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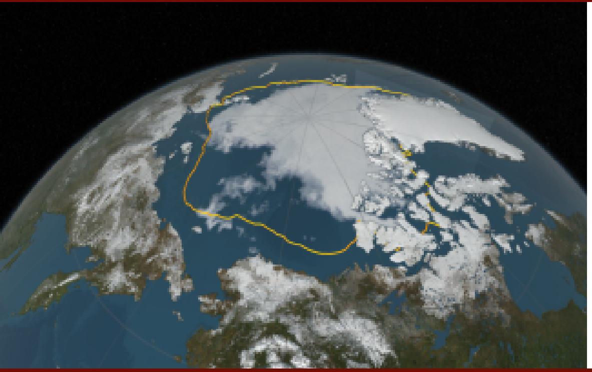
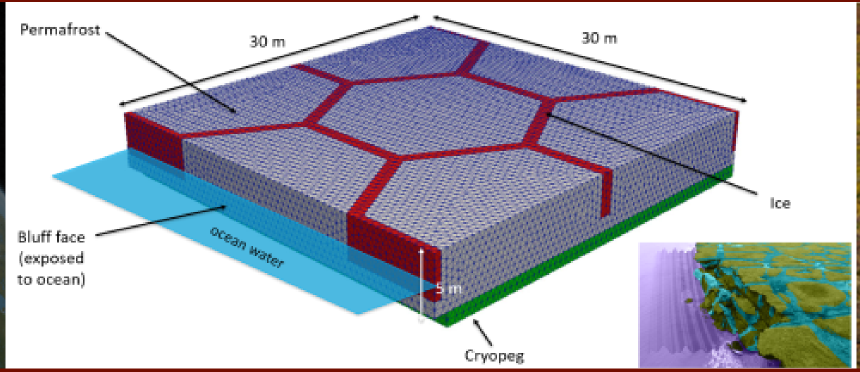
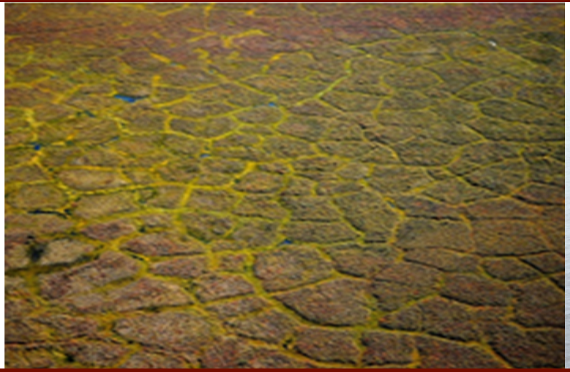
Exceptional service in the national interest







Development of the Arctic Coastal Erosion Model with a Demonstration at Drew Point, AK

Jennifer M. Frederick[1], Diana Bull[1], Alejandro Mota[1], Irina K. Tezaur[1], Benjamin Jones[2], Emily Bristol[3], Robert C. Choens[1], Chris Flanary[4], Craig Jones[4], and Melissa Ward Jones[2]

1 Sandia National Laboratories, U.S.
2 University of Alaska, Fairbanks, U.S.
3 University of Texas at Austin, U.S.
4 Integral Consulting, Inc., U.S.

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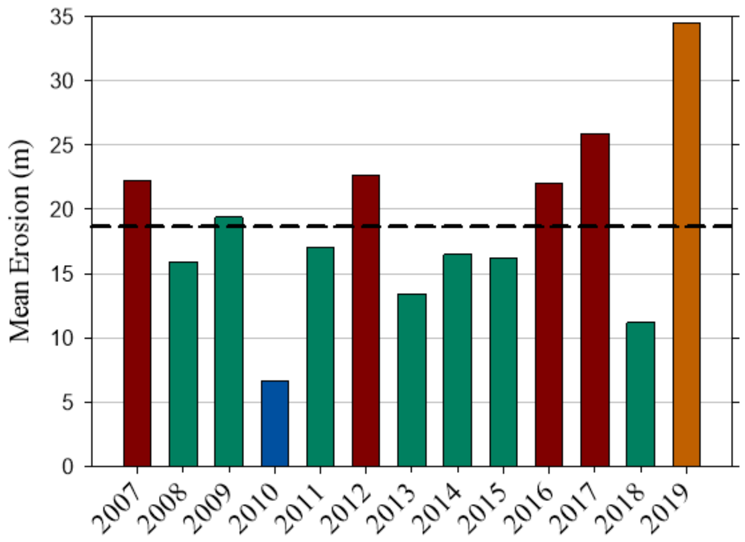
Motivation

The Arctic is warming at **4 times** the rate of the global average resulting in **accelerated rates of coastal erosion**!

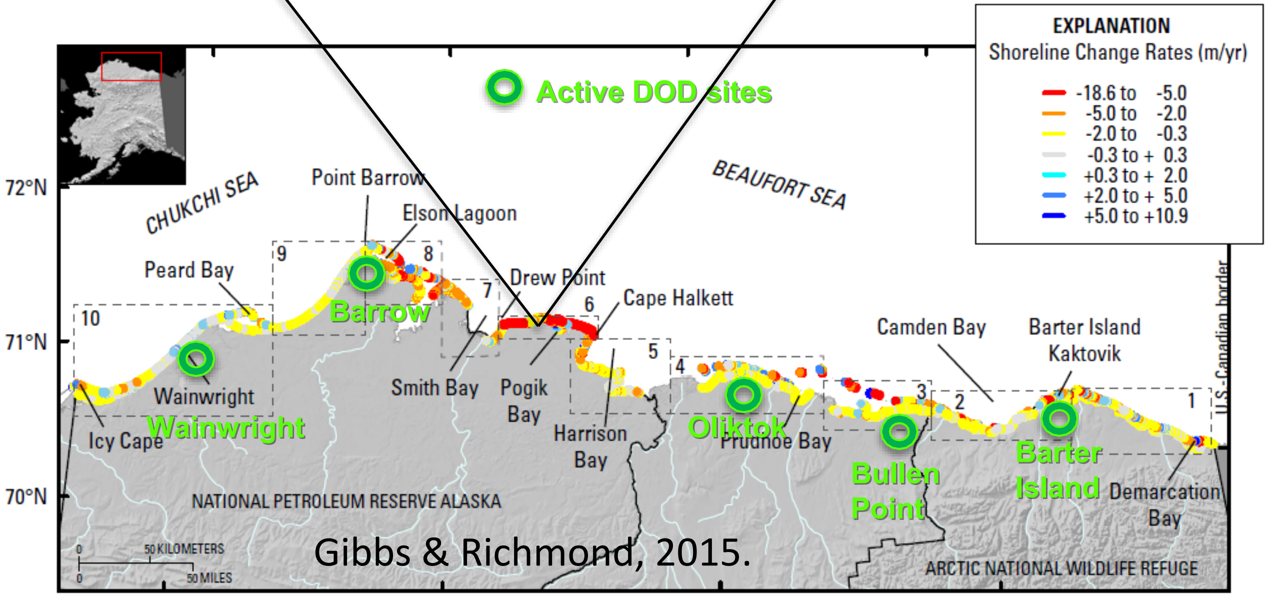
- Primary culprit is **loss of Arctic sea ice**: since 1979 sea ice has lost 51% in area and 75% in volume
  - ➢ Increasing **ice-free season**
  - ➢ Increasing **wave energy** and **storm surge**
  - ➢ Increasing **sea water** temperatures

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).



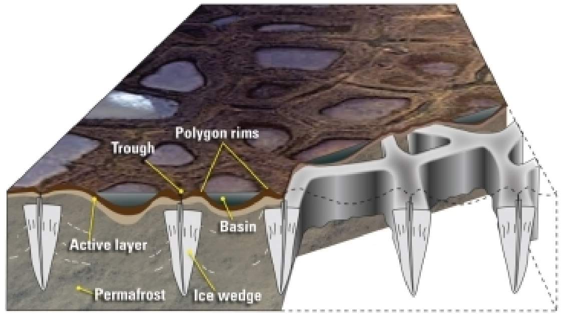
Certain locations lost >250 m b/w 2007-2019!



Permafrost Thaw & Erosion

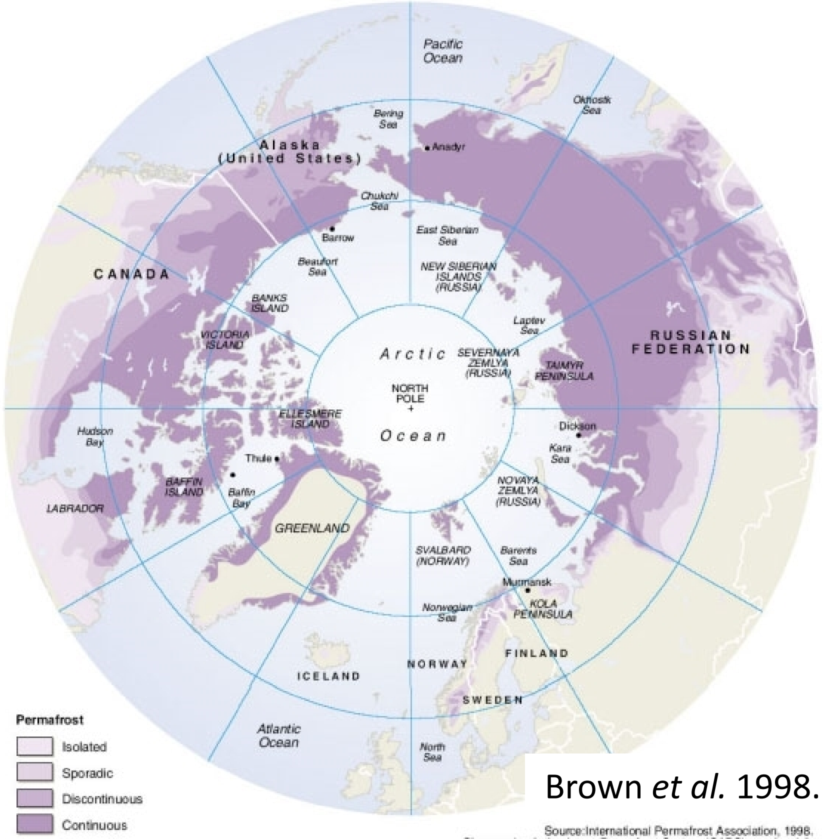
What is permafrost?

