Calibration of the ACE (Arctic Coastal Erosion) Model

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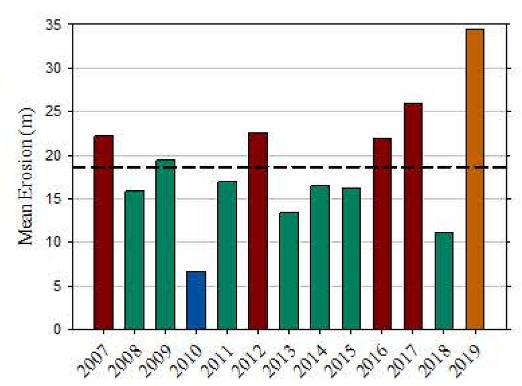
Motivation

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

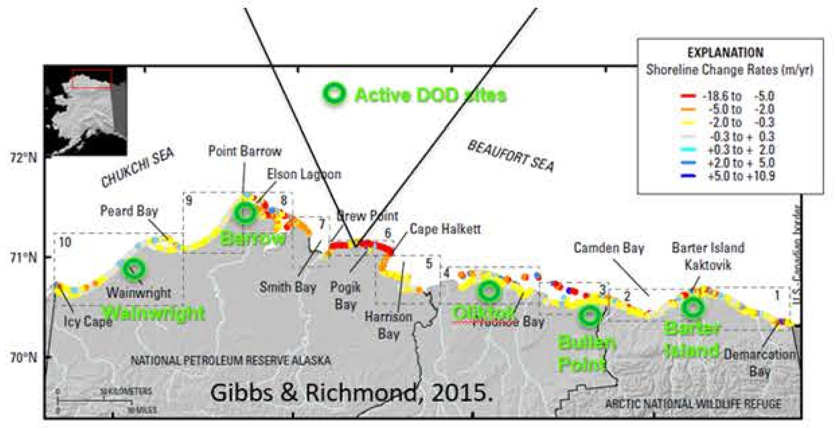
- Primary culprit is **loss of Arctic sea ice**: since 1979 sea ice has lost 51% in area and 75% in volume
  - Increasing **ice-free season**
  - Increasing **wave energy** and **storm surge**
  - Increasing **sea water** temperatures



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

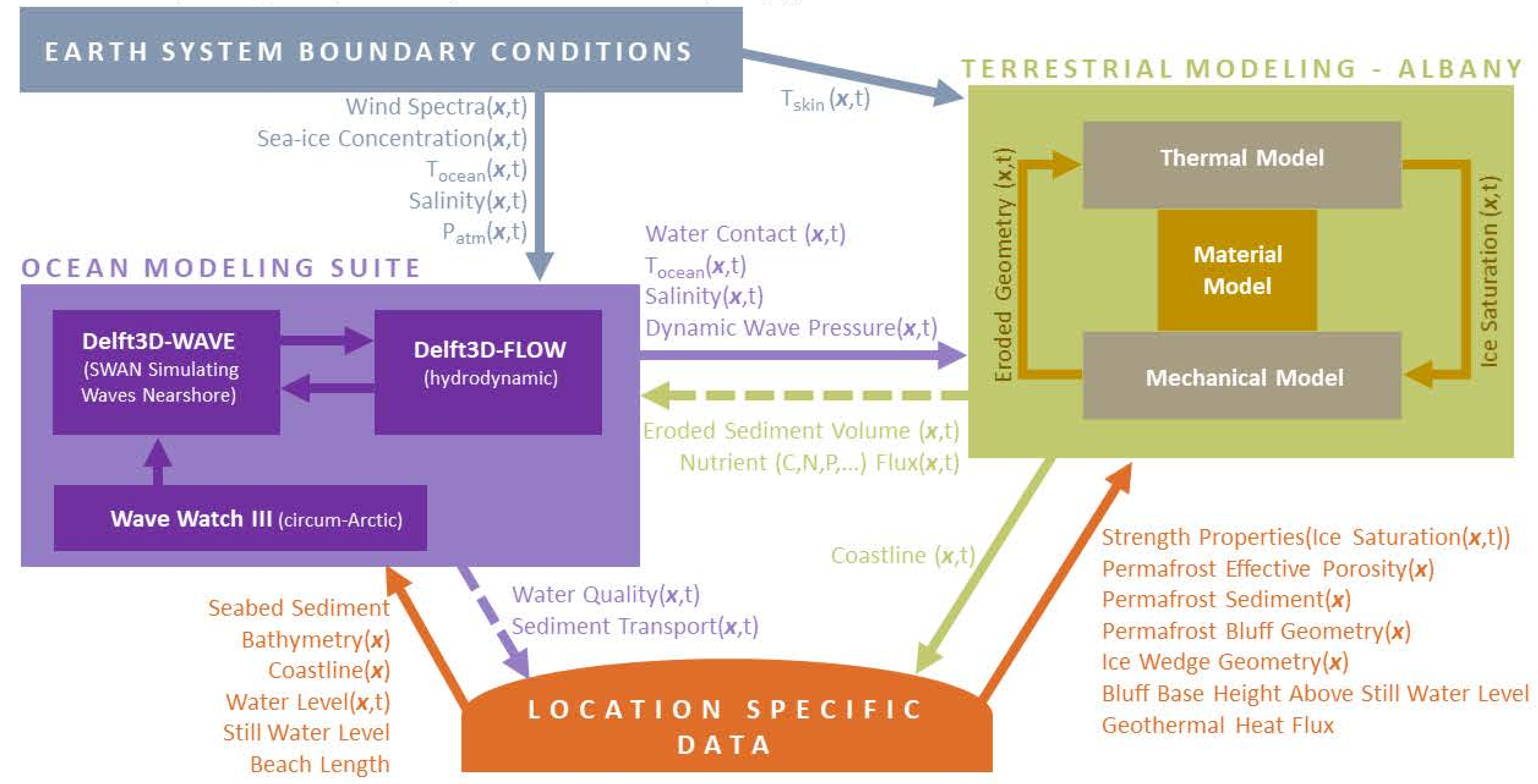
Erosion is threatening:

- **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).



ACE Model: Component Coupling

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



Oceanographic Modeling Suite

WW3: Development of wave field in the Arctic to develop nearshore BC's
- surface winds
- ice cover

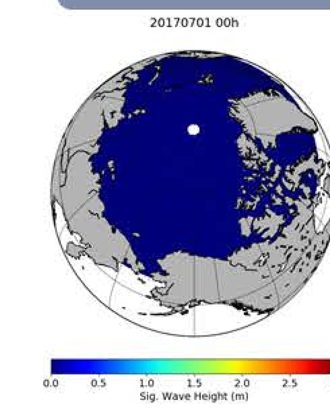
SWAN: Wave set-up conditions 2-way coupled with circulation
- high resolution near shore environment
- wave energy inclusive of induced current effects

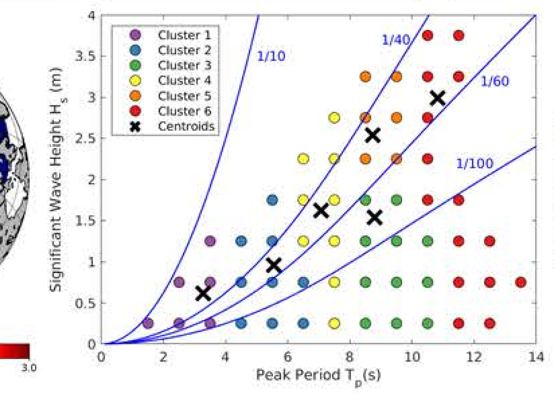
Delft3D-FLOW: Circulation and thermal conditions 2-way coupled with waves
- capture induced currents in nearshore
- capture set-up (storm surge and runup)

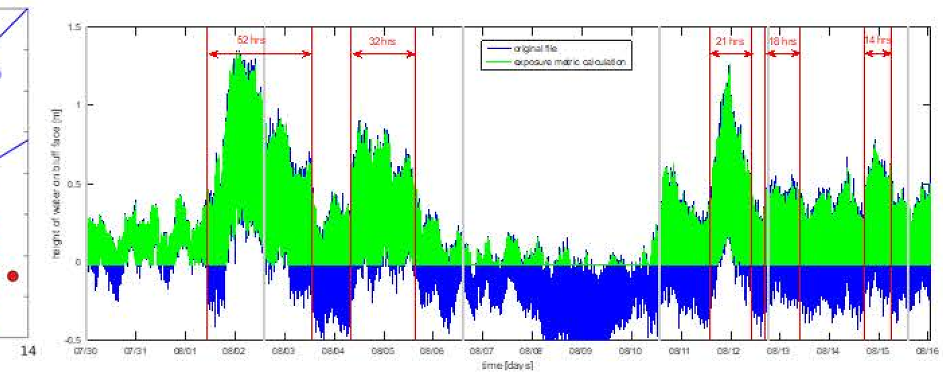
Historic
- 2007-2019 (ASRv2 & ERA5)

