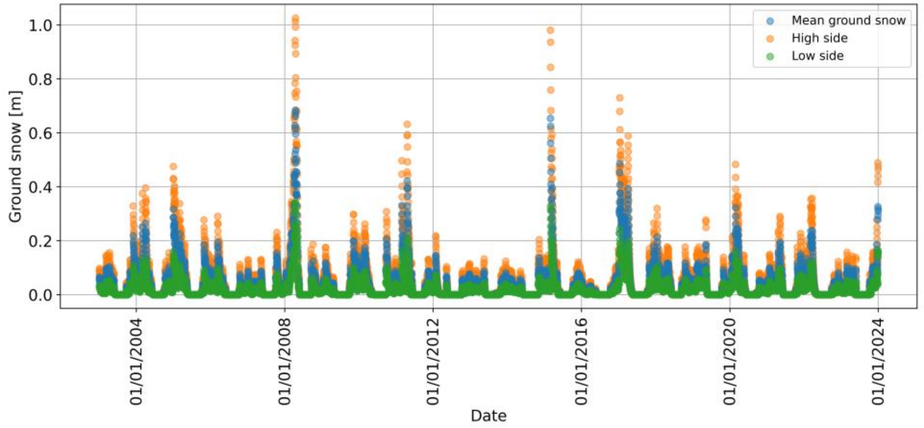
[1]http://gtnpdatabase.org/boreholes/view/365
[2] https://climate-change.canada.ca/climate-data/#/daily-climate-data

Initial thermal state: -6.2° Celsius based on mean annual ground temp 2008-2009 from borehole data[1]

Hindcast: (2003 – 2014)

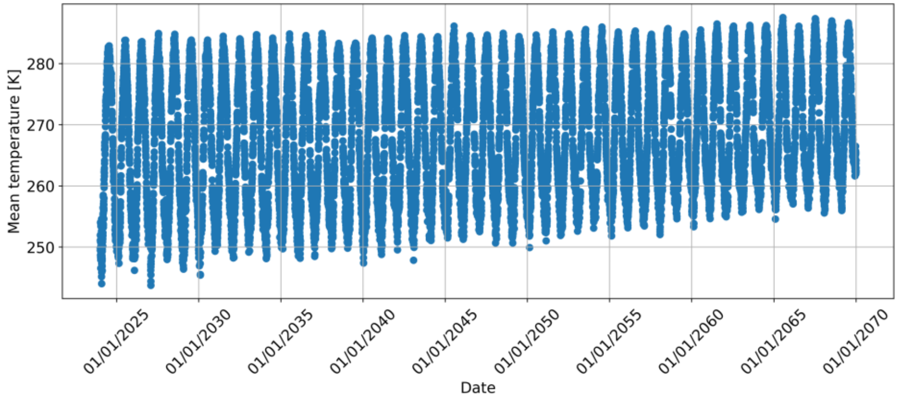
- Daily mean air temperature and precipitation from weather station 2203058 in Paulatuk[2]
- Snow depth calculated from air temp and precipitation data
- Uneven snow depth applied on east and west sides of runway

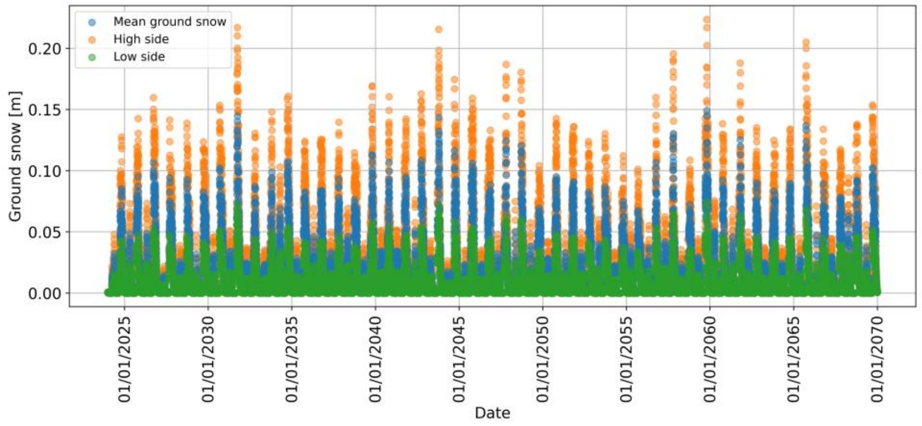




Forecast: (2024 – 2035)

- Daily mean air temperature and precipitation from E3SM w/ RCP 3.7*
- Snow depth calculated from air temp and precipitation data
- Uneven snow depth applied on east and west sides of runway



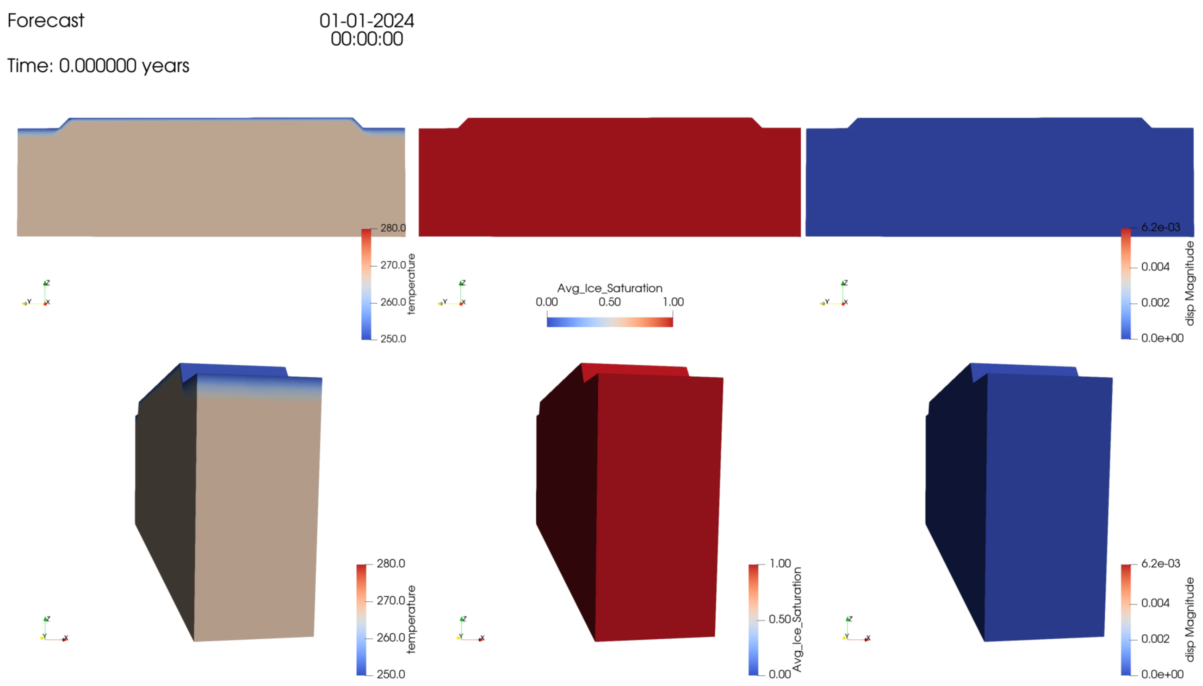


* Representative Concentration Pathway 3.7, the 3rd highest projected emissions considered in climate analyses.

