Assessing permafrost demise and infrastructure destabilization using the Arctic Coastal Erosion (ACE) model

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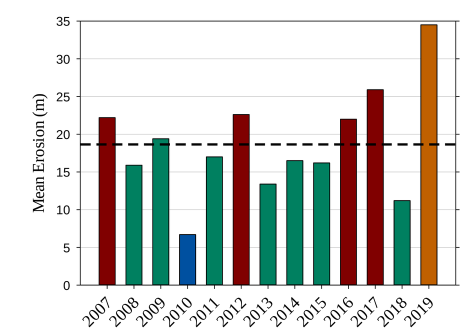
Motivation

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

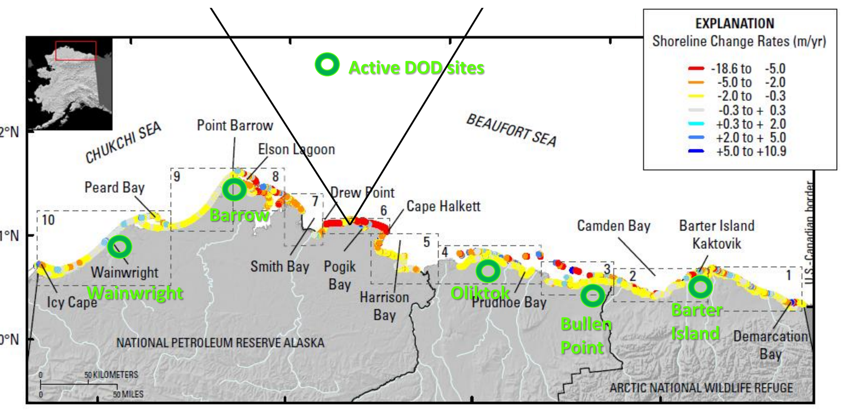
- Primary culprit is **loss of Arctic sea ice**: since 1979 sea ice has lost 51% in area and 75% in volume
  - ➢ Increasing **ice-free season**
  - ➢ Increasing **wave energy** and **storm surge**
  - ➢ Increasing **sea water** temperatures



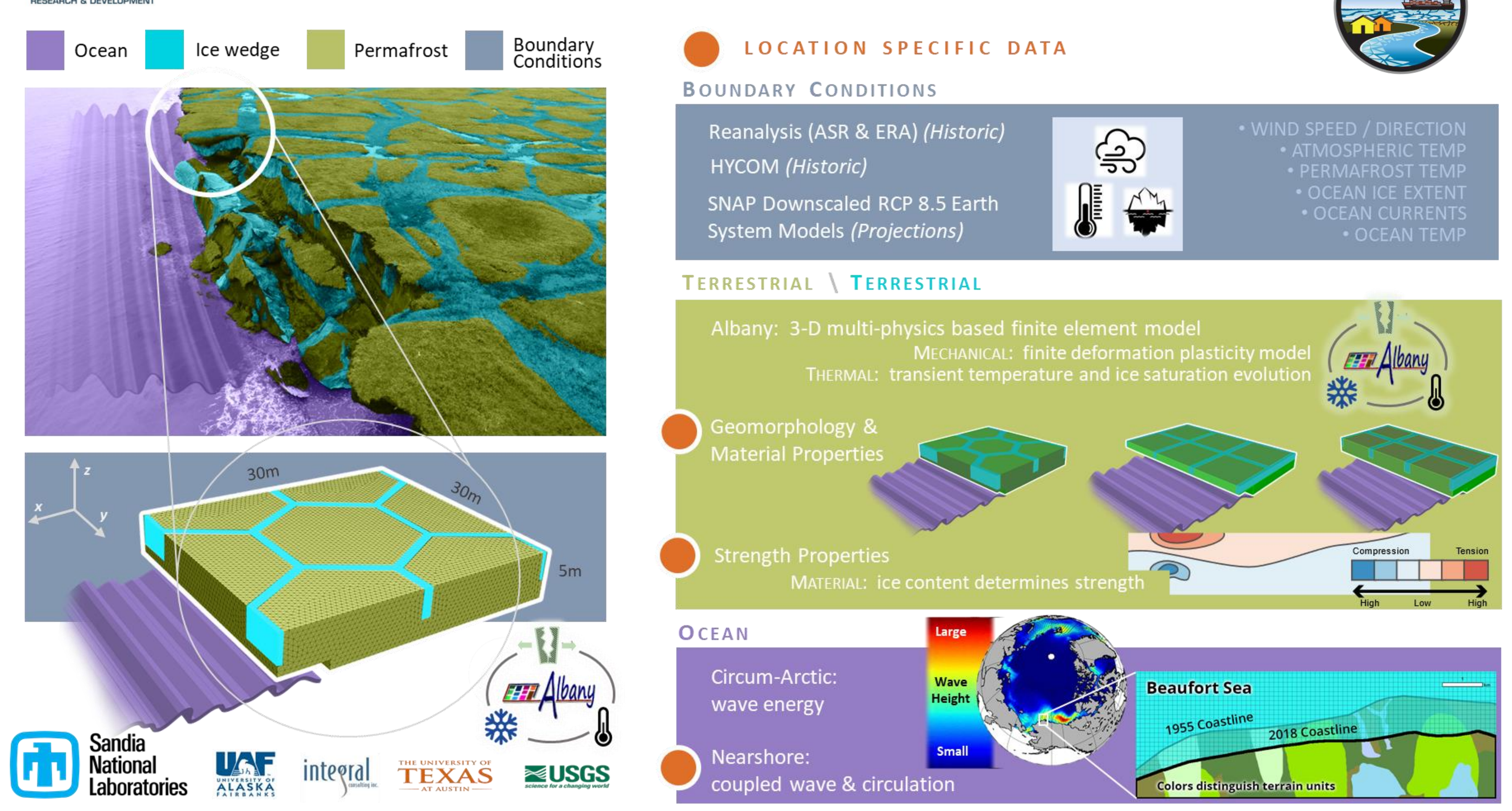
Certain locations lost >250 m (~2 football fields in length) b/w 2007-2019!