- Ground that remains frozen for 2+ consecutive years.
- 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.



Polar Media Archive

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



Brown *et al.* 1998.

Source: International Permafrost Association, 1998. Circumpolar Active-Layer Permafrost System (CAPS), version 1.0.


Martin *et al.* 2009.

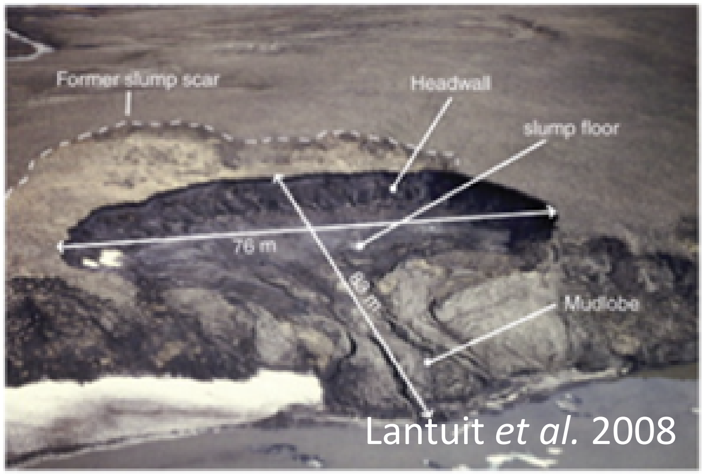
Unique coastal permafrost erosion process in Arctic:

- Predominant geomorphology: **ice-wedge polygons**
  - ➢ Ice acts to **bind** unconsolidated soils in permafrost.
  - ➢ Ice wedges **grow/expand** up to 10s meters wide and deep.
  - ➢ Permafrost thaw can cause subsidence, slumping, **weakening**.

Coastal Permafrost Failure Mechanisms

Sandia National Laboratories

- **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].
  - ➢ 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.

Coastal Permafrost Failure Mechanisms

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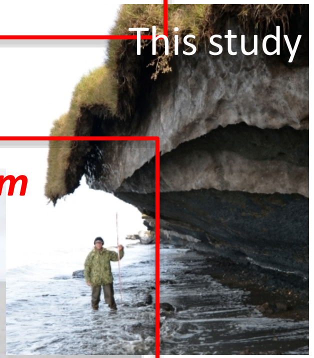
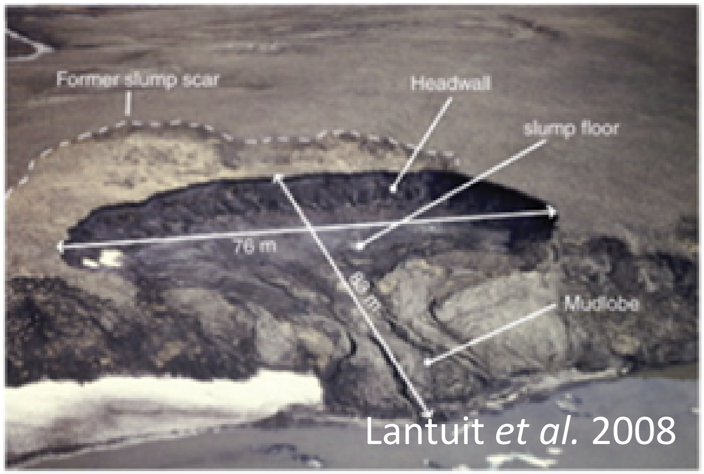




Retrogressive thaw slumping

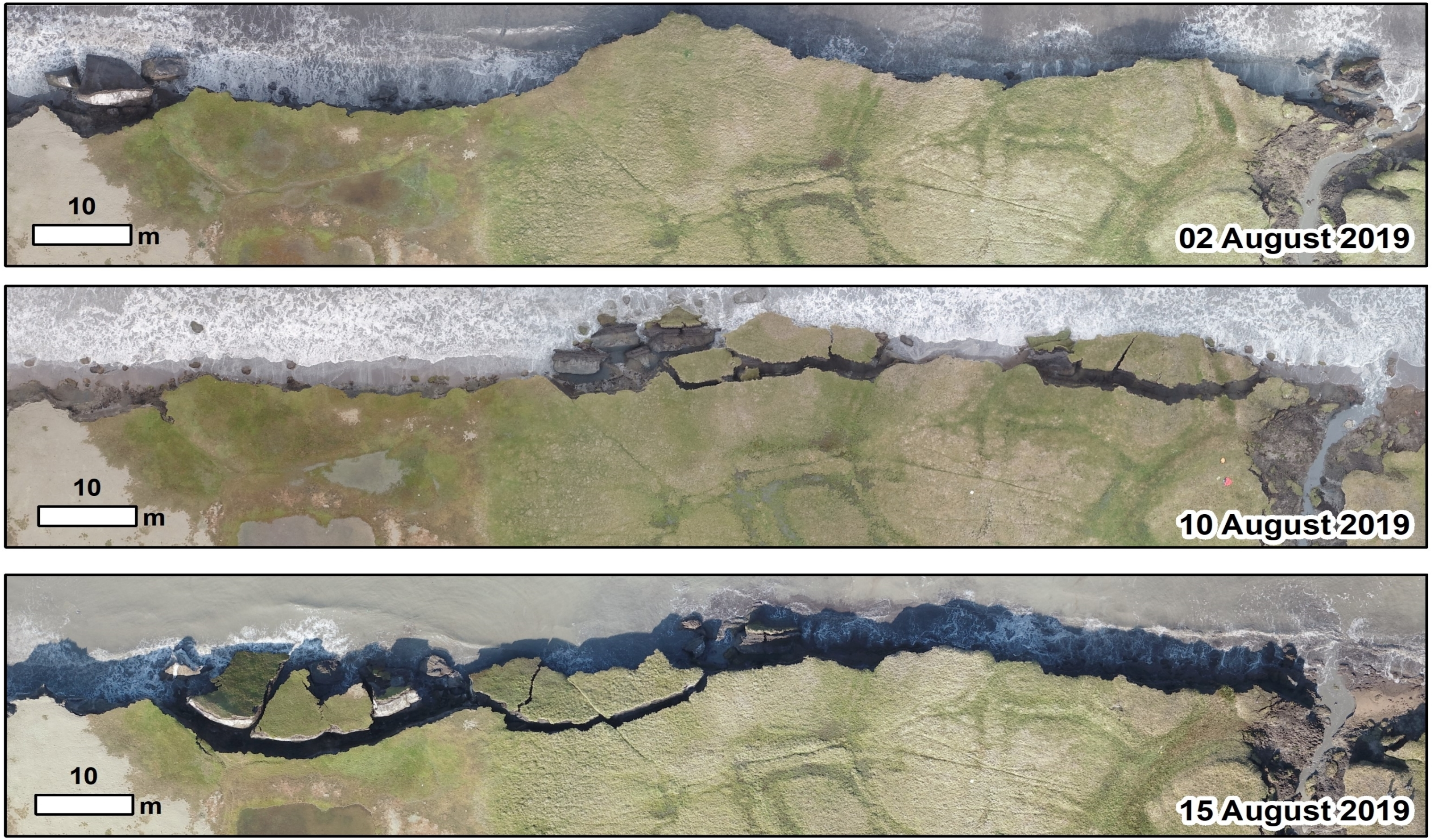
Active layer detachment

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.

