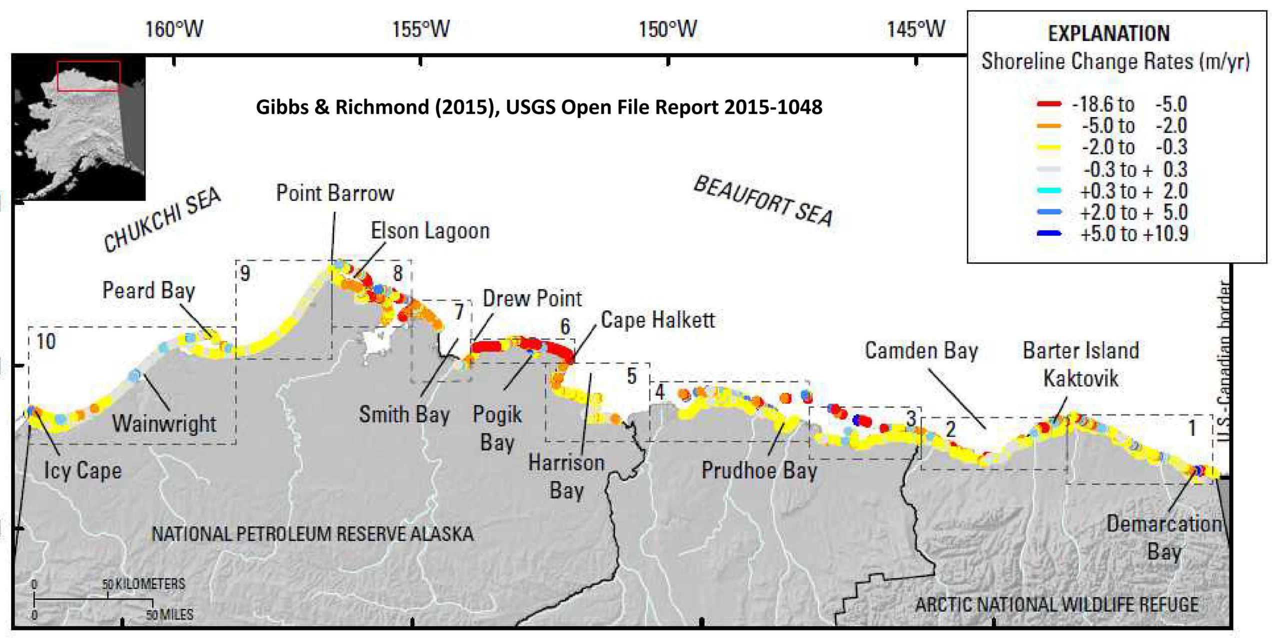
Development of a Tightly Coupled Numerical Model for Arctic Coastal Erosion, Infrastructure Risk, and Evaluation of Associated Coastal Hazards

Jennifer M. Frederick*[1], Diana L. Bull[1], Alejandro Mota[1], Matthew. A. Thomas[2], Benjamin Jones[3], Craig Jones[4], Jeremy Kasper[3], Craig Connolly[5], James McClelland[5], and Jesse Roberts[1]

* jmfrede@sandia.gov [1] Sandia National Laboratories [2] U.S. Geological Survey [3] University of Alaska, Fairbanks [4] Integral Consulting Inc. [5] University of Texas