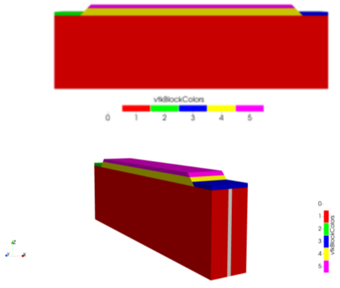
Ice wedge location relative to runway matters!

Sandia National Laboratories

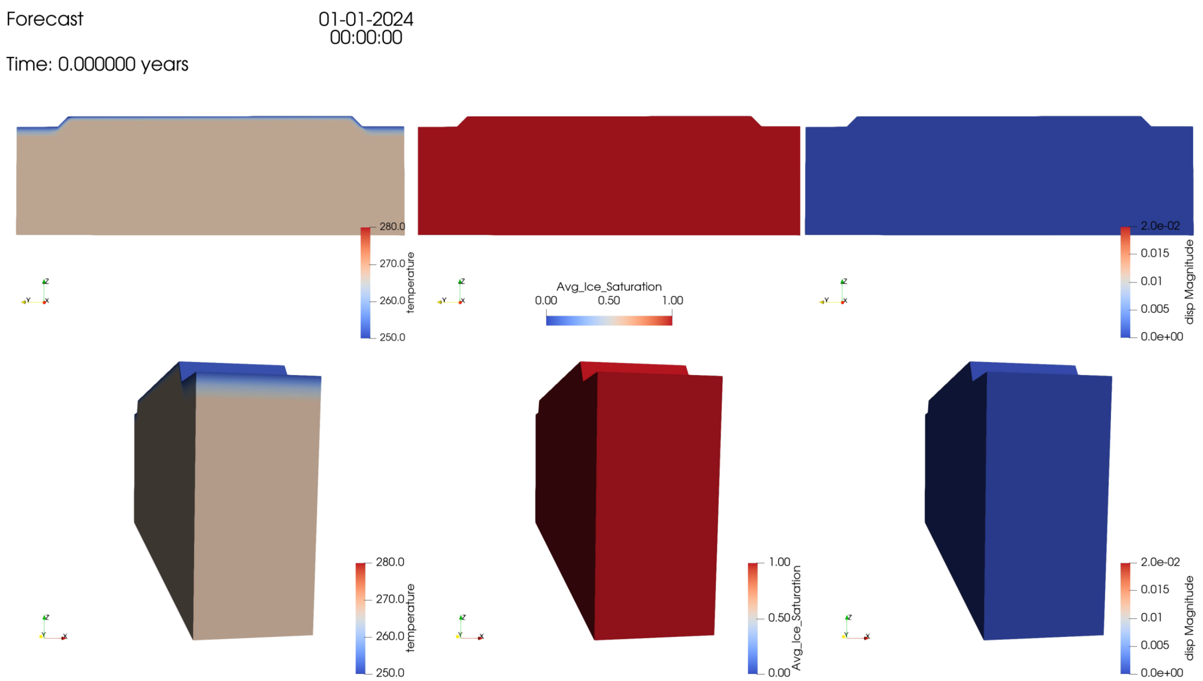
Ice wedge parallel to runway



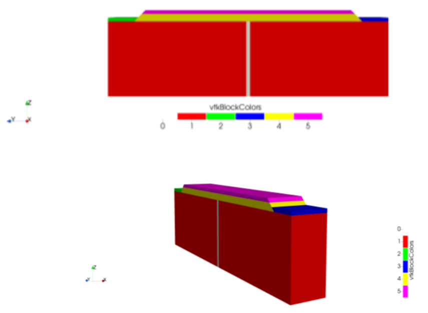
Hindcast: ~5 mm settlement
Forecast: ~6 mm settlement



Ice wedge perpendicular to runway



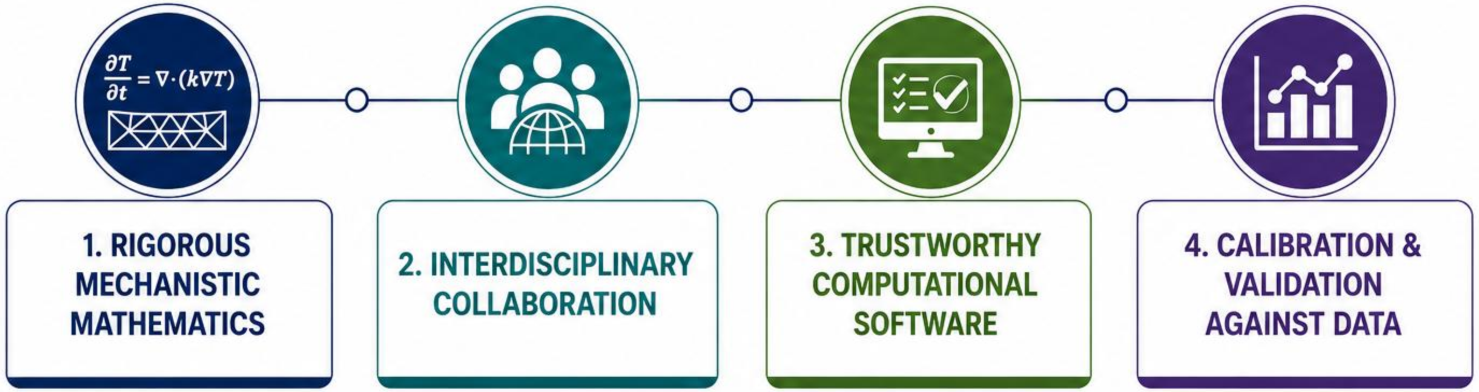
Hindcast: ~18 mm settlement
Forecast: ~20 mm settlement