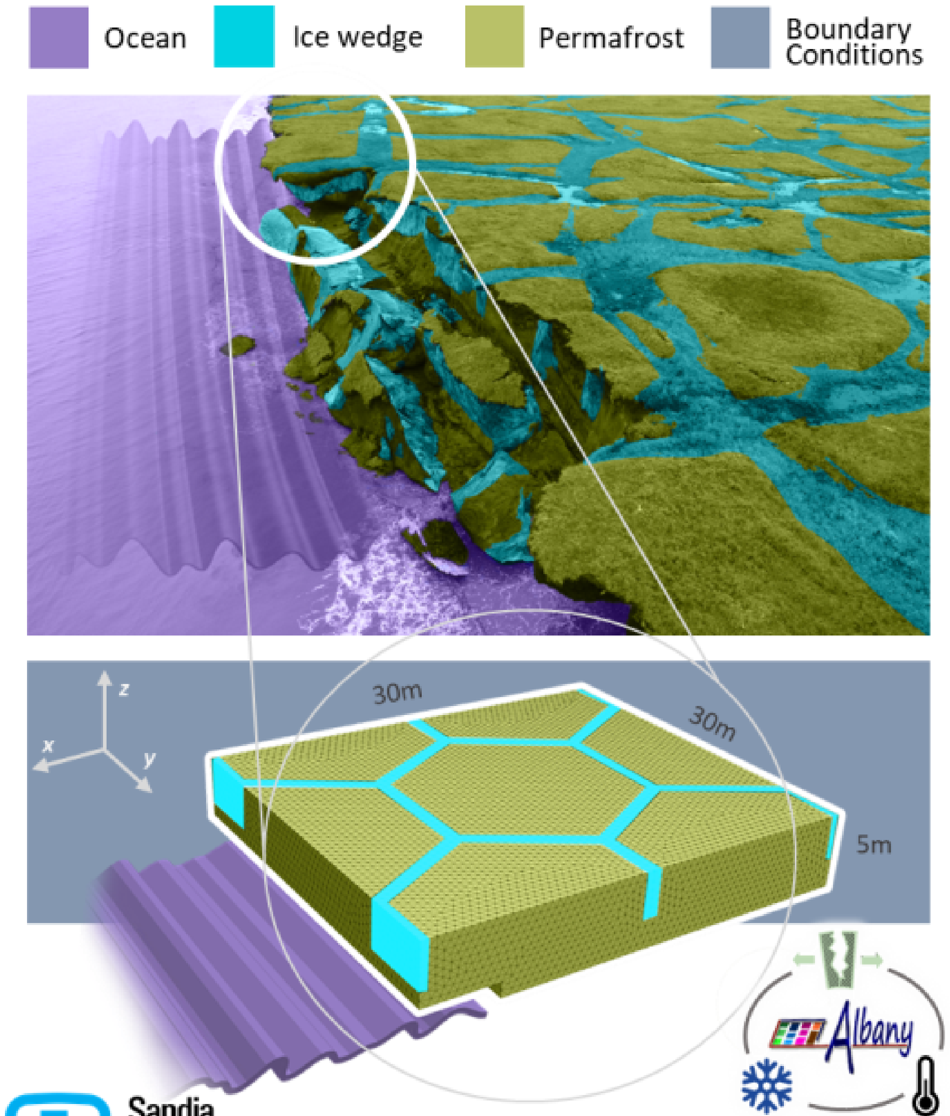
Example of Bluff Erosion During 2019 UAV Surveys*



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

*Images courtesy of Ben Jones, UAF

Arctic Coastal Erosion (ACE) Model



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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

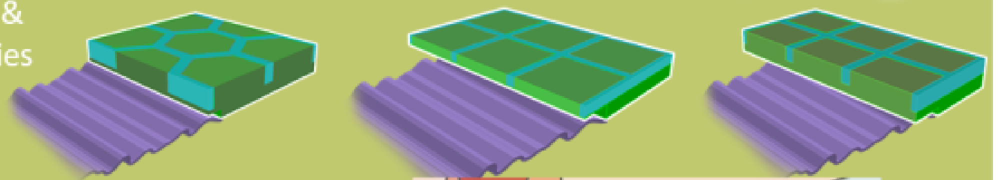
Terrestrial \ Terrestrial

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

Mechanical: finite deformation plasticity model

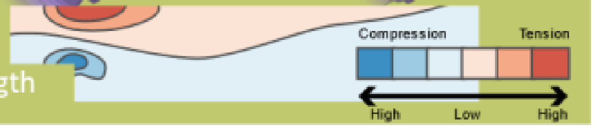
Thermal: transient temperature and ice saturation evolution

Geomorphology & Material Properties



Strength Properties

Material: ice content determines strength

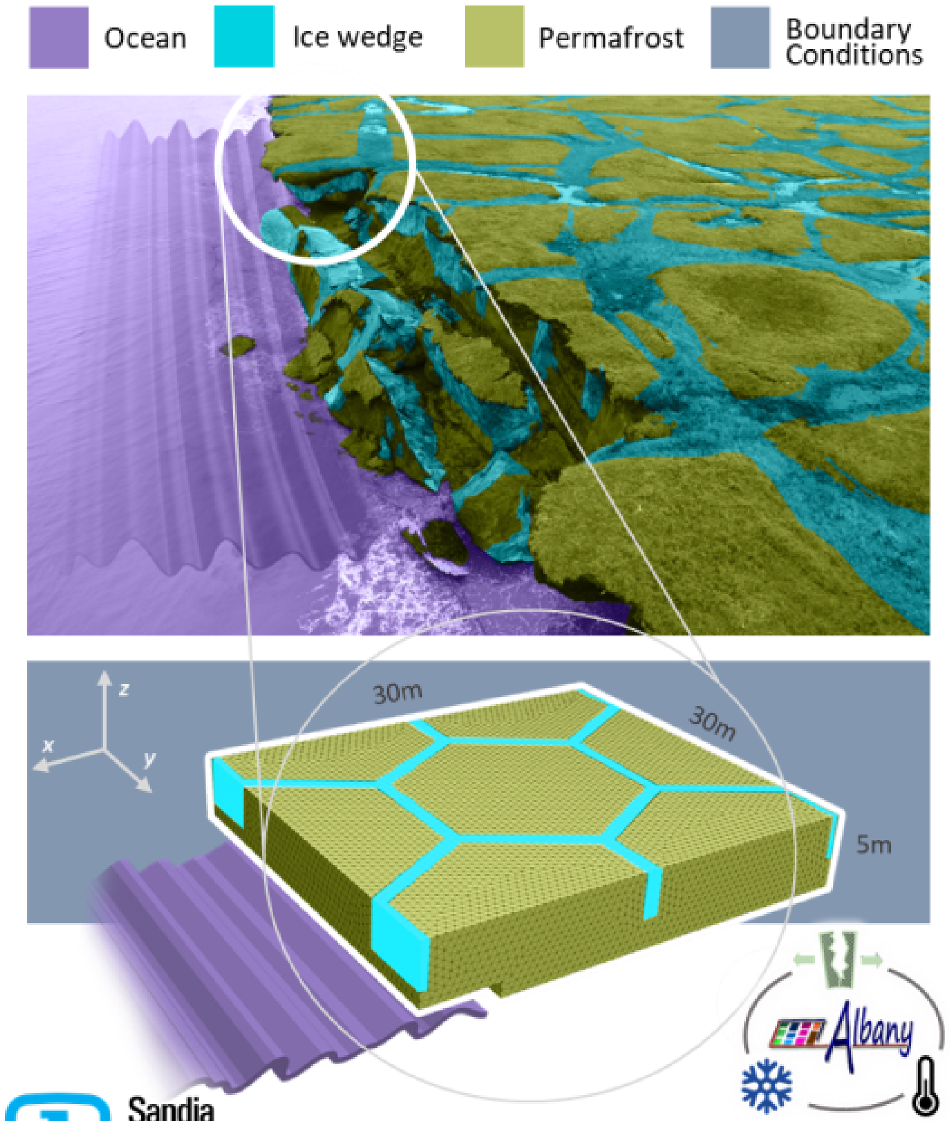


Ocean

Circum-Arctic: wave energy

Nearshore: coupled wave & circulation

Arctic Coastal Erosion (ACE) Model



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This talk

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

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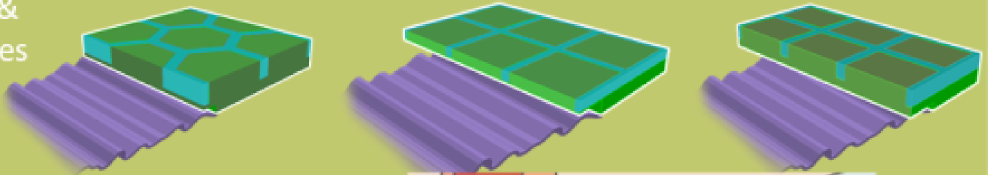

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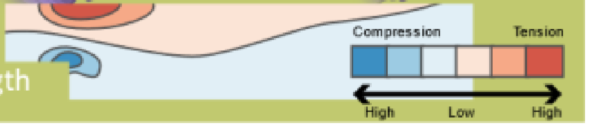
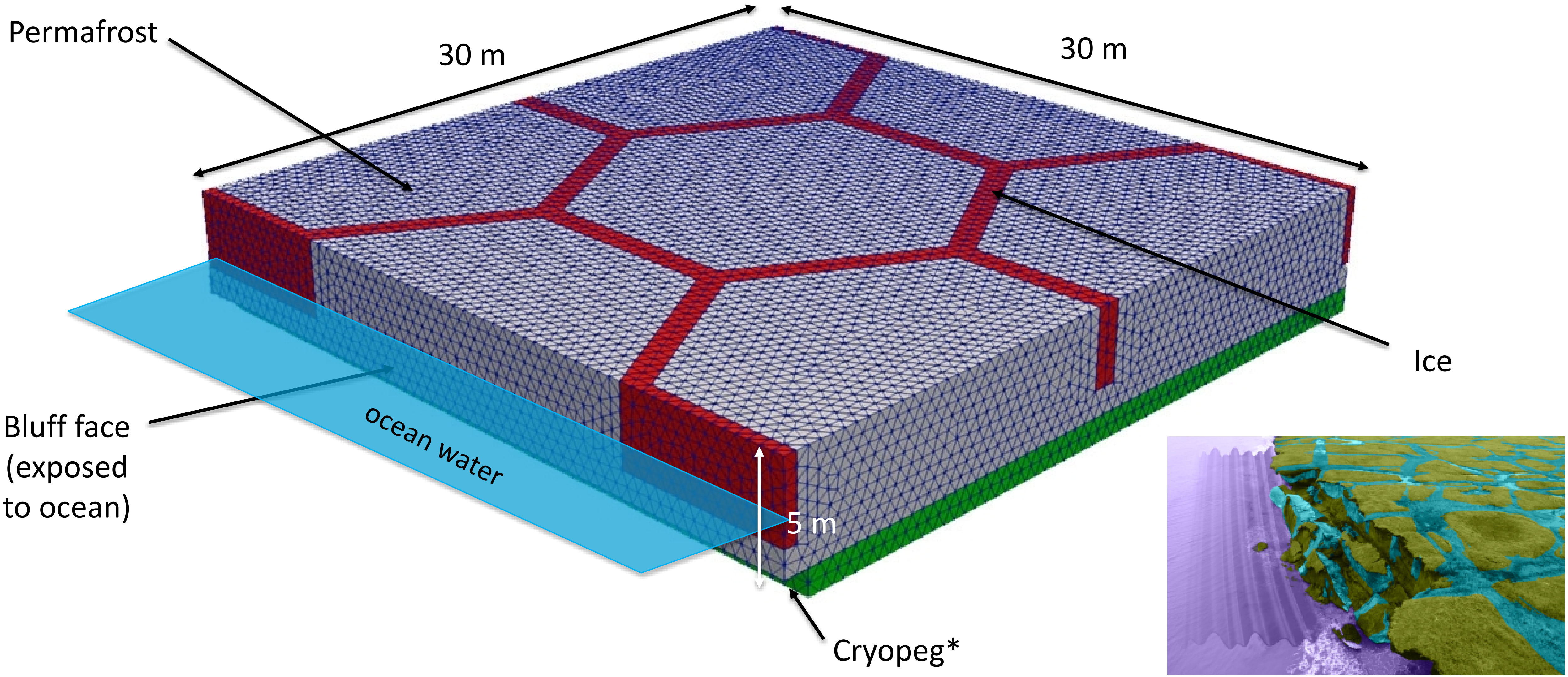