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).



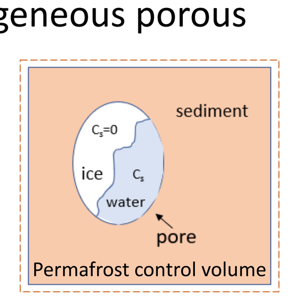
Arctic Coastal Erosion (ACE) Model



Thermal Model

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

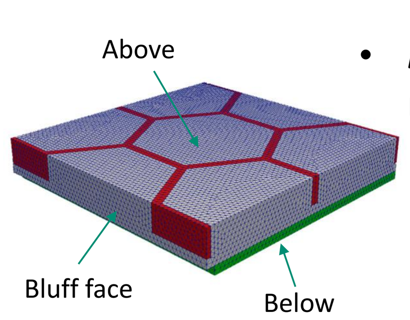
$$(\bar{\rho}\overline{c_p} + \tilde{\Theta})\frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{K} \cdot \nabla T)$$



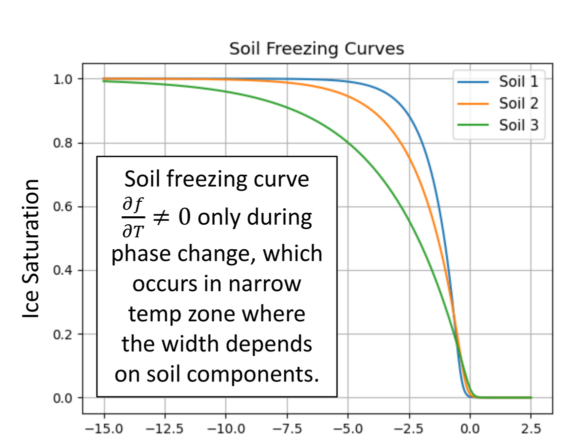
where $\tilde{\Theta} := \rho_f L_f \frac{\partial f}{\partial T}$ incorporates phase changes through soil freezing curve, $\frac{\partial f}{\partial T}$.

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

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



- ***Boundary conditions*** (from wave model/data)
  - ➢ Local geothermal heat flux from below
  - ➢ 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.