E. Bayat *et al.*, 2025

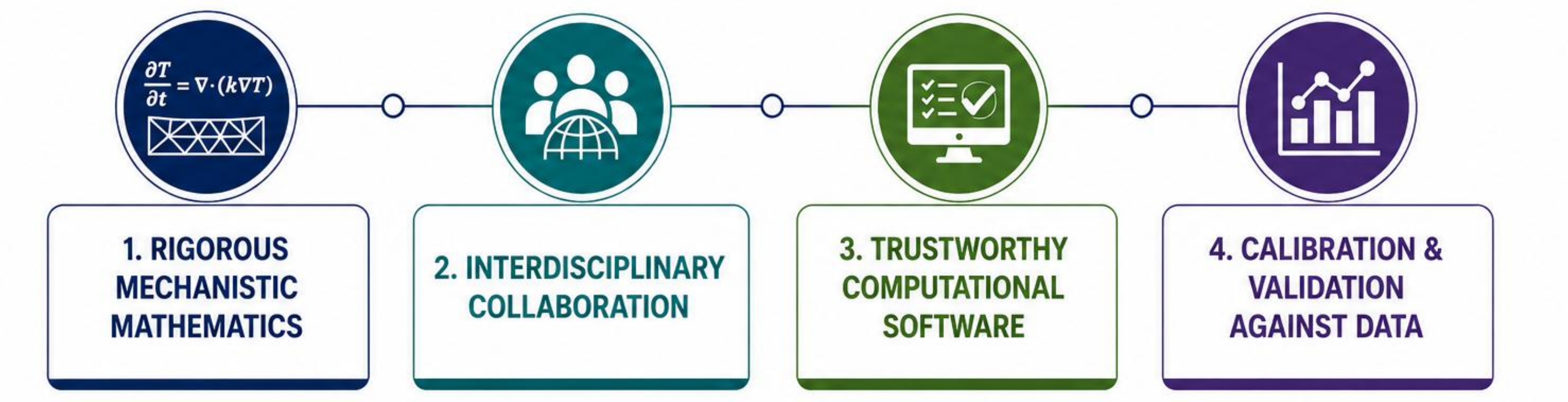
Arrows show permafrost deformation vectors.

Conclusions & take-aways



Conclusions & take-home message

The development of ACE highlights the **essential** role of **rigorous mechanistic modeling** and **interdisciplinary collaboration** in predictive Earth system modeling and beyond.



- **Rigorous mechanistic mathematical** models based on fundamental principles are critical to reliable predictions
- **Interdisciplinary collaborations are crucial**: mathematicians must work together with computer scientists, domain scientists and experimentalists in building models
- **Software quality practices** and **method verification** are essential when developing models
- Computational models should be **calibrated** and **validated** using **experimental** and **observational data** when possible

References from our group

Sandia National Laboratories

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

[2] 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.

[3] J. Frederick, A. Mota, D. Bull, I. Tezaur. “Thermo-chemo-mechanical coupling for Arctic Coastal Erosion”, J. Comput. Appl. Math. 397 113533, 2021.

[4] 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.

[5] E. Bayat, D. Bull, J. Frederick, A. Mota, B. Jones, I. Tezaur, C. Flanary, E. Bristol, M. Ward Jones, C. Choens, C. Jones. “The Arctic Coastal Erosion Model: Overview, Developments and Calibration at Drew Point, Alaska”, *Journal of Advances in Modeling Earth Systems*, 18(3) e2025MS05045, 2026.

This talk.

[6] E. Bayat, D. Bull, J. Frederick, A. Mota, I. Tezaur. “Arctic Critical Infrastructure. Assessing and Predicting the Risk to Critical Permafrost Infrastructure from Climate Change: A New Thermomechanical Approach”, Sandia National Laboratories Report, SAND2024-12315R, 2024.

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Thank you!
Questions?

Nimbus Horizon

Start of Backup Slides

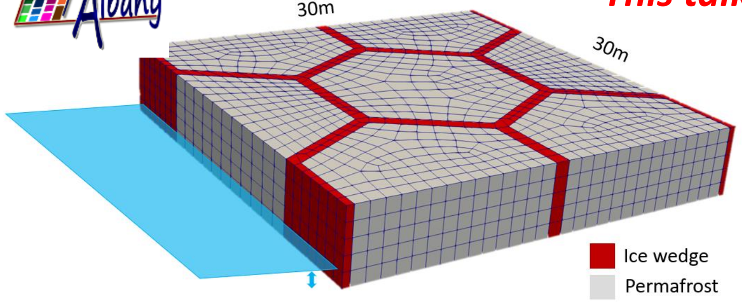
Proposed solution: multi-scale approach

INTERFACE

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**

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

This talk



Micro-Scale Model

10's of meters & storm duration

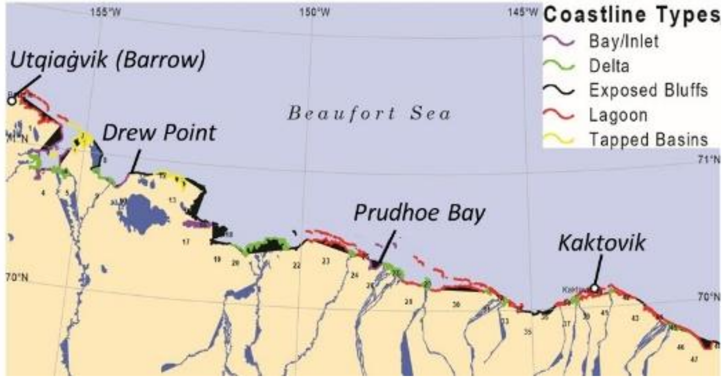
One set of input variables defining the geomorphology and geophysics of the terrestrial model.

- 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

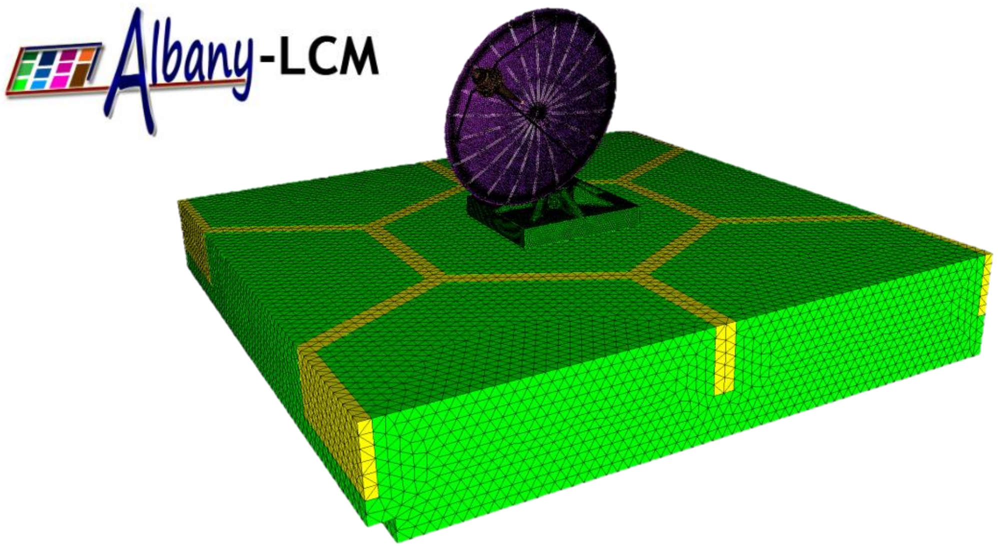
Extension to Arctic Critical Infrastructure (ACI) modeling

<u>Motivation</u>: "Nearly **4 million people** and **70%** of current **infrastructure**" [Hjort, 2018] situated on **Arctic permafrost** is **at risk** as permafrost continues to thaw!