Ocean

Circum-Arctic: wave energy

- Nearshore: coupled wave & circulation

Anatomy of a Canonical Computational Domain



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

Finite Element Implementation Within Albany

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.***
- All software available on ***GitHub***.

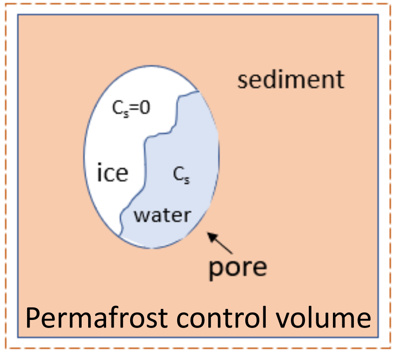
https://github.com/sandialabs/LCM

https://github.com/trilinos/trilinos

Thermal Model

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

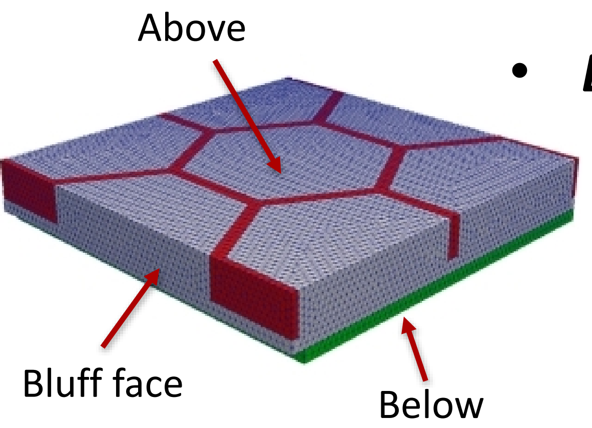
$$(\overline{\rho c_p} + \widetilde{\Theta})\frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{K} \cdot \nabla T)$$



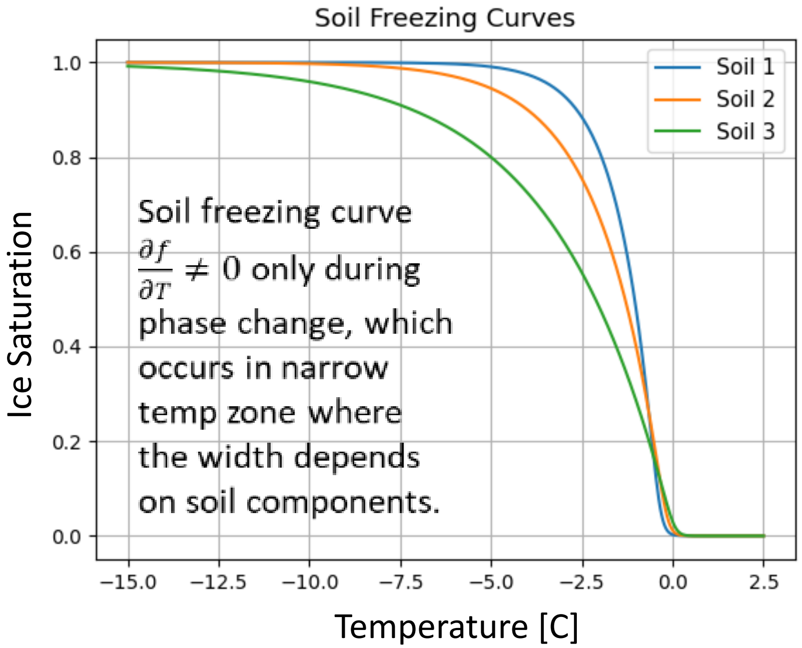
where $\widetilde{\Theta} := \rho_f L_f \frac{\partial f}{\partial T}$ incorporates phase changes through soil freezing curve, $\frac{\partial f}{\partial T}$.

➢ Computes ***temperature*** T and ***ice saturation*** f

$\bar{\rho}$: 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
  - ➢ Mean annual air temp* from above
  - ➢ Air/ocean temp at bluff face
  - ➢ Ocean salinity at bluff face**



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

Mechanical Model

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

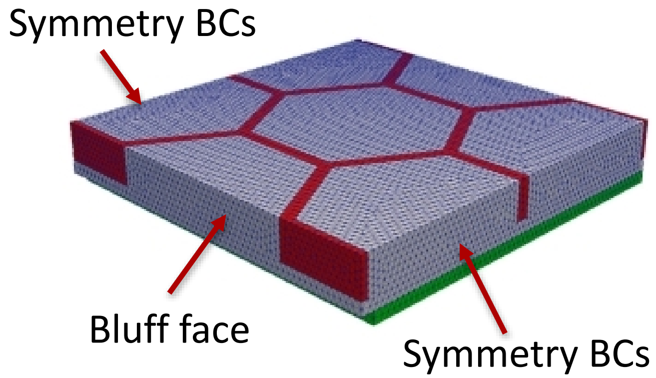
$$\Phi[\boldsymbol{\varphi}] := \int_{\Omega} A(\boldsymbol{F},\boldsymbol{Z})\, dV - \int_{\Omega} \rho \boldsymbol{B}\cdot\boldsymbol{\varphi}\, dV - \int_{\partial_T\Omega} \boldsymbol{T}\cdot\boldsymbol{\varphi}\, dS$$

$A(\boldsymbol{F},\boldsymbol{Z})$: 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; simplest material model w/ plastic behavior.

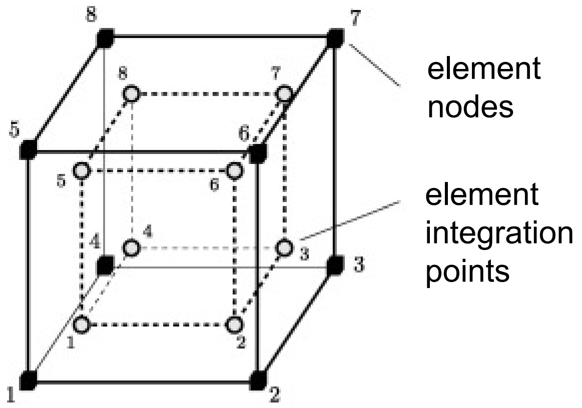
- ***Boundary conditions:***
  - ➢ ***Symmetry BCs*** on lateral sides
  - ➢ ***Wave pressure Neumann BC*** on bluff face* (from wave model).
  - ➢ **Damage variable** on bluff face in contact with ocean (introduces softening due to dissolution)

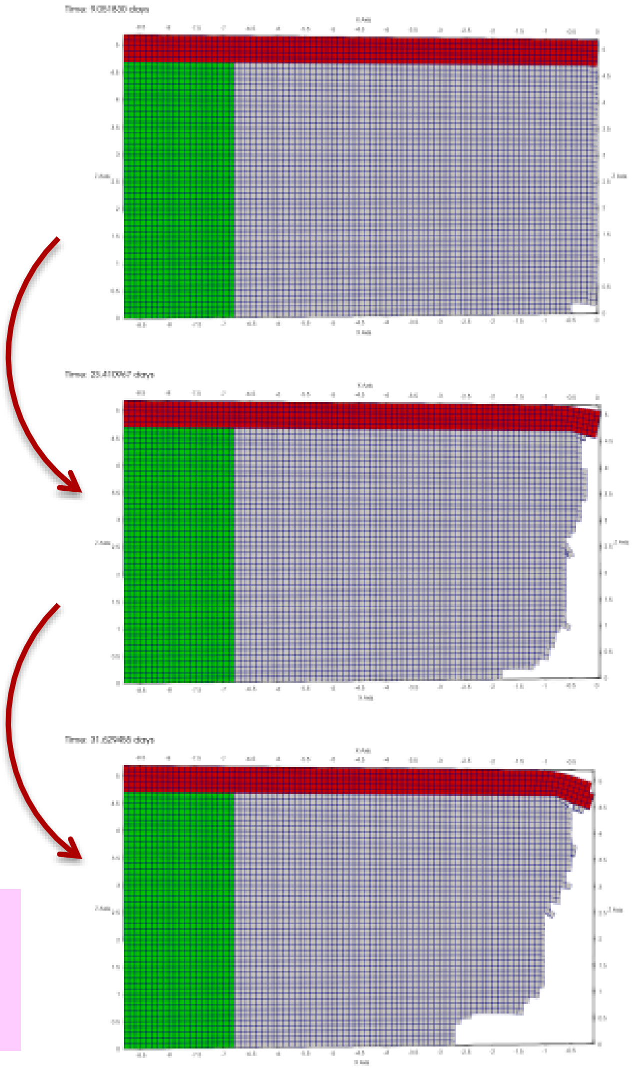


* Holthuijsen 2007.