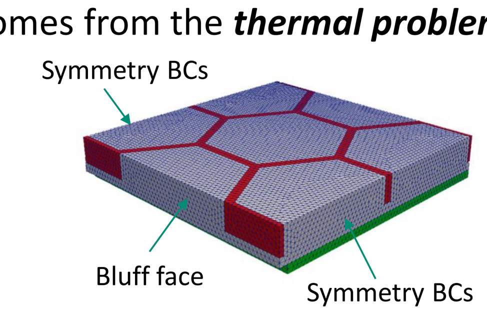
Mechanical Model and Mesh Erosion

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

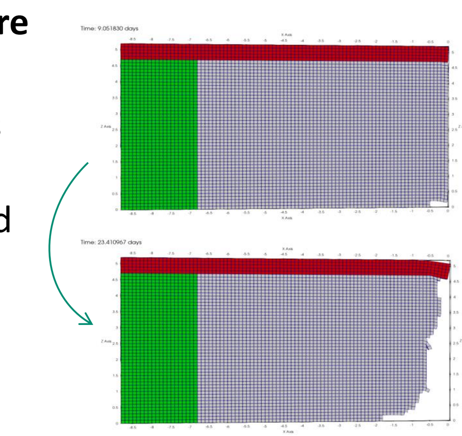
$$\Phi[\boldsymbol{\varphi}] := \int_{\Omega} A(\boldsymbol{F}, \boldsymbol{Z})\, dV - \int_{\Omega} \rho \boldsymbol{B} \cdot \boldsymbol{\varphi}\, dV - \int_{\partial_T \Omega} \boldsymbol{T} \cdot \boldsymbol{\varphi}\, dS$$

$A(\boldsymbol{F}, \boldsymbol{Z})$: 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 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***
- ***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 (increases softening due to dissolution by lowering elastic modulus E)

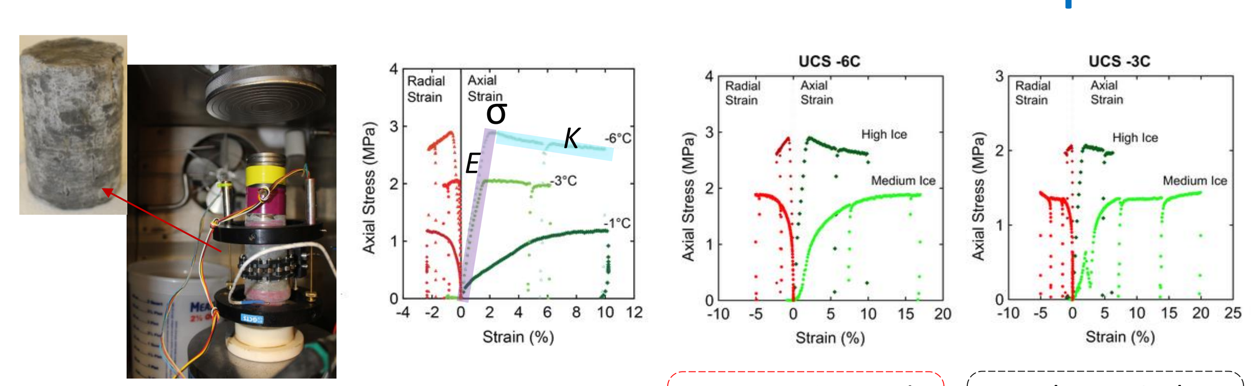


- "Failed" elements are **removed** from the mesh when any of three **failure criteria** are reached for all integration points within an element
  - ➢ ***Strain criterion:*** when material reaches a critical value of the stress in tension or compression
  - ➢ ***Strain criterion:*** when material reaches 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.



* Holthuijsen, 2007.