Projected
- 2020 – 2040 (SNAP-dynamically downscaled RCP8.5)

50m & 100m Bathymetric Contours
- Statistical wave environment parameters output every deg longitude







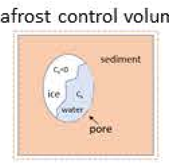
Thermal Model

Thermal PDE's implemented in Albany evolve temperature and ice saturation in permafrost

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

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

Permafrost control volume



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

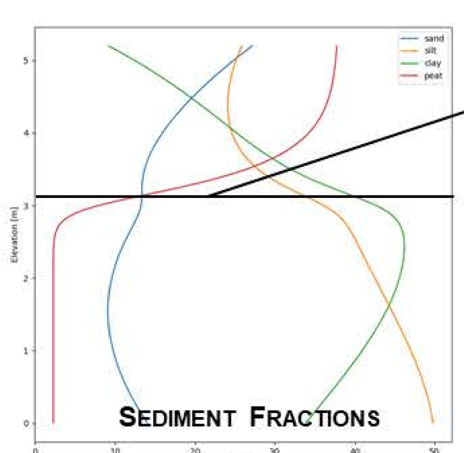
- $\bar{\rho}$: density from mixture model
- $\overline{c_p}$: specific heat from mixture model
- $\boldsymbol{K}$: thermal diffusivity tensor
- ρ_f: ice density
- L_f: latent heat of water-ice phase change
- f: ice saturation ($\in [0,1]$)
- $\frac{\partial f}{\partial T}$: soil freezing curve (depends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

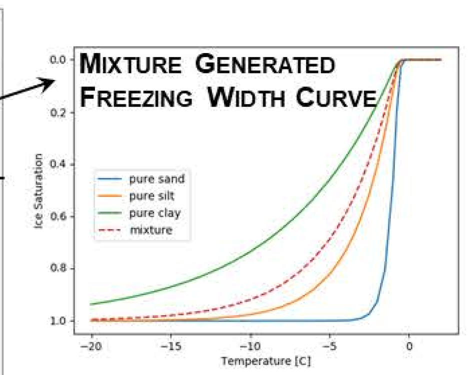
Developed thermal properties (conductivity, heat capacity, etc.) from mixture models of constituent material properties

- Sediment type and fraction
- Water content

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

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





Mechanical Model

Mechanically, Albany is a finite deformation plasticity model

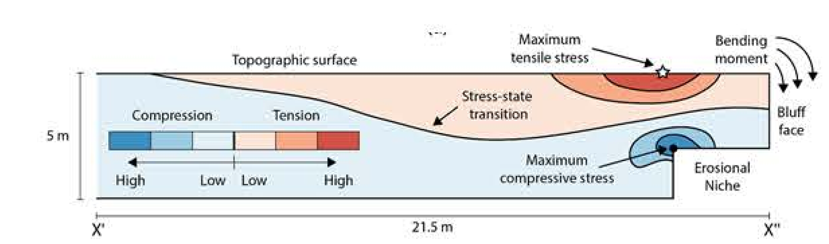
- 3x3 tensor of compressive, tensile, and shear components computed everywhere in the model (J2 class)
- Constitutive relationships require stress-strain curves up to failure as function of ice volume for local permafrost samples

Domain will deform according to computed stress

Domain changes geometry (through mesh adaptation) according to following 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 low ice content)
- Kinematic criterion (solver stability): remove element when material has tilted/displaced excessively

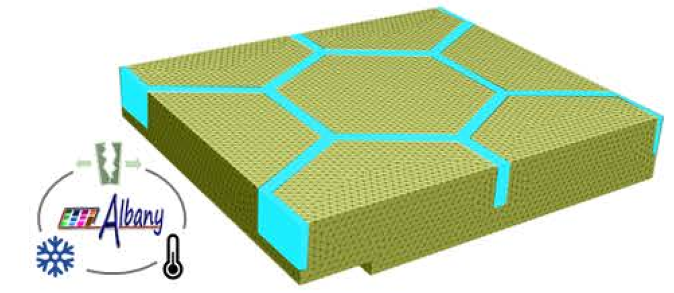
Dynamic pressure from ocean waves computed as an additional stress on boundary cells