From newsweek.com.

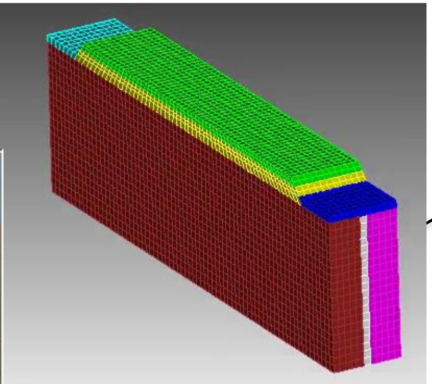
Goals of ACI project:

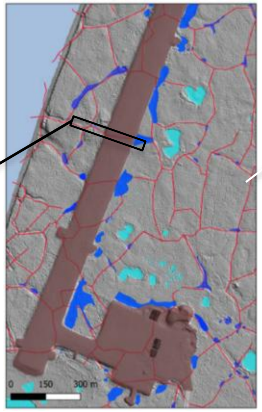
- Introduce a **novel computational** framework based on the **ACE thermo-mechanical terrestrial model** to **estimate** and **predict** risk to **Arctic infrastructure**.
  - ➢ Since ACE is a FEM code, it is **straightforward** to put **infrastructure** on top of permafrost in simulation (bottom right)
  - ➢ ***Easier than ACE***: not targeting infrastructure right on coast, so no block failure, **only subsidence**
- Explore a variety of **infrastructure-permafrost combinations**, their **failure mechanisms** and possible solutions to **decrease risk**

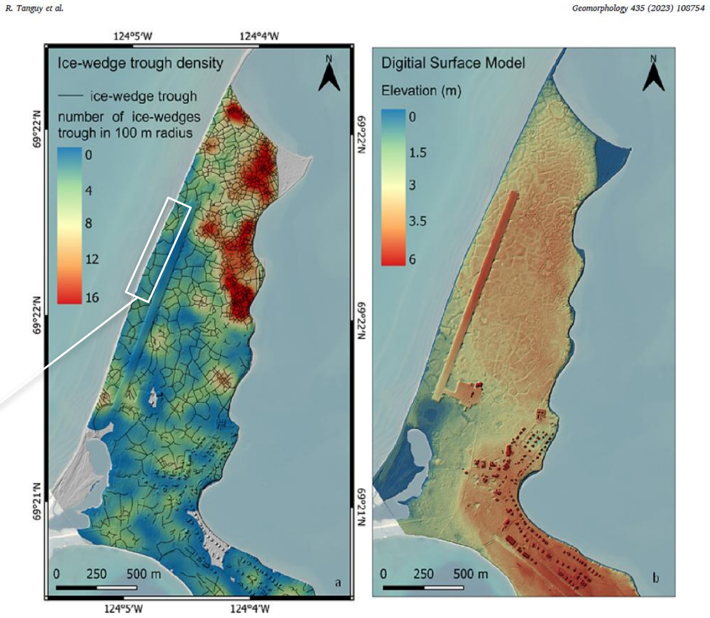


ACI demonstration: Paulatuk peninsula airstrip

Tanguy, R. et al. (2023) Permafrost degradation in the ice-wedge tundra terrace of Paulatuk Peninsula (Darnley Bay, Canada), Geomorphology, 435, 108754.