Erosion Failure Criteria

- **Stress criteria:** 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 criteria:** 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

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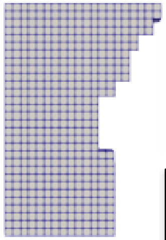
Potential key advantages:

- Failure modes develop from **constitutive relationships** in FEM model (no empirical relationships!)
- 3D unsteady heat flow can include **chemistry**
- Thermal and mechanical problems can be advanced using **different time-steppers** (e.g., implicit-explicit coupling)
- **Tightly coupled** mechanical + thermal states

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

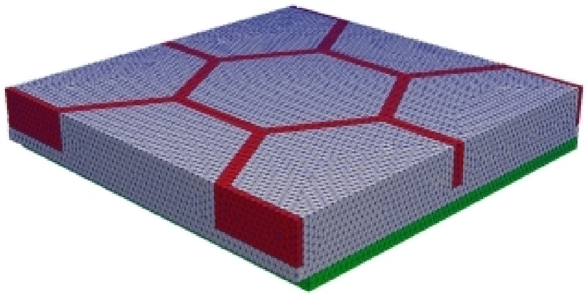


Eroded geometry

Thermal:

Inputs: geometry, sediment type, porosity, salinity

Outputs: temperature field, ice saturation



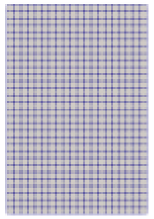
Albany

Ice saturation

Mechanical:

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

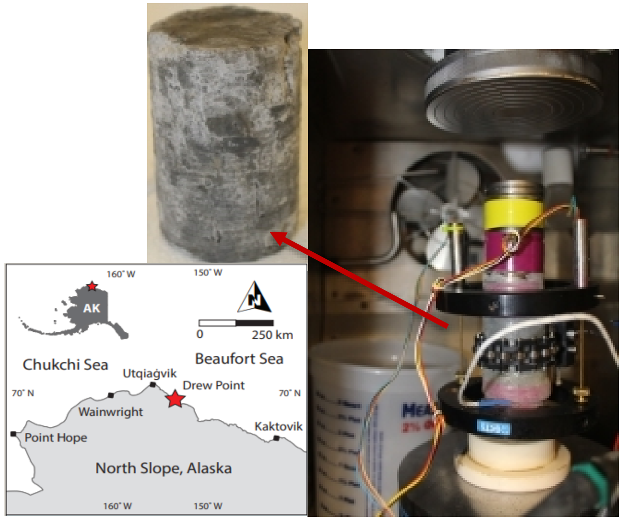
Outputs: displacements, eroded geometry

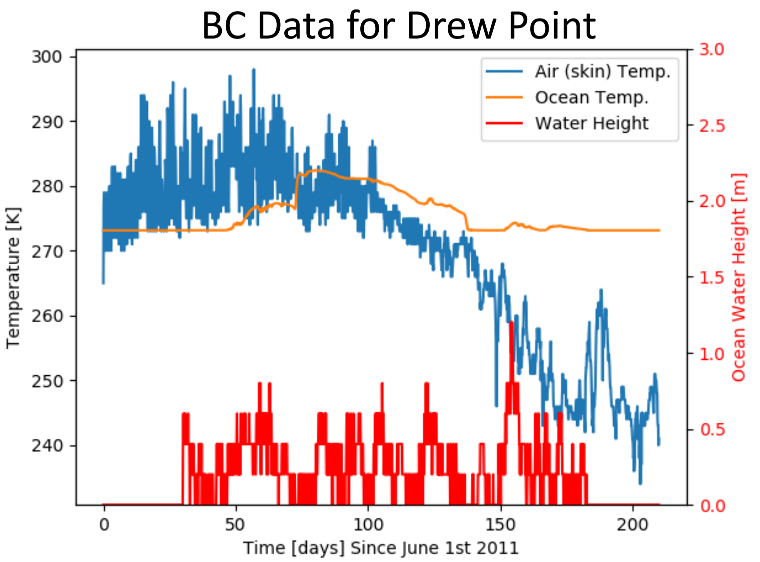


Parameters & Inputs

Parameters estimated from core lab experiments:

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



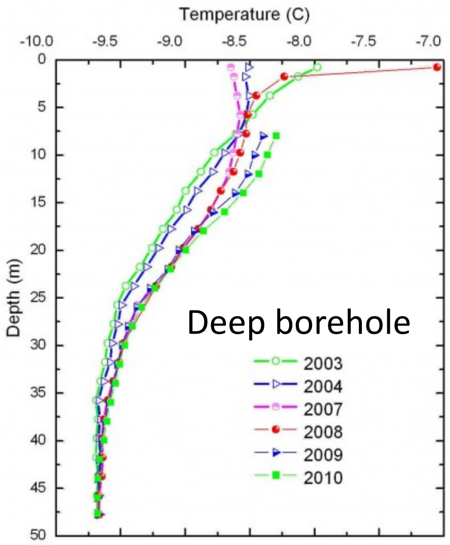


Parameters from literature:

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

Parameters estimated from observational data at Drew Point, 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, organic layer (peat) thickness (Aug. 2019 field campaign)

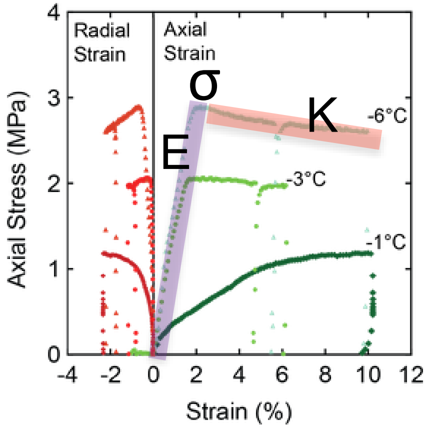


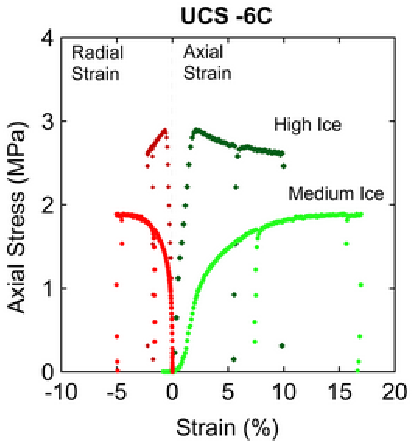
Parameters from wave model (WW3+SWAN+Delft3D):

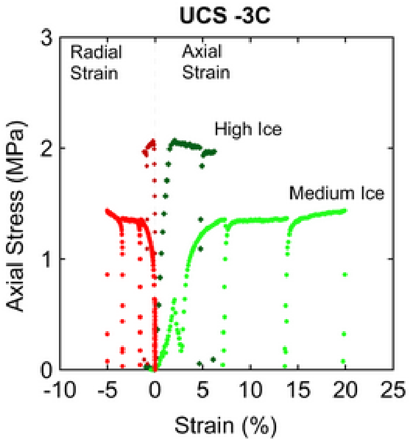
integral consulting inc.

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

Material Model Calibration to Experimental Data



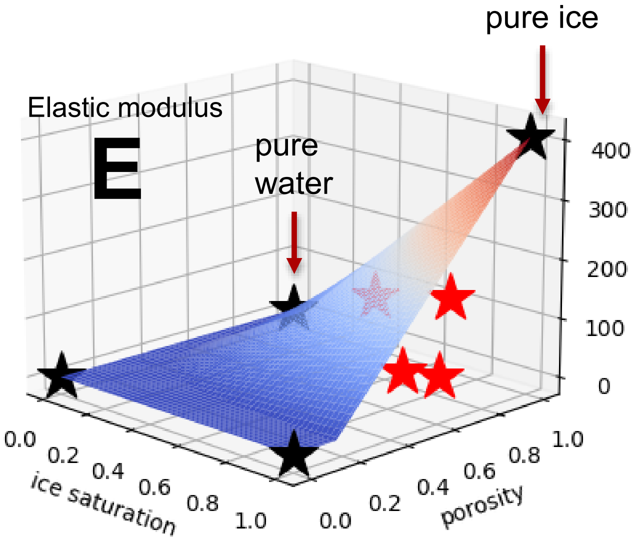


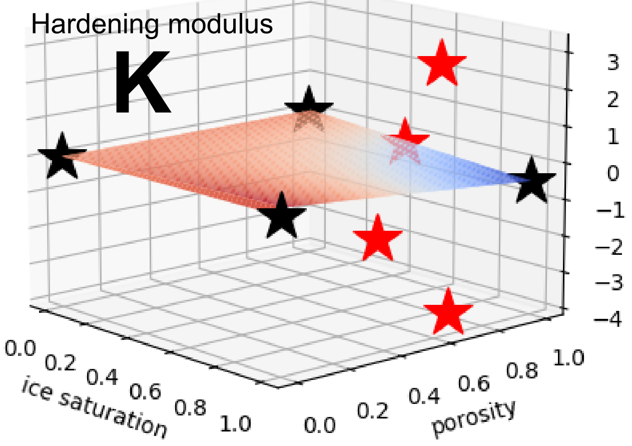


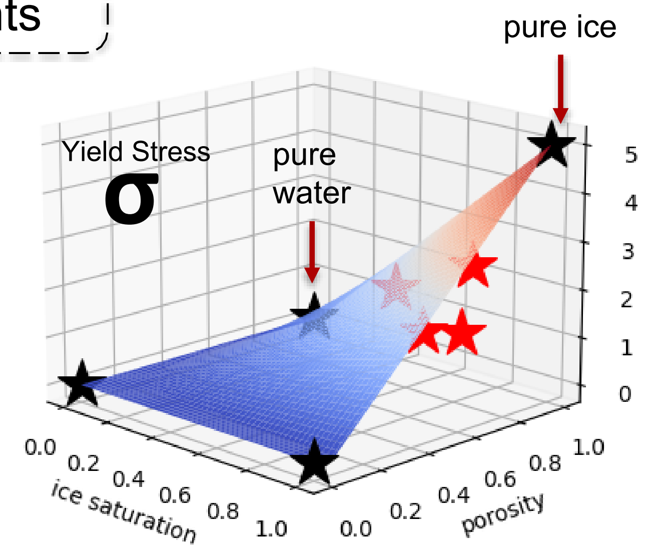
Experimental results on permafrost core samples were analyzed to create fits for **E, K, σ** as a function of **ice saturation** and **porosity**.