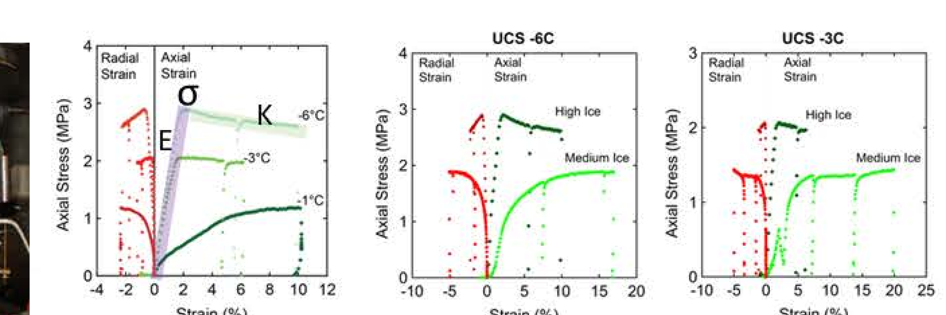
Finite deformation ***time-dependent*** variational formulation for ***solid mechanics problem*** obtained by minimizing the energy functional:

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

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

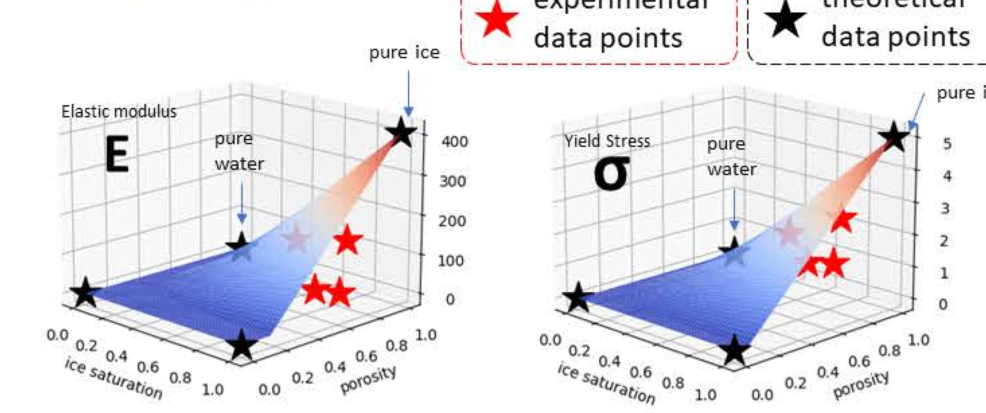


Material Model



★ experimental data points

★ theoretical data points

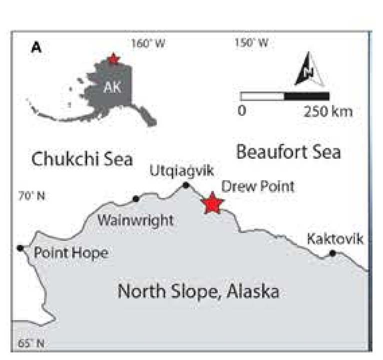


Experimental results on permafrost core samples were analyzed to create fits for **E, K, σ** as a function of **ice saturation** and **porosity**.

Calibration Case & Results

Summer 2018 at Drew Point Alaska

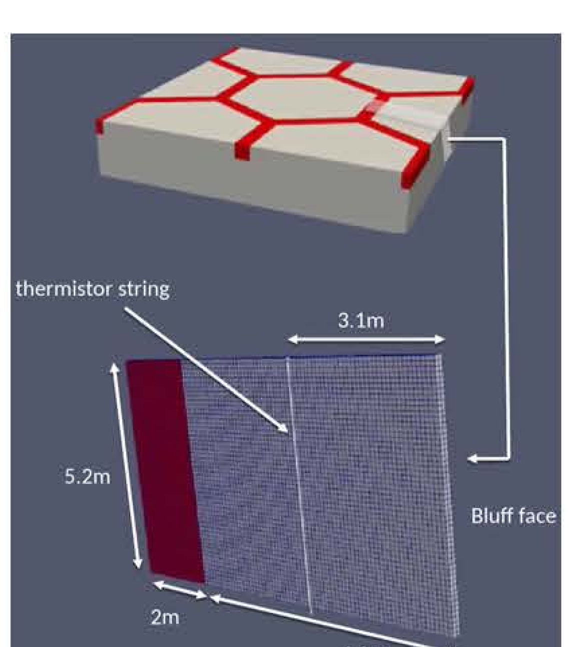
- Erosion Measurements
  - UAV, calibrated camera
- Niche Measurements
  - Temperature profile in bluff
- Permafrost Characteristics
  - Material, geochemical, and mechanical properties from core analysis



