Sensitivity studies on erosion criteria for the Arctic Coastal Erosion (ACE) Model

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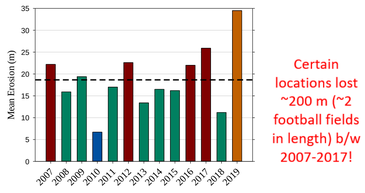
Motivation

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

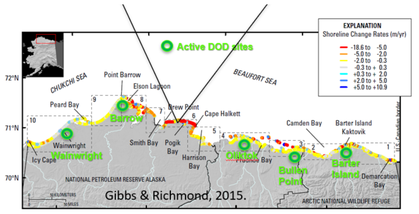
- Primary culprit is **loss of Arctic sea ice**: since 1979 sea ice has lost 51% in area and 75% in volume
  - ➢ Increasing **ice-free season**
  - ➢ Increasing **wave energy** and **storm surge**
  - ➢ Increasing **sea water** temperatures

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).

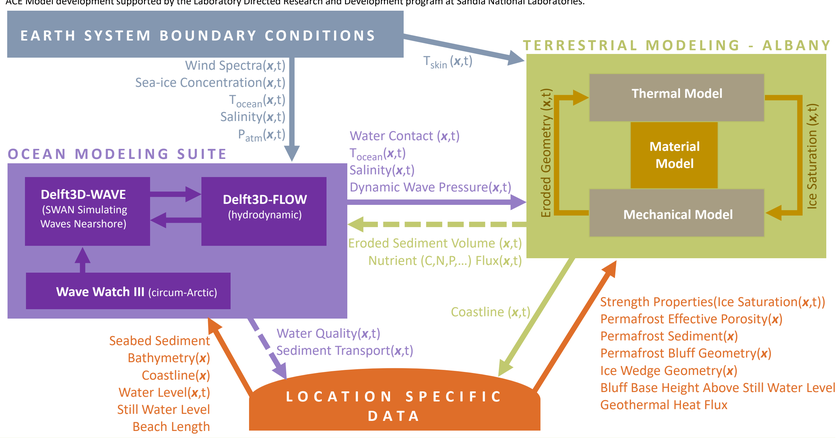


Certain locations lost ~200 m (~2 football fields in length) b/w 2007-2017!



ACE Model: Component Coupling

ACE Model development supported by the Laboratory Directed Research and Development program at Sandia National Laboratories.

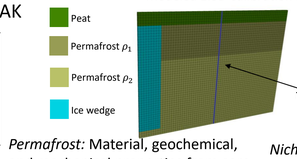


Calibration Case & Results

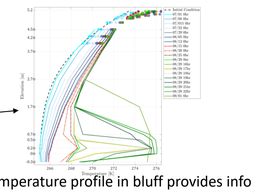
Summer 2018 at Drew Point AK

Erosion: UAV, calibrated camera

Modeled 2.5D calibration slice

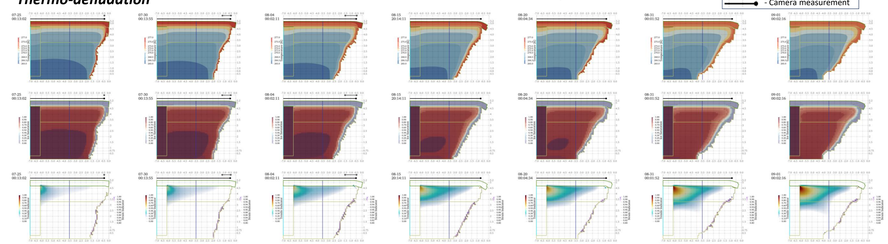


Permafrost: Material, geochemical, and mechanical properties from core analysis



Niche shape: Temperature profile in bluff provides info on when thermistor was exposed to ocean/atmospheric temperature

Thermo-denudation



Terrestrial Model

Thermal Model

*Terrestrial model components and coupling implemented in Albany

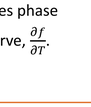
Thermal PDE's evolve temperature and ice saturation in permafrost

→ PDE's respond to BC's as well as a salinity enhanced melting

→As material fails, new portions of permafrost are exposed to B.C.s

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

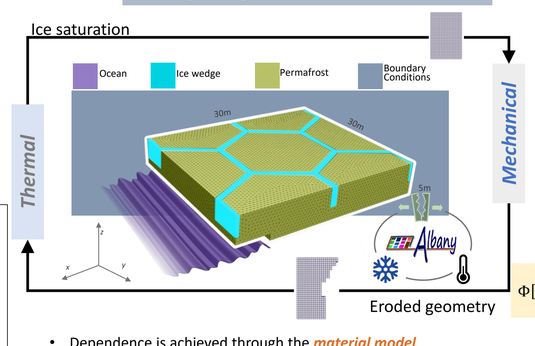
$$(\overline{\rho c_p} + \widetilde{\Theta})\frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{K} \cdot \nabla T)$$