★ experimental data points

★ theoretical data points

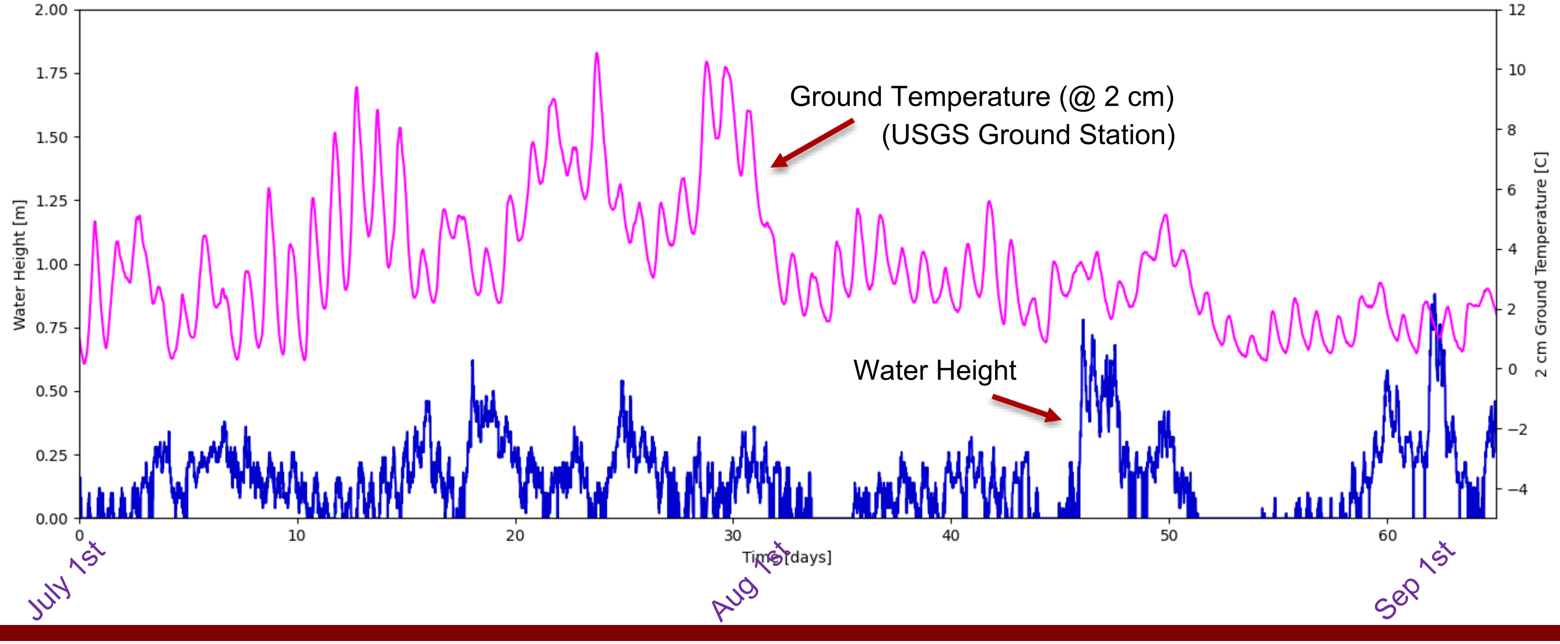


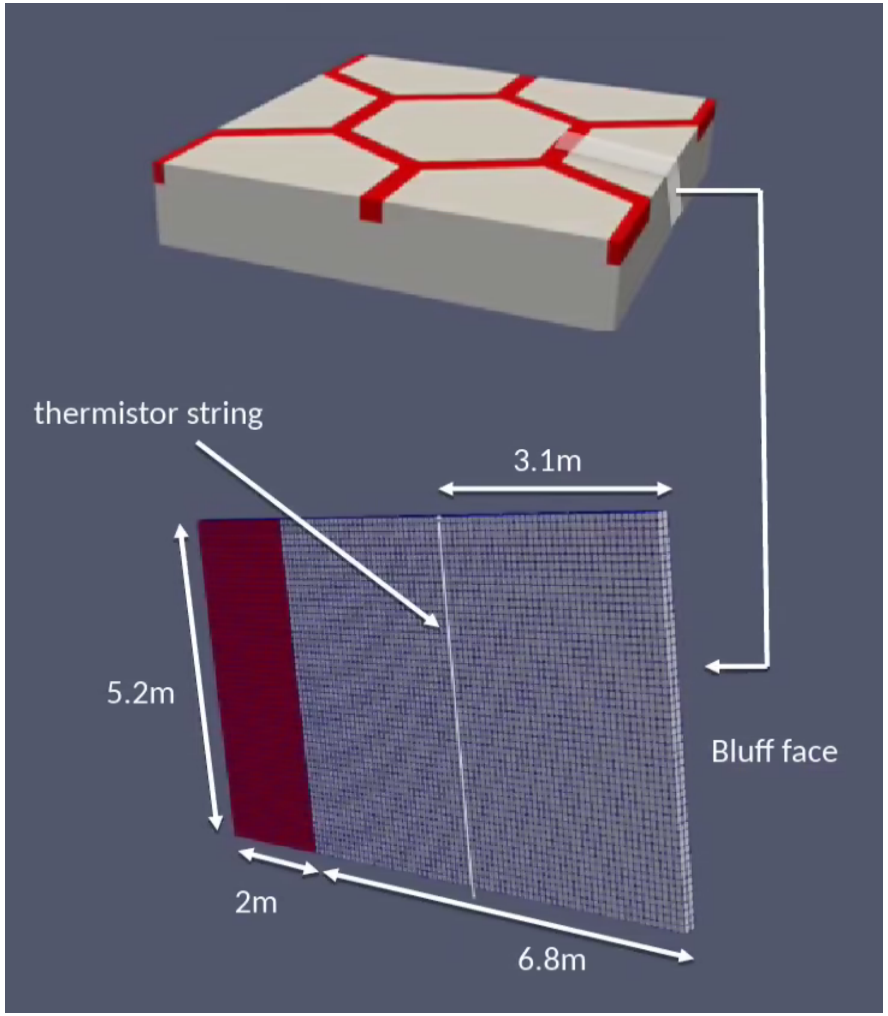




Thermo-Mechanical Coupling: 2.5D slice*

- Computational domain is ***2.5D cross-section*** of archetypal 3D bluff geometry discretized using a uniform hex grid.
  - ***Pseudo-realistic problem*** in which a slice of permafrost is exposed to ***realistic oceanic and atmospheric forcing BC data*** occurring at Drew Point, Alaska in summer 2018
  - ***Initial temperature field*** obtained from vertical thermistor string placed into DP1-1 ice core at Drew Point.