Material Model Calibration to Experimental Data

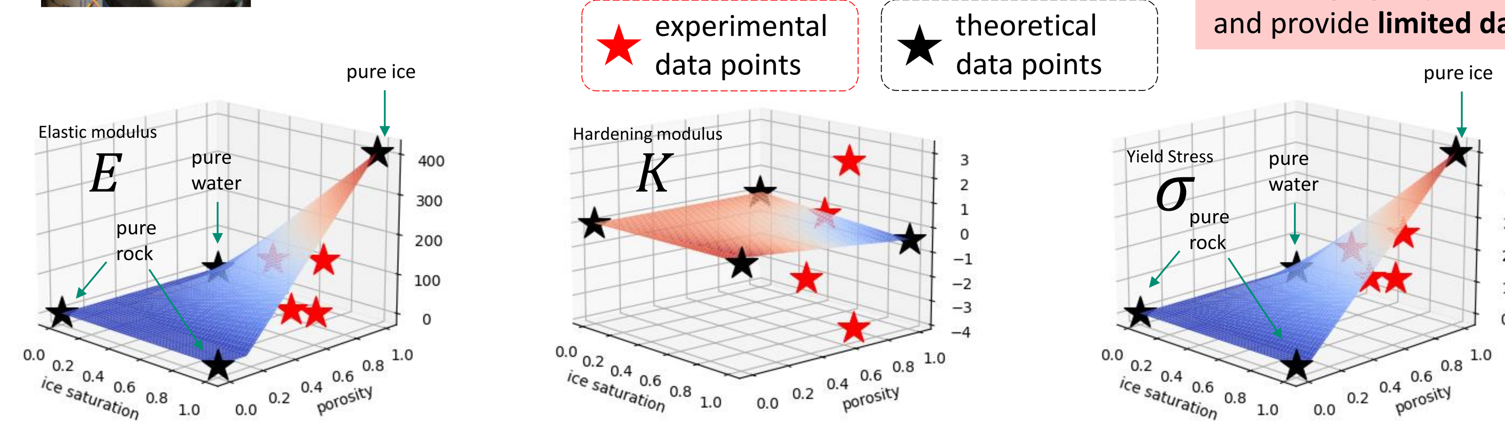


Experimental results on permafrost core samples used to create fits for E, K, σ as a function of **ice saturation** and **porosity**.

Experiments are very **challenging** to perform and provide **limited data**!

★ experimental data points

★ theoretical data points



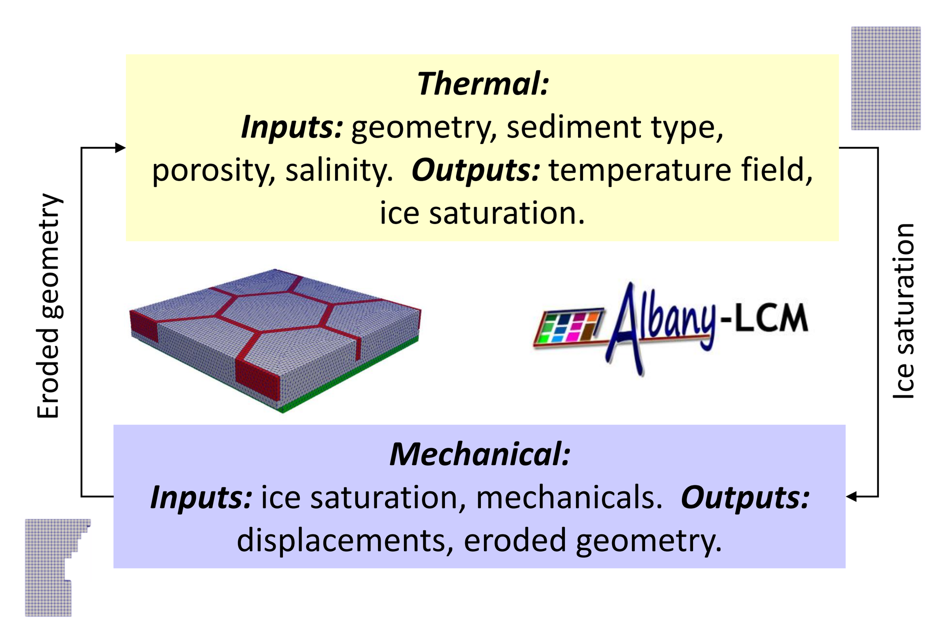
Coupled Thermo-Mechanical Formulation

Potential key advantages:

- Failure modes develop from **constitutive relationships** in FEM model
- Thermal and mechanical problems can be advanced using **different time-steppers** (e.g., implicit-explicit coupling)