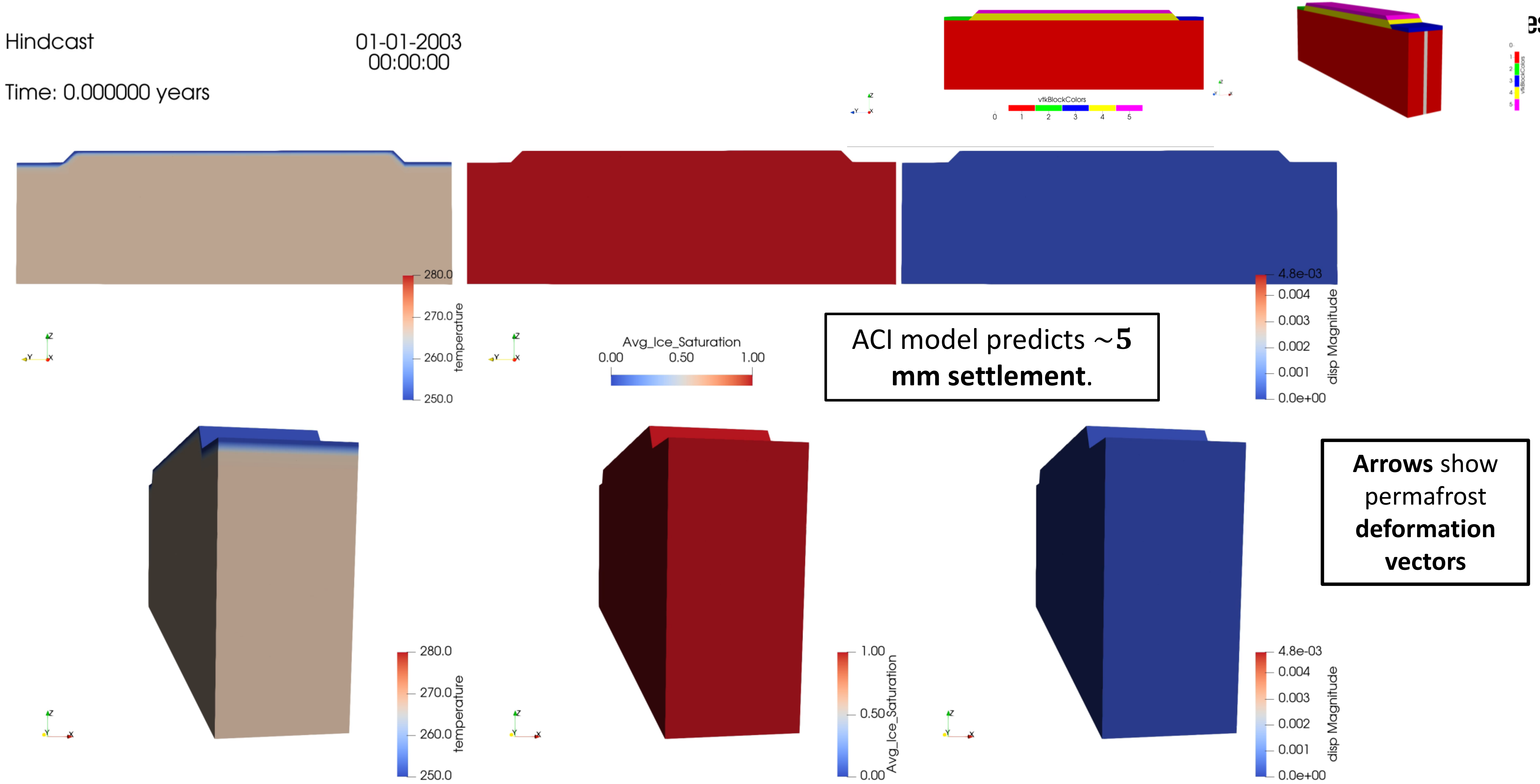






- Located within the Inuvialuit Settlement Region of the Amundsen Gulf, south Darnley Bay, in **northern Canada**.
  - ➢ Permafrost characteristics are **similar** to those from Drew Point, Alaska.
- Airstrip is **1.3 km long** and **55 m wide**, with a mean **altitude of 4.2 m**, artificially installed over a **~2 m thick gravel pad** overlying the tundra and **numerous ice-wedge troughs**.
- Airstrip slopes towards a depression with a maximum angle of 0.37°, suggesting that **subsidence** is occurring
  - ➢ **Snow accumulation** at side of airstrip acts as insulator and prevents ground from cooling ⇒ melting of snow causes **thaw-ponds**, which **retain heat** from solar radiation ⇒ **downward heat diffusion** from ponds induces **permafrost degradation** and **subsidence** [Allard et al., 2020].

Hindcast: ice wedge parallel to runway direction



ACI model predicts ~**5 mm settlement**.

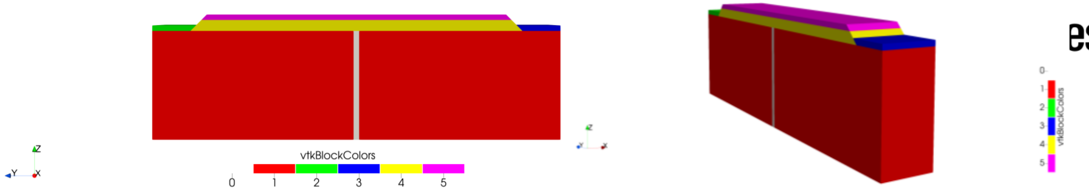
Arrows show permafrost **deformation vectors**

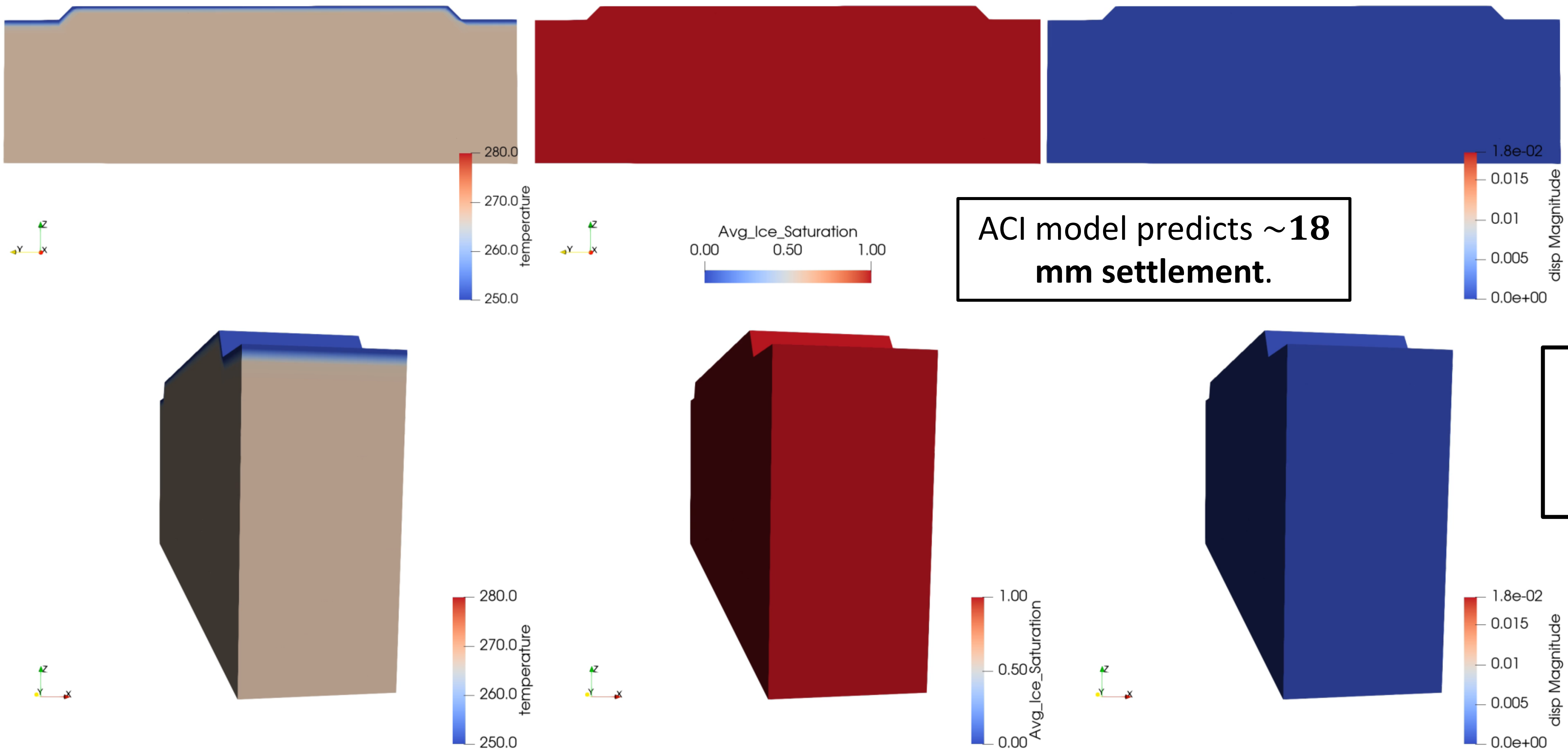
Hindcast: ice wedge perpendicular to runway direction