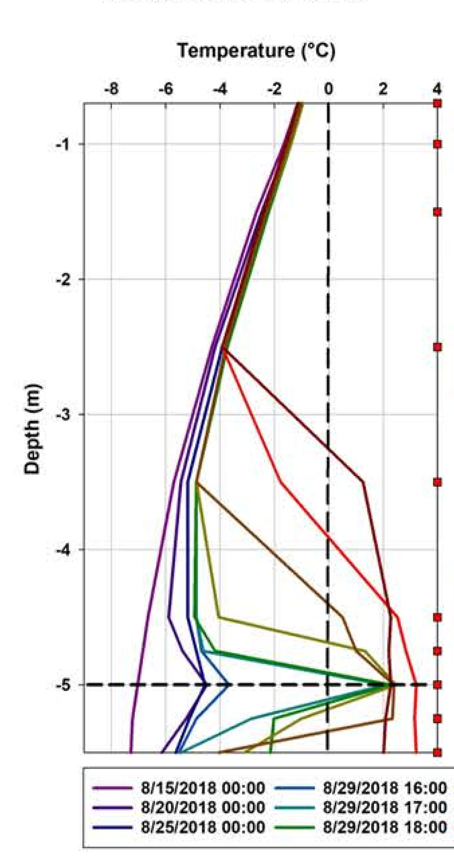
Computational domain is ***2.5D cross-section*** of archetypal 3D bluff geometry discretized using a uniform hex grid.

Adaptive time-stepping (maximum time step 900sec)

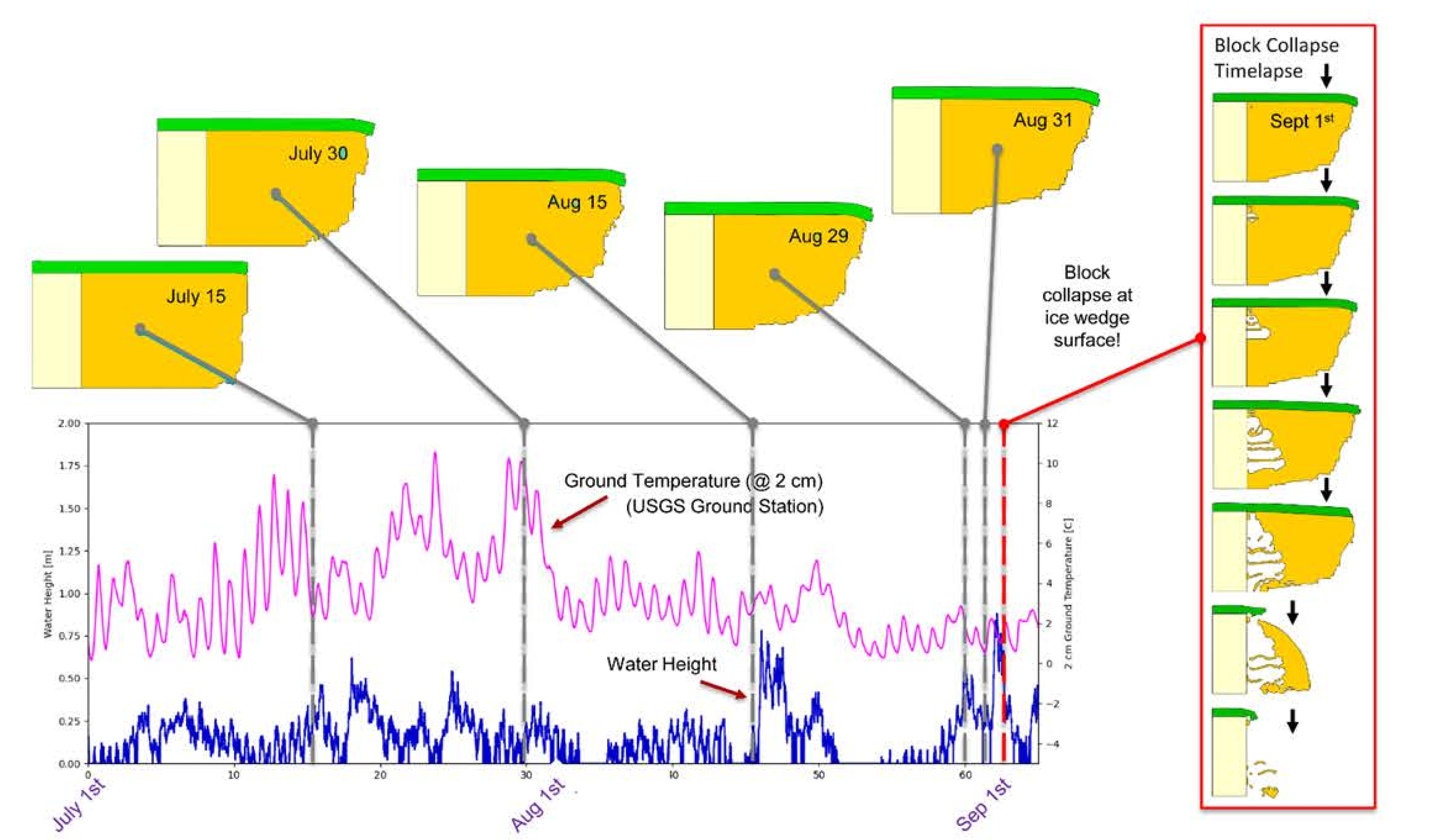
- implicit Newmark solver for the mechanical problem
- explicit forward Euler solver for the thermal problem