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

$\overline{\rho}$: 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, sediment fraction)

Coupling (Schwarz framework)



- Dependence is achieved through the ***material model***
- Modeling framework uniquely allows for any form of erosion
- Adaptive time-stepping enables exponential changes in time scale to capture dynamics of thermal & mechanical models

Mechanical Model

Mechanical PDE's based on finite deformation plasticity model

- 3x3 tensor of compressive, tensile, and shear components computed everywhere in the model (J2 class)

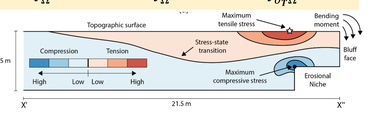
→ Domain will deform according to computed stress

→ *Dynamic pressure from ocean waves* computed as an additional stress on boundary cells

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

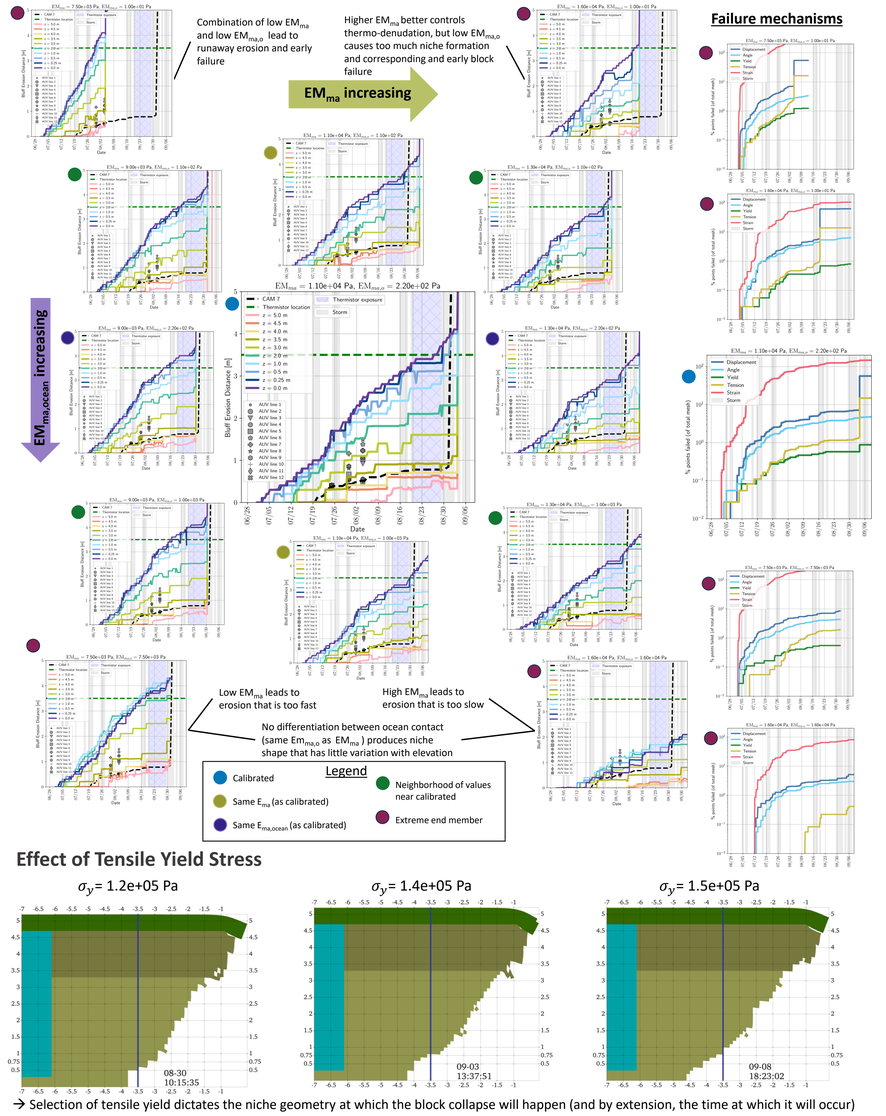
$$\Phi[\boldsymbol{\varphi}] \coloneqq \int_\Omega A(\boldsymbol{F},\boldsymbol{Z})\,dV - \int_\Omega \rho \boldsymbol{B}\cdot\boldsymbol{\varphi}\,dV - \int_{\partial_T\Omega} \boldsymbol{T}\cdot\boldsymbol{\varphi}\,dS$$