EP23D-2351

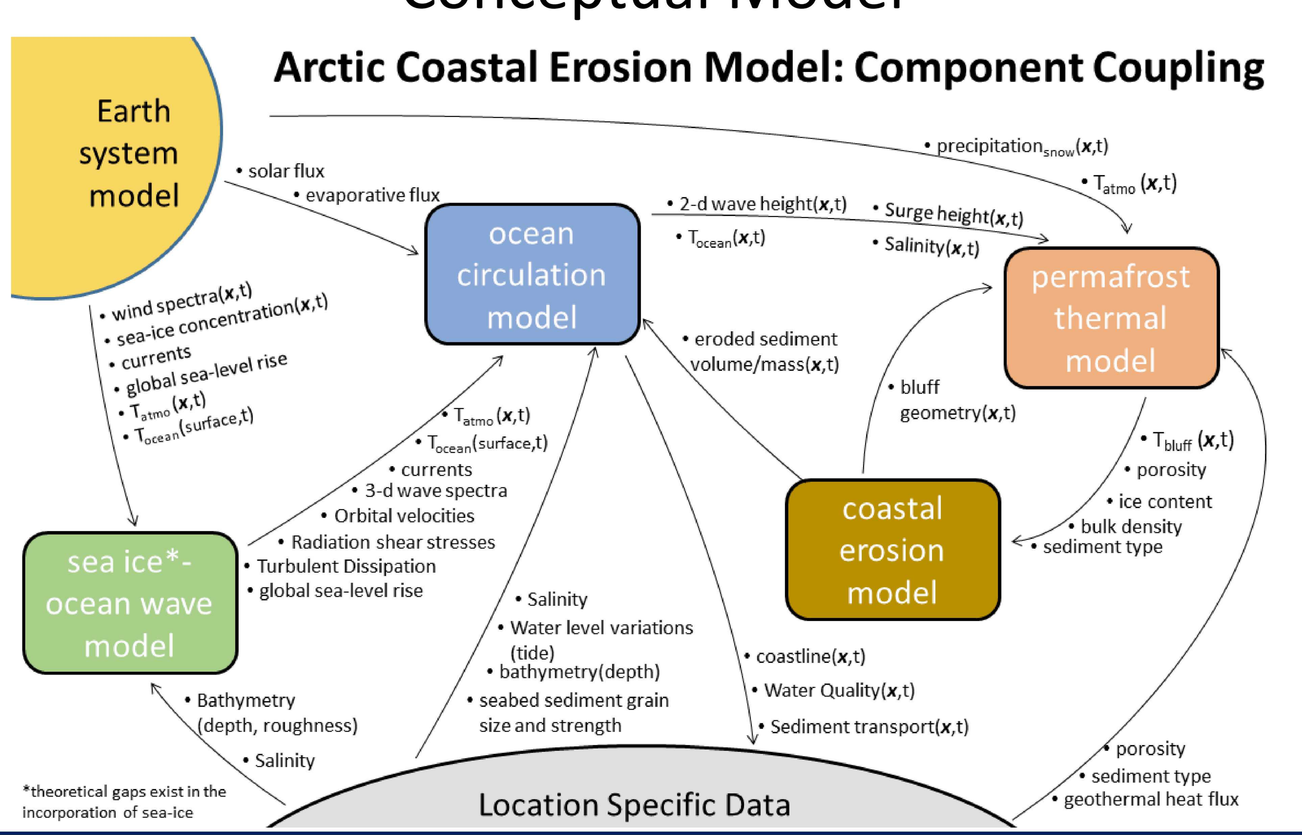
Introduction



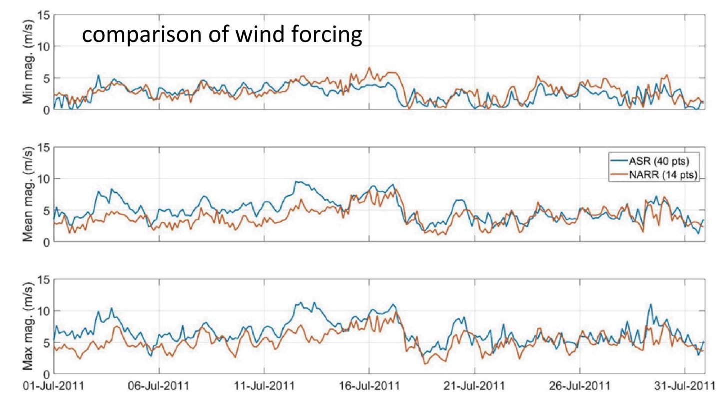
- One-third of the global coastline consists of Arctic permafrost coasts.
- The U.S. and Canadian coastlines exhibit the highest erosion rates in the Arctic and are among the highest rates in the world.
- Rates of coastal erosion are increasing: 1955-1979 - 6.8 m/yr; 1979-2002 – 8.7 m/yr; 2002-2007 – 13.6 m/yr; 2007-2016 – 17.2 m/yr [Jones et al. 2009, Jones at al. 2018].
- Block failure erosion is most common along Alaskan Arctic coastline.
- Rapid Arctic coastal erosion stands to adversely impact native, scientific, industrial, and military communities in Alaska.
- Sandia National Laboratories (SNL), the U.S. DOE, and the U.S. DOD operate research and defense sites along rapidly degrading coastline (Utqiaġvik, Atqasuk, Oliktok Point).