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

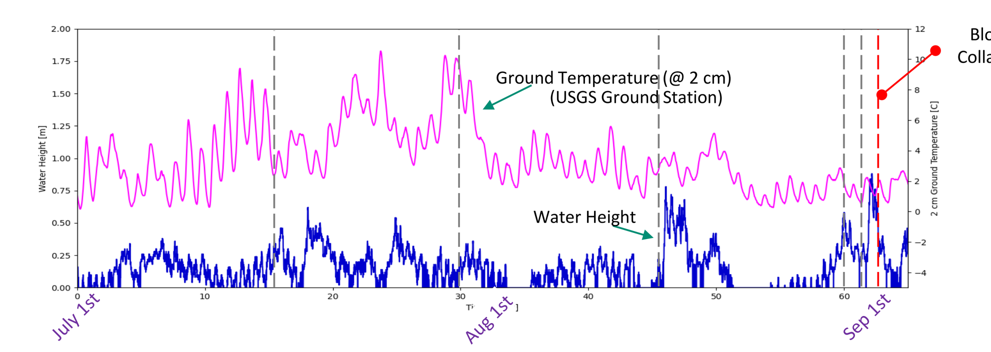
Thermal:
Inputs: geometry, sediment type, porosity, salinity. ***Outputs:*** temperature field, ice saturation.

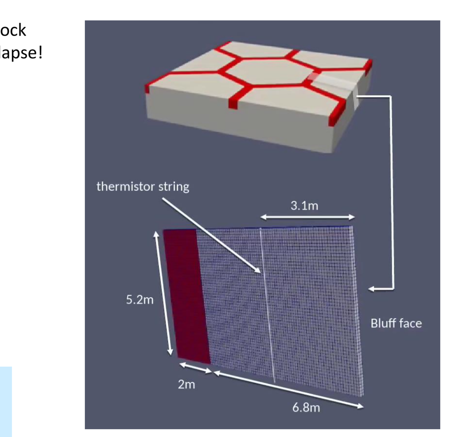


Mechanical:
Inputs: ice saturation, mechanicals. ***Outputs:*** displacements, eroded geometry.