Hindcast

01-01-2003
00:00:00

Time: 0.000000 years

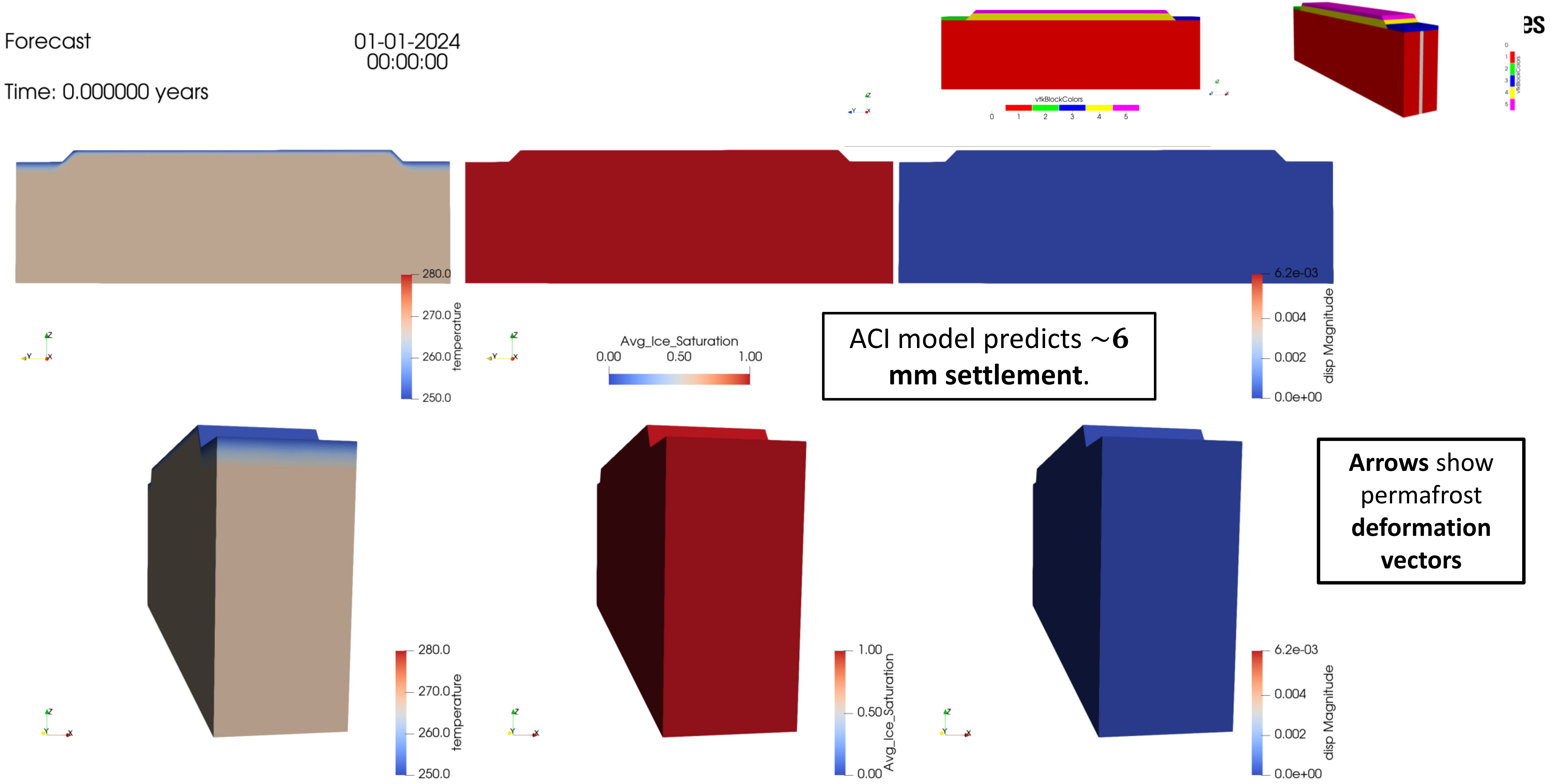




ACI model predicts ~**18 mm settlement**.

Arrows show permafrost **deformation vectors**

Forecast: ice wedge parallel to runway direction



ACI model predicts ~**6 mm settlement**.

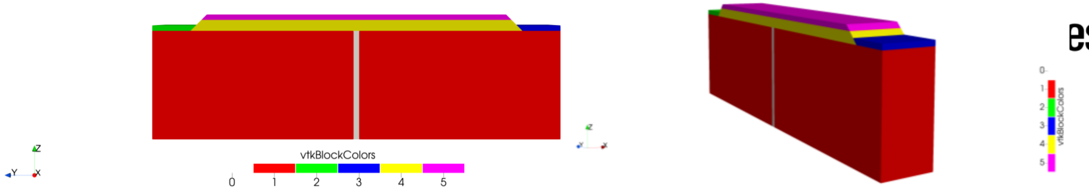
Arrows show permafrost **deformation vectors**

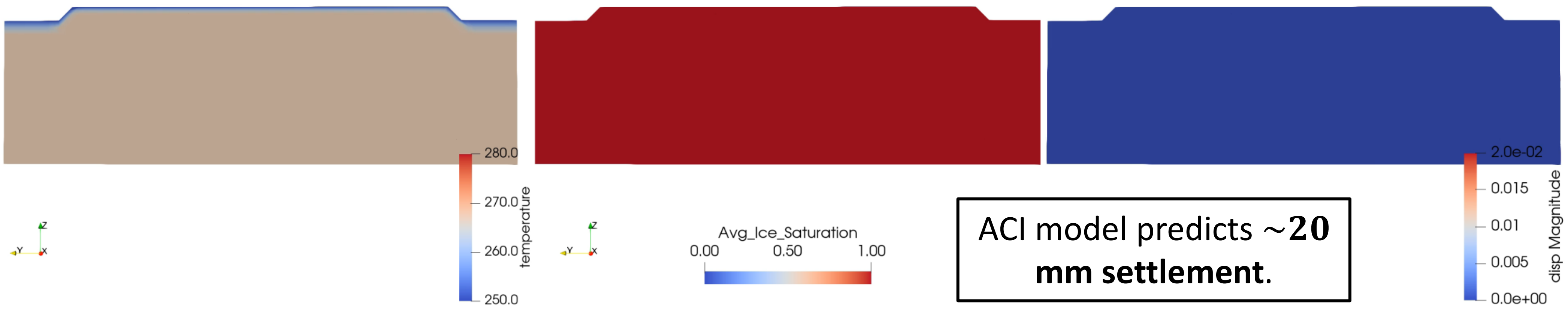
Forecast: ice wedge perpendicular to runway direction