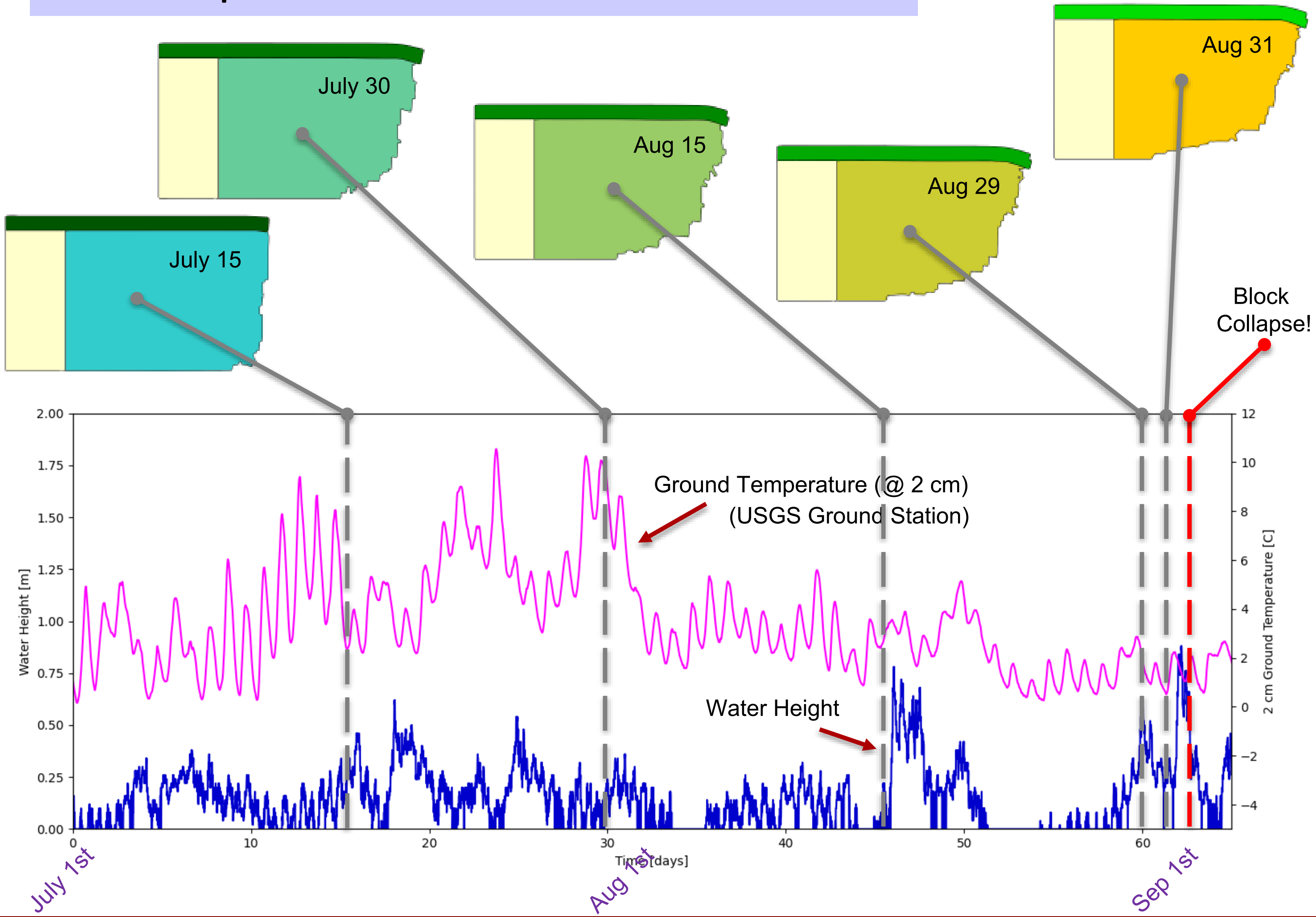


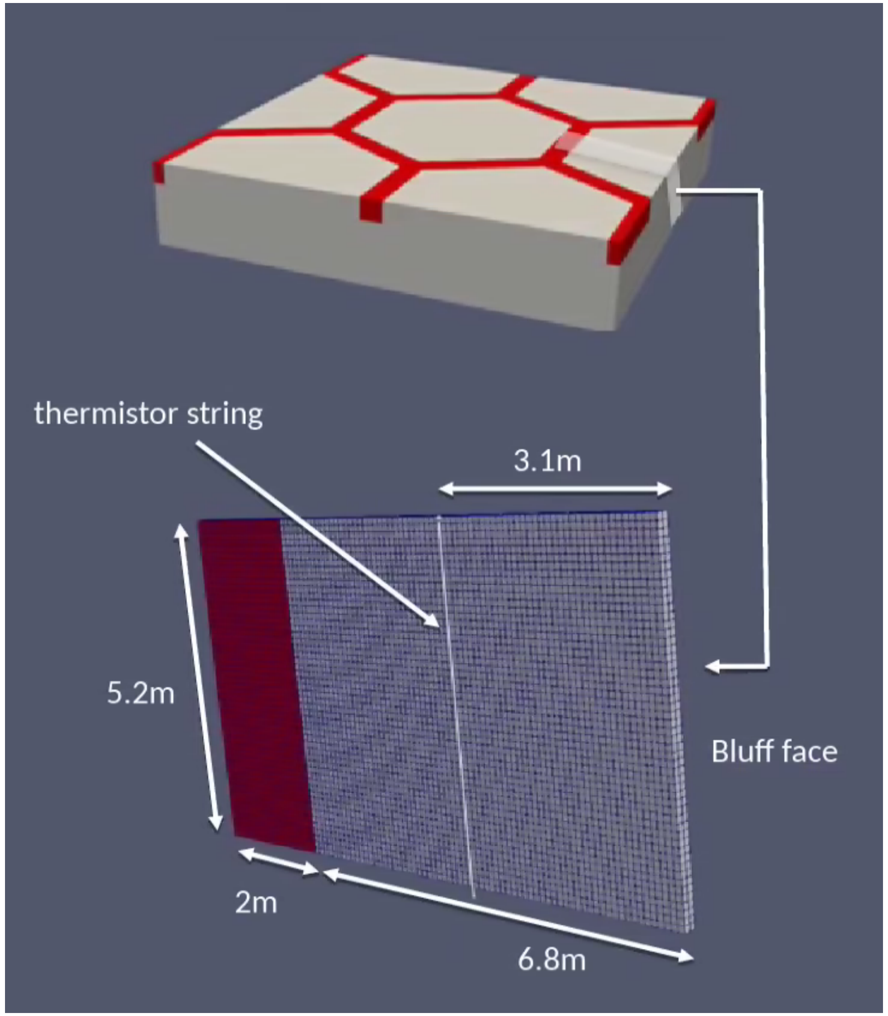


* For details, see: Frederick, Mota, Tezaur, Bull, *J. Comput. Appl. Math*. 2021.

Thermo-Mechanical Coupling: 2.5D slice*

Bluff profiles over simulation time:





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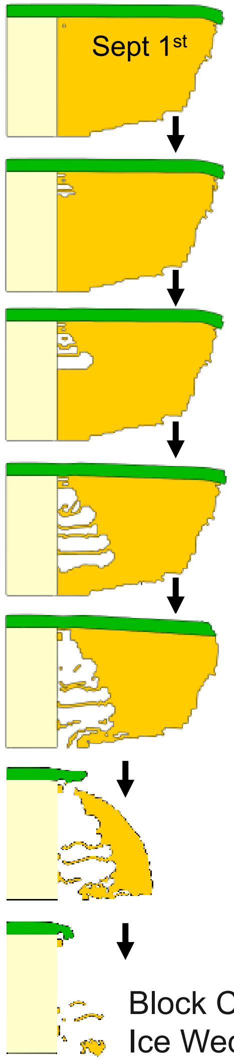
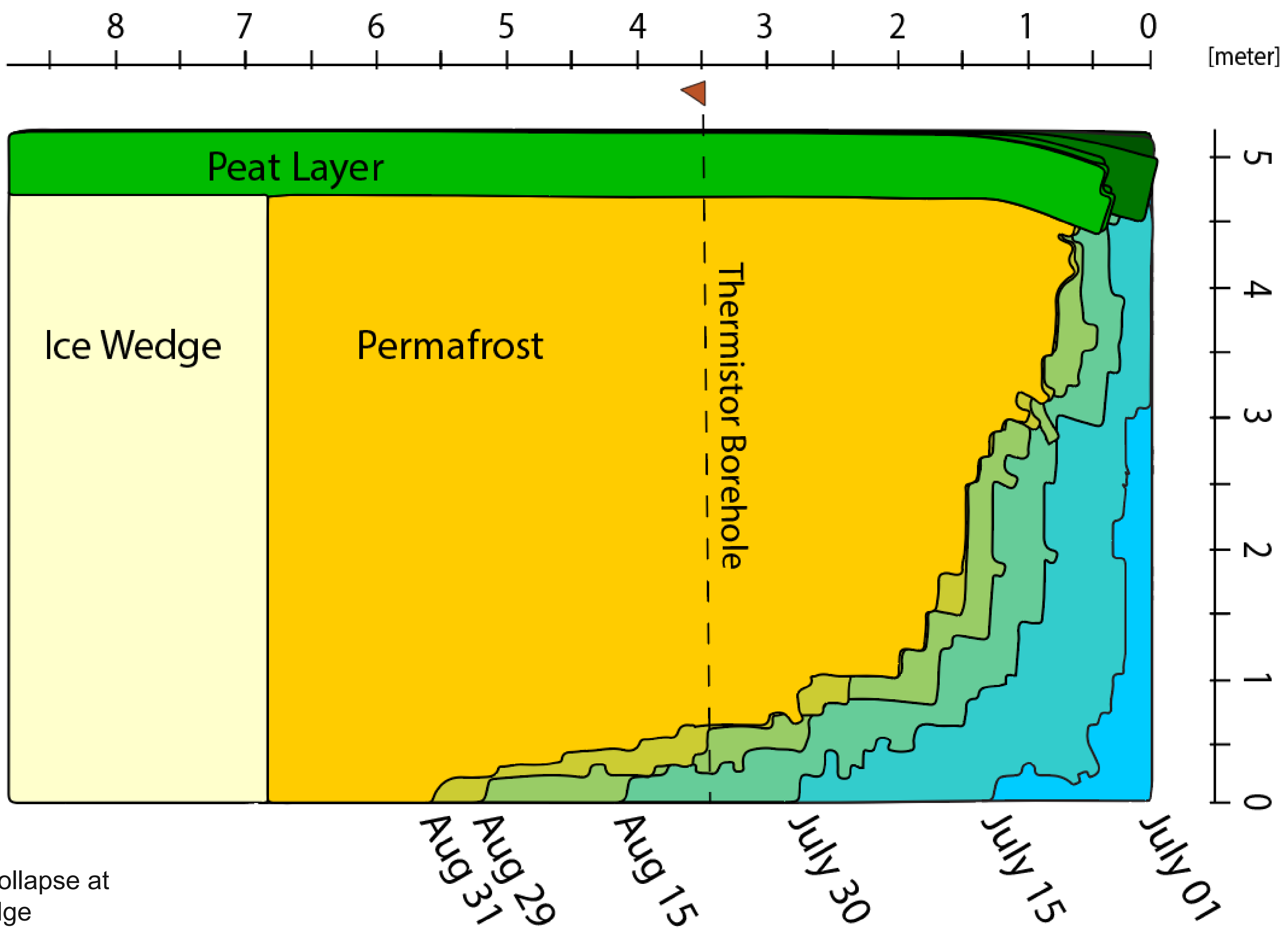
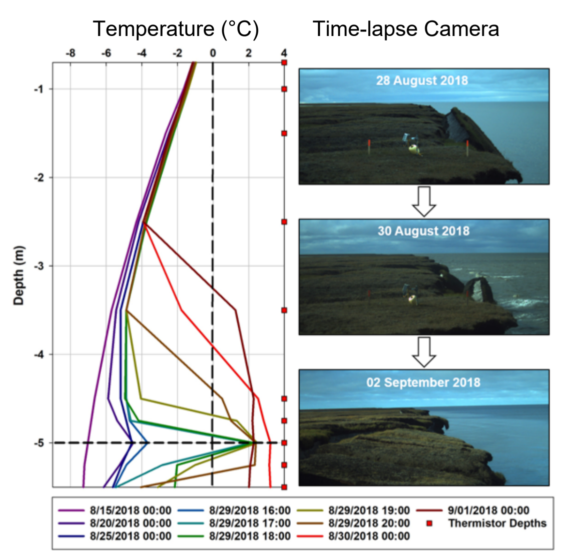
Thermo-Mechanical Coupling: 2.5D slice