- SNL has recently funded a project to develop a predictive coupled model for Arctic coastal erosion, focusing on Drew Point.

Block failure along Alaskan Arctic coastline (Drew Point).
Images: Ben Jones, University of Alaska, Fairbanks

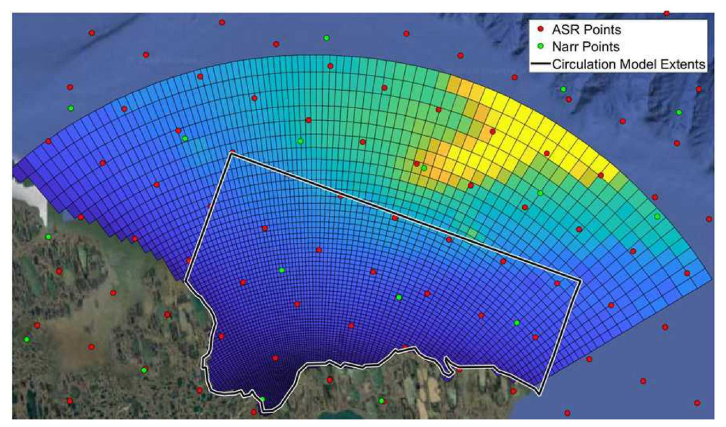
Conceptual Model

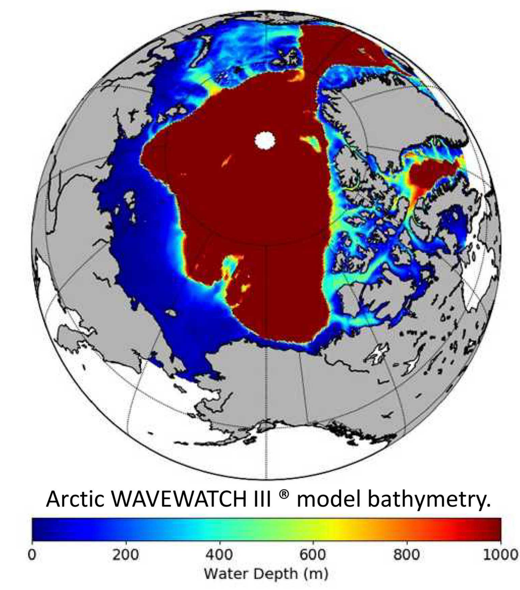


Oceanographic Model



Multiple atmospheric reanalysis datasets were used to supply the wind forcing and sea ice extent for the WW3 model. These reanalysis data sets included the Arctic System Reanalysis v2 (ASR) and the North American Regional Reanalysis (NARR). Using multiple atmospheric forcing datasets provided a range of hindcast predictions and helps describe the uncertainty in model simulations.
SWAN model bathymetry and DFlow-FM model extend is shown below.