Forecast

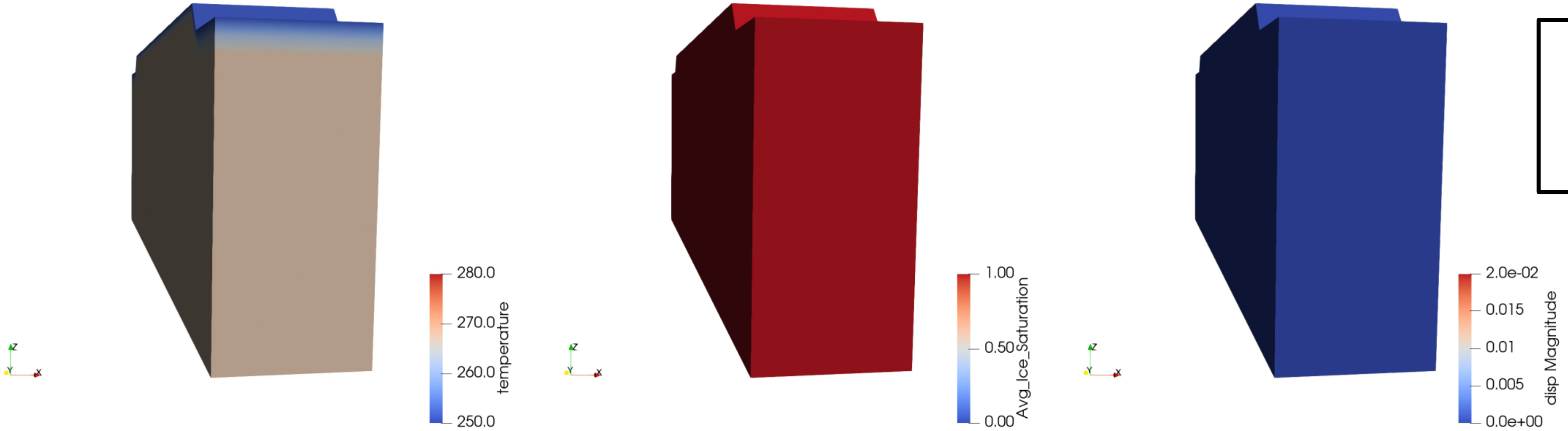
01-01-2024
00:00:00

Time: 0.000000 years





ACI model predicts ~**20 mm settlement**.



Arrows show permafrost **deformation vectors**

Other references

[6] 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.

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[8] 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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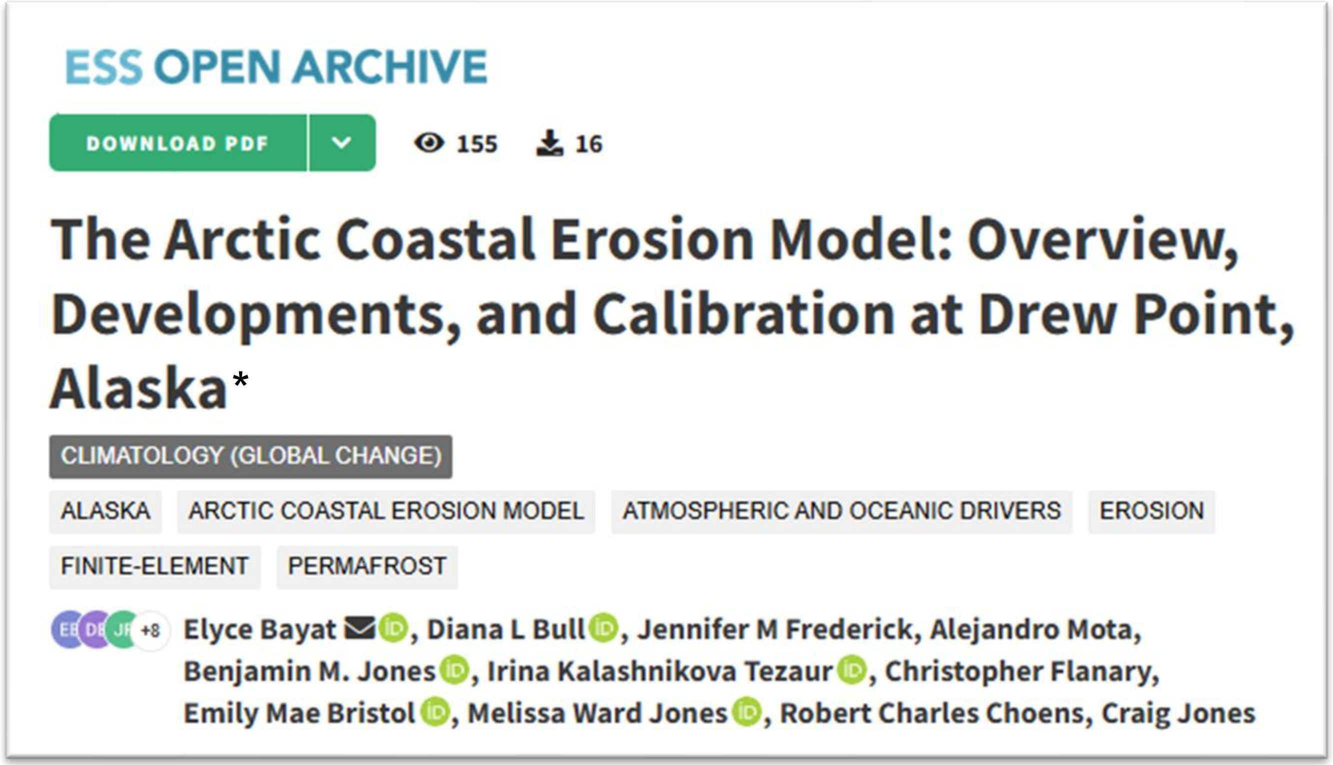
[10] T. Ravens, B. Jones, J. Zhang, C. Arp, J. Schmutz. “Process-based coastal erosion modeling for Drew Point, North Slope, Alaska”. Journal of Waterway, Port, Coastal, and Ocean Engineering, 138, 2, 122-130, 2012.

[11] 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.

Main takeaways from Drew Point 2.5D slice study

- The calibrated ACE model ***matches total magnitudes of erosion*** w.r.t. camera measurements:
  - 12.5% error for ***thermo-denudation***
  - 5.06% error for ***block failure***
- The ***temporal evolution*** also matched camera measurements:
  - A ***daily RMSE*** of 0.16 m was achieved for ***denudation*** → ***shows that ACE correctly predicts erosion rate, not just total erosion at end of summer***
  - **Block failure** occurred within **2 days** of the observed
- ACE predicted ***reasonable agreement*** between modeled and observed ***ground temperatures***, with highest deviations between 1.5-2 K



Results suggest that the ***calibrated ACE model*** possesses ***sufficient physics*** such that it is capable of ***predicting permafrost erosion rates.***

* https://essopenarchive.org/doi/full/10.22541/essoar.174086594.45589925/v1

Main takeaways from Paulatuk airstrip study

- $> 3 \times$ **more settling** occurs when **ice wedge** is **perpendicular** (vs. parallel) to the runway direction.
- Slightly **more settling** occurs in **forecast** runs than hindcast
  - Prescribed warming is **intermediate** (RCP 3.7)
  - More settling expected for **higher warming/emissions scenario**, RCP 8.5.
- ACE model is **well-poised** to simulate **permafrost** & **infrastructure interaction**, as **material mechanical** model is responsive to permafrost **thermal state** and **weather drivers** (e.g., atmospheric temperature)