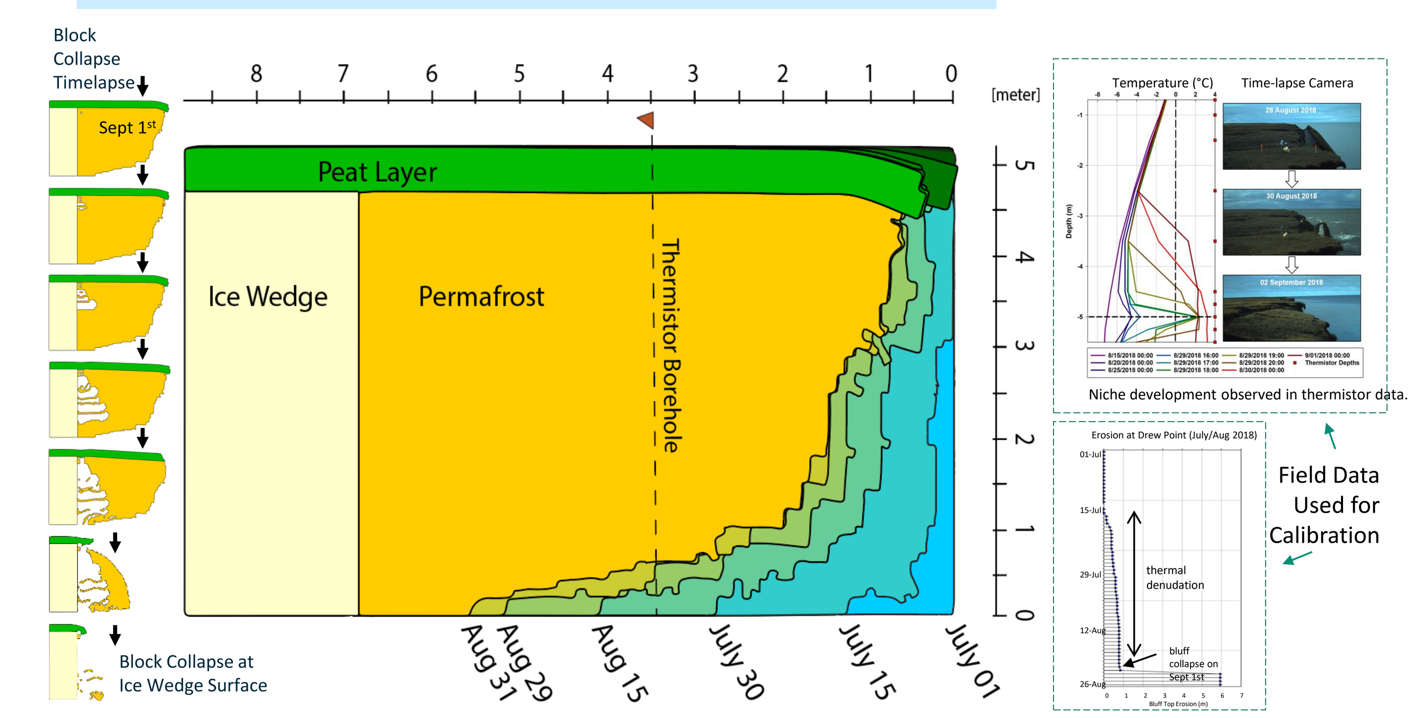
ACE Simulation Results: 2.5D Slice

- Computational domain is ***2.5D cross-section*** of archetypal 3D bluff geometry discretized with uniform hex grid
  - ➢ ***Pseudo-realistic problem*** with ***realistic oceanic*** and ***atmospheric forcing BC data*** occurring at Drew Point, AK in summer 2018
  - ➢ ***Temperature*** initialized from vertical thermistor string in DP1-1 ice core at Drew Point





Calibrated ACE model is ***capable of simulating*** Sept. 1, 2018 ***block collapse event*** observed at Drew Point, AK!



Upscaling under InteRFACE Project

Goal: 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
- Looking to establish **6-7 terrestrial configurations**
- ACE requires **unique information** not available in landscape work

Offshore waves

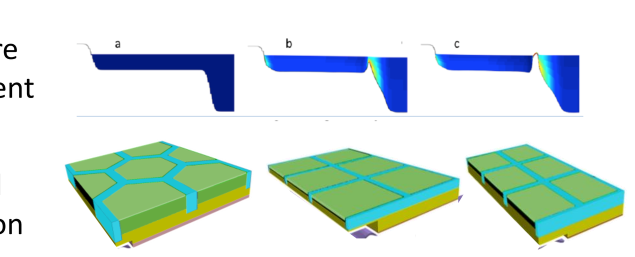
×

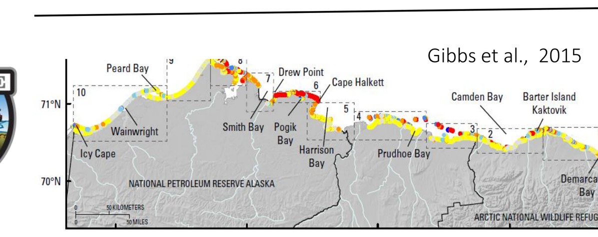
Nearshore environment

×

Terrestrial configuration

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



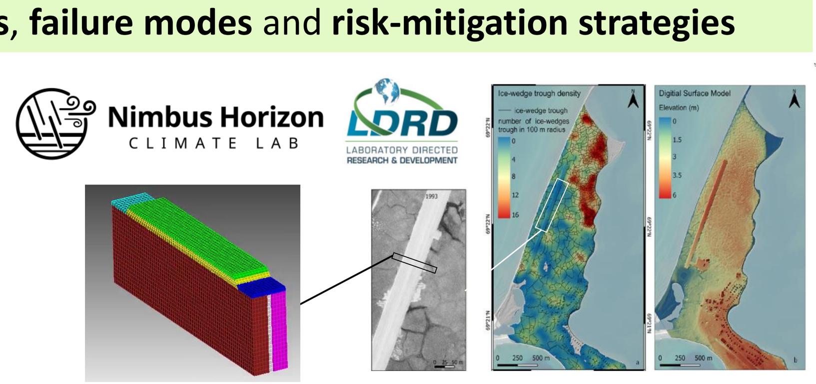


Gibbs et al., 2015

Arctic Critical Infrastructure (ACI) Modeling

Goal of ACI: leverage ACE to develop a computational model capable of analyzing various **permafrost-infrastructure scenarios, failure modes** and **risk-mitigation strategies**

- We are **maturing** our permafrost degradation simulation capabilities for use on Arctic **infrastructure impact**
- ***Initial exemplar***: Paulatuk airstrip in northern Canada (right)



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] 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", *ELSCAM*. 397 113533, 2021.
[4] D. Bull et al. "Arctic Coastal Erosion: Modeling and Experimentation". *Sandia National Laboratories report*, SAND2020-10223, 2020.

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