$A(\boldsymbol{F},\boldsymbol{Z})$: 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



Sensitivity Studies

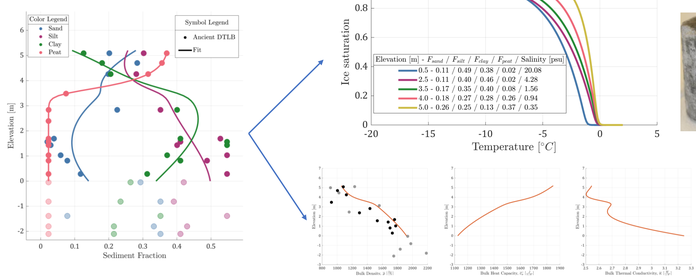
Effects of Minimum Allowable Elastic Moduli



Material Models

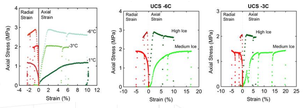
→ Developed **thermal** properties (conductivity, heat capacity, etc.) from mixture models of constituent material properties

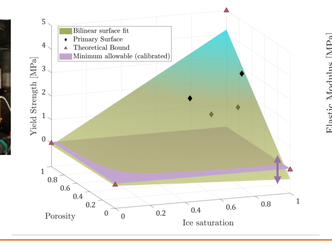
→ Soil freezing curve dependent on sediment fraction, salinity

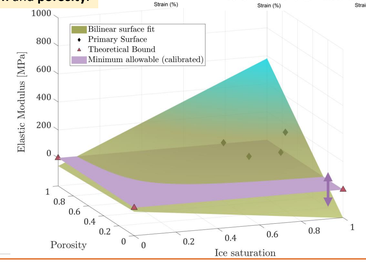


- Constitutive relationships for the **mechanical** model
- Require stress-strain curves up to failure as function of ice saturation and porosity for local permafrost samples
- Asymmetric yield stress under tension and compression

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







Effect of Tensile Yield Stress

→ Selection of tensile yield dictates the niche geometry at which the block collapse will happen (and by extension, the time at which it will occur)

Erosion

Domain changes geometry (through mesh adaptation) according to following **erosion/failure criteria**:

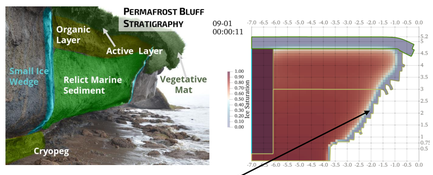
Stress criterion: remove element when critical value of yield stress in tension or compression is surpassed (typically high ice content)

Strain criterion: remove element when it has deformed beyond a critical value; defined as a function of peat content (typically most active in regions of low ice saturation)

Kinematic criterion (solver stability): remove element when material has tilted/displaced excessively

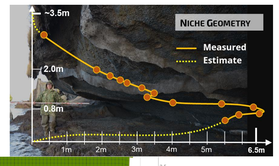
Distinct mechanisms of erosion:

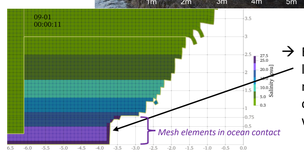
Thermo-denudation – thawing of exposed material



→ Ice saturation evolution captures thaw at the bluff face
→ Lowered elastic modulus and yield strength of permafrost material at low ice saturation allow increased strain accrued and higher rates of compressive yield for exposed thawed material

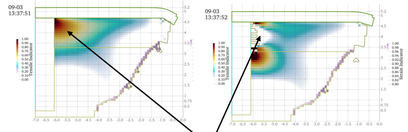
Niche Formation – dissolution of thawed material into ocean





→ Enhanced salinity and distinct (and lowered) minimum allowable elastic modulus for material in contact with ocean capture thawing and material weakening due to ocean contact

Block Failure – tensile failure of frozen material



→ Tensile stresses in material reach tensile yield and corresponding elements are removed

For further information:

Frederick, J. M., A. Mota, I. Tezaur, and D. L. Bull (2021), A thermo-mechanical terrestrial model of Arctic coastal erosion, *Journal of Computational and Applied Mathematics*, Vol. 397, doi:10.1016/j.cam.2021.113533.

Bull et al. (2020), Arctic Coastal Erosion: Modeling and Experimentation, SAND2020-10223, *Sandia National Laboratories*, Albuquerque, NM.

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