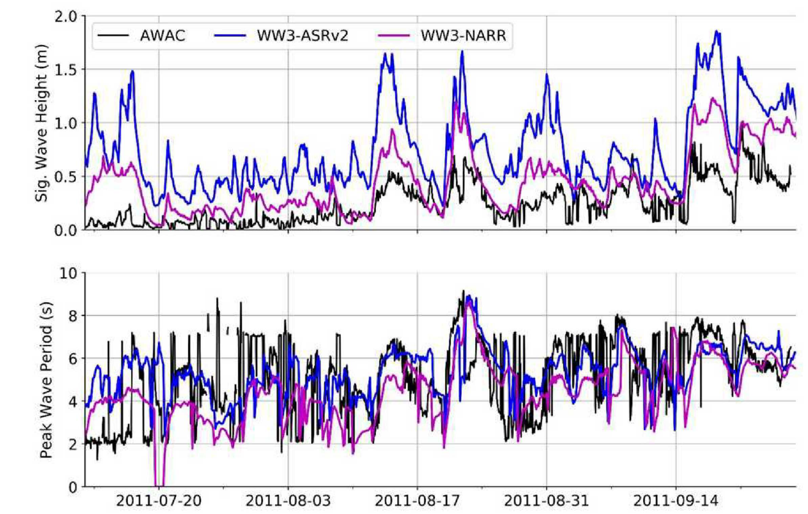




Arctic WAVEWATCH III ® model bathymetry.

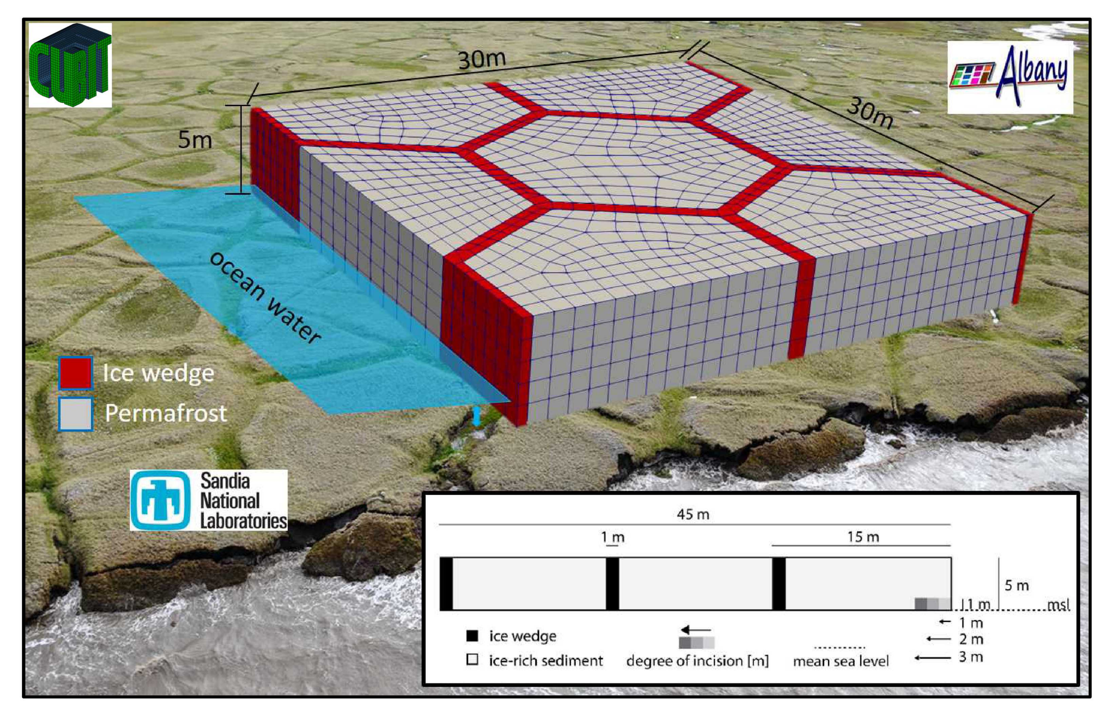
- The initial step for the modeling system evaluation was simulating waves in the largest domain, the WW3 model. All of 2011 was simulated using 3-hourly ASR winds and sea ice and blended NARR/ASR winds and ASR sea ice. The WW3 model data were compared to a single measured data location, a Nortek AWAC acoustic Doppler current profiler deployed at Barter Island during the summer and fall of 2011.
- This comparison provided an initial assessment of the variation in wave results using different atmospheric reanalysis datasets. The ASR wind forcing is shown to cause over predictions of wave heights at the selected location while NARR forcing resulted in better agreement to the measure wave heights. Both reanalysis datasets predicted the peak period well.