Block Collapse Timelapse

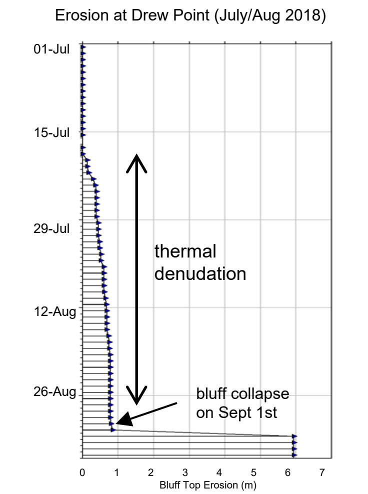


Block Collapse at Ice Wedge Surface



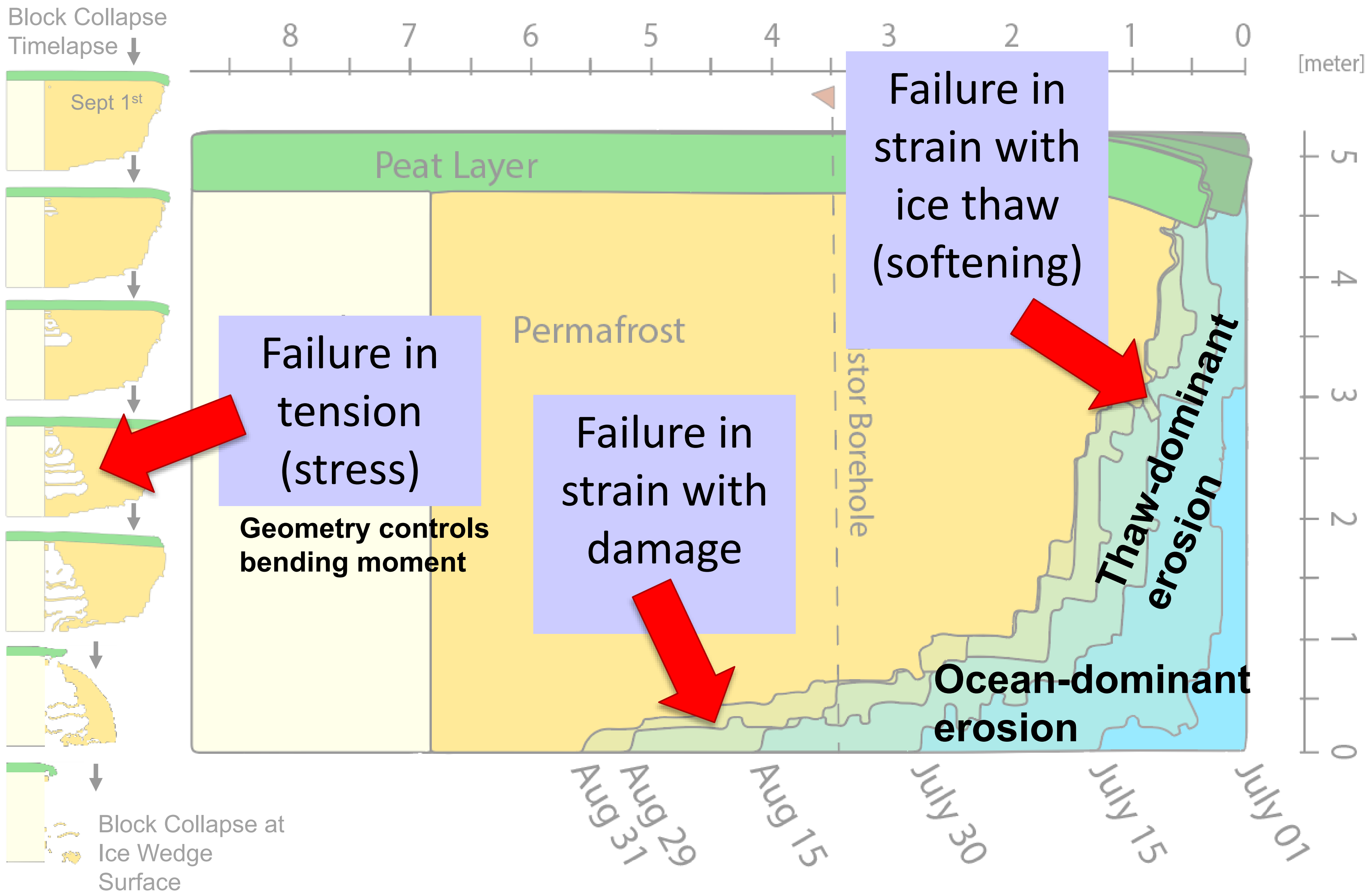


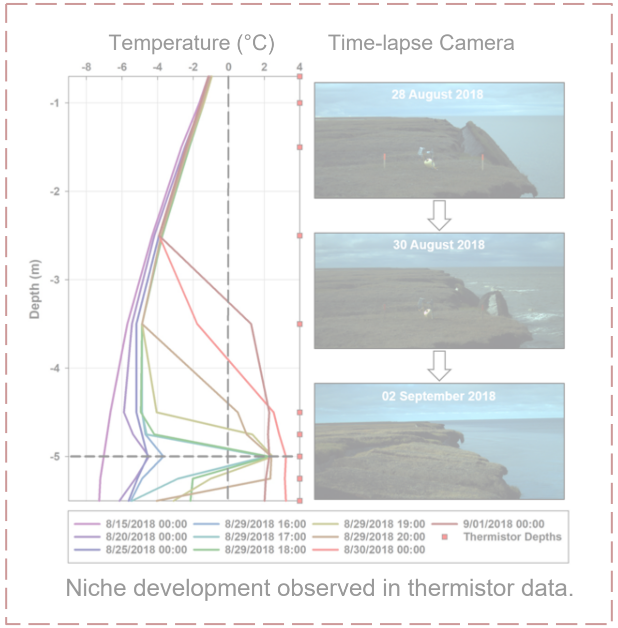
Niche development observed in thermistor data.

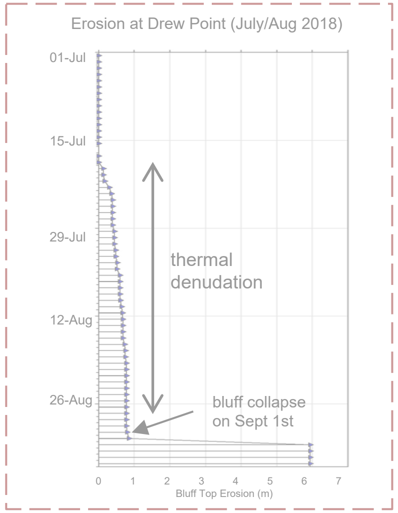


Field Data Used for Calibration

Thermo-Mechanical Coupling: 2.5D slice







Field Data Used for Calibration

Current & Future Work: InteRFACE

- Develop typological understanding of Arctic coastline (terrestrial and oceanographic) to upscale models of erosion and flooding:
  - ACE Model implementation with representative terrestrial configurations
  - Offshore wave environment typology

- Currently selecting the terrestrial configurations using the typological assignments
  - Looking to establish 6-7 terrestrial configurations
  - ACE requires unique information not available in landscape work

Offshore Waves

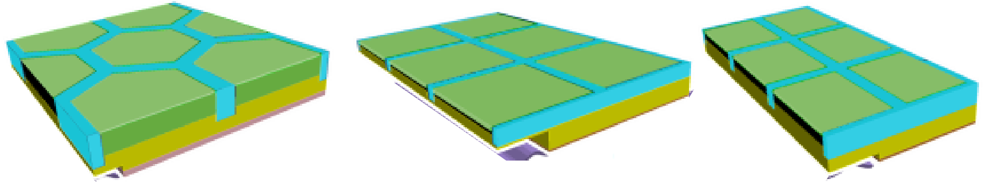
Historic	Tp (s)	Hs (m)	Wave Direction	Water Level (m)	Wind Direction	Wind Speed (m/s)	Wave-Wind Orientation
Cluster 1	5.00	1.11	33	-0.15	29	5.5	N-N
Cluster 2	6.30	1.55	113	-0.10	113	6.0	E-E
Cluster 3	7.30	1.40	270	+0.15	263	4.9	W-W
Cluster 4	8.10	2.50	98	-0.20	113	13.0	E-E
Cluster 5	8.75	2.00	330	+0.10	280	7.5	W-W
Cluster 6	9.90	3.00	280	+0.20	316	12.0	W-W

x

Nearshore Environment

x

Terrestrial Configuration



InteRFACE