Vertical Thermistor:
Measure niche formation



Time-lapse Camera:
Measure denudation & collapse



The ACE model has been calibrated and used to simulate an observed block collapse event at Drew Point, AK on Sept. 1, 2018 (right panel), when forced with realistic oceanic and atmospheric boundary conditions (bottom panel). Permafrost, ice and peat are shown in orange, yellow and green, respectively.

Upscaling in 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

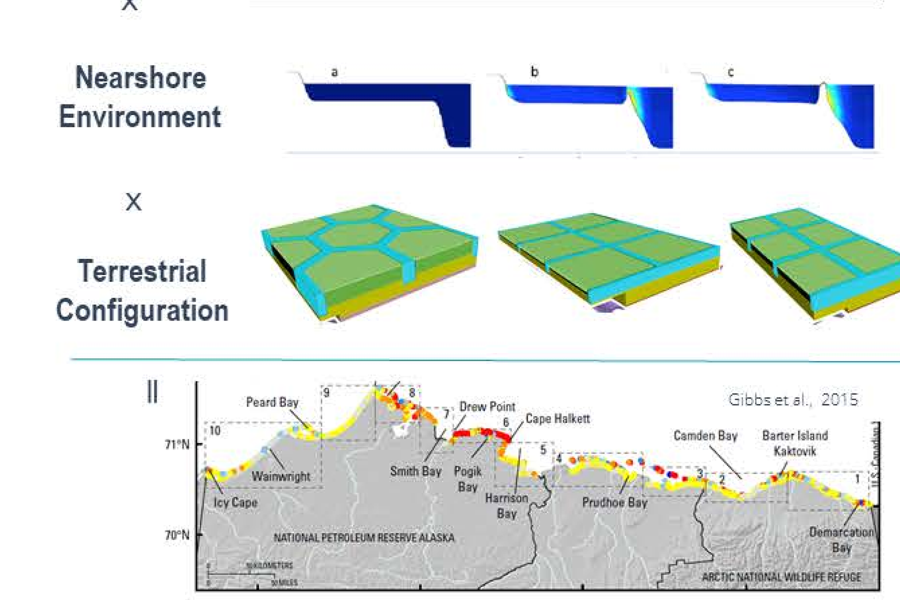
Historical	Tp (s)	Hs (m)	Wave Direction	Water Level (m)	Wind Direction	Wind Speed (m/s)	Wave-Wind Orientation
Cluster 1	5.00	1.11	33	-0.15	29	5.5	N-N
Cluster 2	6.30	1.55	113	-0.10	113	6.0	E-E
Cluster 3	7.30	1.40	270	+0.15	263	4.9	W-W
Cluster 4	8.10	2.50	98	-0.20	113	13.0	E-E
Cluster 5	8.75	2.00	330	+0.10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



For further information:

Eymold, W.K., Flanary, Erikson, L.H., C., Nederhoff, K., Chartrand, C., Jones, C. , Kasper, J.L., Bull, D.L. 2022. Typological representation of the offshore oceanographic environment along the Alaskan North Slope. Continental Shelf Research.

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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