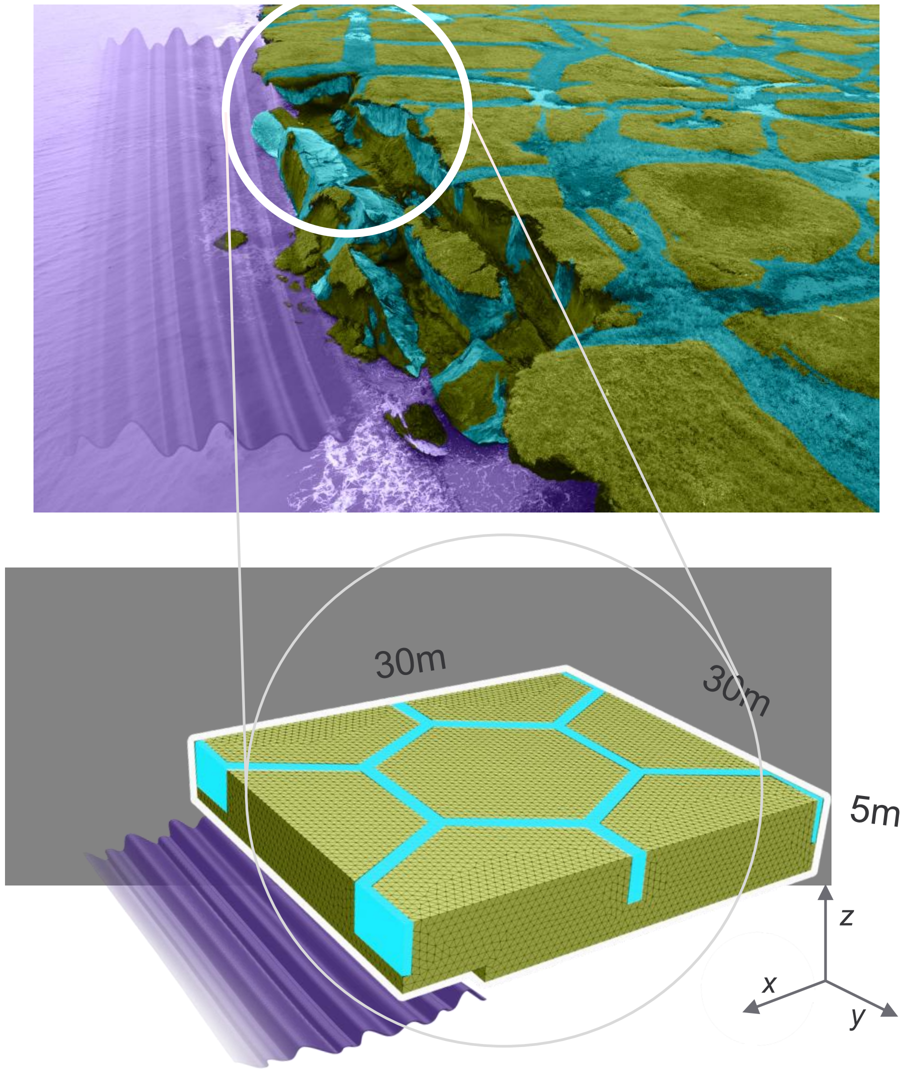
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT
WHERE INNOVATION BEGINS

LDRD PROJECT NUMBER: **24-1155**
LDRD PROJECT TITLE: Arctic Critical Infrastructure. Assessing and Predicting the Risk to Critical Permafrost Infrastructure from Climate Change: A New Thermomechanical Approach
PROJECT TEAM MEMBERS: Elyce Bayat (8931), Diana Bull (8931), Jennifer Frederick (8931), Alejandro Mota (8363), Irina Tezaur (8734)

* https://www.sandia.gov/app/uploads/sites/127/2024/09/ACI-LDRD-report-SAND2024-12315R.pdf

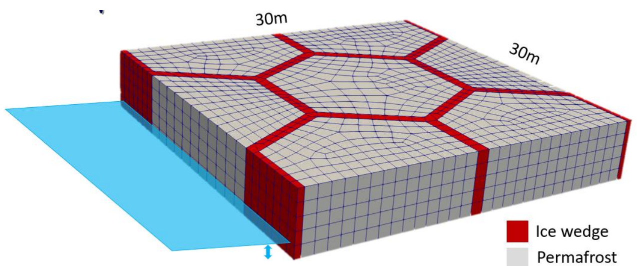
Summary

- We have developed a ***thermo-mechanical*** coupled FEM model, ***ACE***, that can simulate ***transient niche development*** and ***permafrost erosion*** within Albany-LCM.
- The model was ***calibrated*** using data from a series of ***experiments*** on frozen soil samples and ***observational data*** collected from Drew Point, Alaska
- The model incorporates ***boundary conditions*** from the ***WW3+SWAN+Delft3D*** wave models and observational data from field campaigns at Drew Point.
- We have ***validated*** ACE using observational data from Drew Point collected in summer 2018.
- We have started to use the ACE terrestrial model to perform assessments of ***critical infrastructure*** situated on top of permafrost.



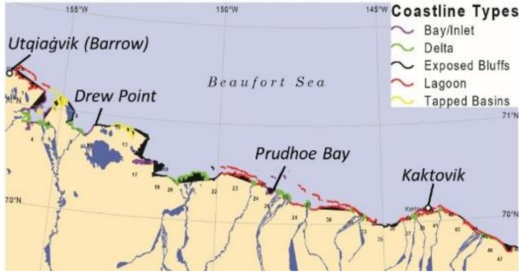
Current and future work

- **InterFACE project: upscale** ACE terrestrial model to meso/macro scales for E3SM* integration
  - Upscaling will be performed from **"catalog"** of 6-7 ACE runs for different terrestrial configurations/locations in northern Alaska
  - **Proposal** submitted to develop **universal constitutive model** using **synthetic permafrost samples**



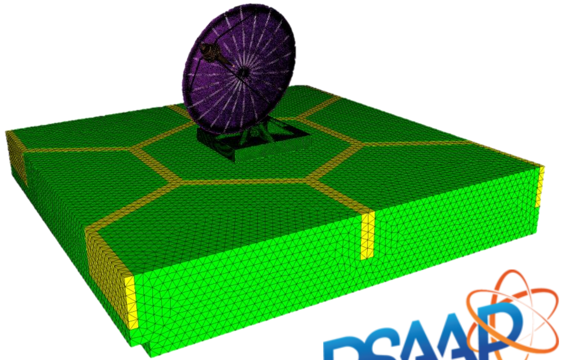
Micro-scale (ACE) model
10s of m, storm duration

Meso-scale model
10s of km, monthly duration



Macro-scale model
100s of km, annual+ duration

- **Arctic Critical Infrastructure (ACI) project:**
  - Use ACE/ACI to study **alternate permafrost-infrastructure configurations** (tanks, pilons, etc.)
  - Develop/integrate **finite deformation cap plasticity model** into ACE (with Prof. R. Regueiro, UC Boulder)
    - Incorporates **volumetric** (or pressure-sensitive) **plasticity**



Nimbus Horizon

* Energy Exascale Earth System Model, the U.S. Department of Energy's flagship climate model.