- The formulation of high temporal fidelity predictions of hydrodynamic and wave parameters along the Alaskan coast necessitates the application of site specific numerical models.
- These models incorporate atmospheric and hydrodynamic factors such as sea ice coverages, winds, and regional water levels to determine relevant parameters such as water levels and wave heights in a region of interest.
- We use a three-model system to simulate conditions around Drew Point on the North Slope of Alaska:
  - Two spectral wave models, WAVEWATCH III® (WW3) and Simulating Waves Nearshore (SWAN), provide wave field information at varying spatial and temporal resolutions in the region of interest.
  - DFlow-FM is a hydrodynamic model used to simulate nearshore circulation including water level variations, currents, and temperature in the region of interest.



Thermo-Chemo-Mechanical Model

- The Arctic Coastal Erosion (ACE) model is being developed in ALBANY (https://github.com/gahansen/Albany).
- ALBANY is an open-source, multi-physics research platform developed mainly at Sandia National Laboratories.
- ALBANY is written in object-oriented C++, is parallel, can handle unstructured grids, and uses the implicit finite element method for solving general partial differential equations.
- The grid is meshed by CUBIT (https://cubit.sandia.gov).
- Advances in the ACE model include calculations of:
  - unsteady 3D stress/strain according to classical solid mechanics formulations (e.g. no empirical relationships or pre-defined stress planes)
  - unsteady 3D permafrost temperature, ice content, and unfrozen water content, that includes effects of salts
  - thermal properties that depend on permafrost state
  - mechanical strength properties that depend on permafrost state
  - material evolution which tightly couples permafrost strength and temperature

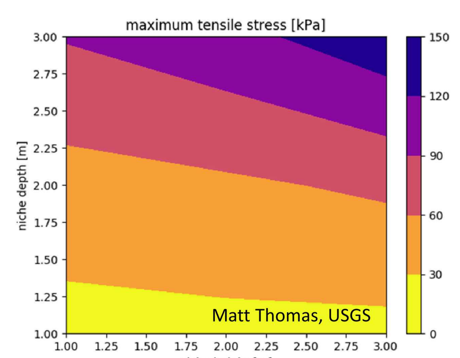


Governing Equations For Mechanics Problem

$$\Phi[\varphi] := \int_\Omega A(\boldsymbol{F}, \boldsymbol{Z})\ \mathrm{d}V - \int_\Omega \rho \boldsymbol{B} \cdot \varphi\ \mathrm{d}V - \int_{\partial_{\boldsymbol{T}}\Omega} \boldsymbol{T} \cdot \varphi\ \mathrm{d}S$$

$\boldsymbol{F} := \nabla\varphi$ deformation gradient; Helmholtz free energy density; body forces (B), like gravity; surface forces (traction T)

We use a simple J2 deformation theory of plasticity (equivalent to non-linear elasticity). *It is not yet permafrost-specific!*



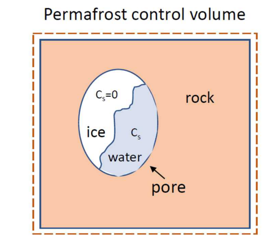
This figure shows how the maximum tensile stress varies with niche geometry. To create this plot, niche depth and height were systematically varied and the maximum tensile stress was calculated. Tensile stress depends more strongly on niche depth. These simulations are based on simple J2 deformation theory, and do not yet include permafrost-specific constitutive relationships.

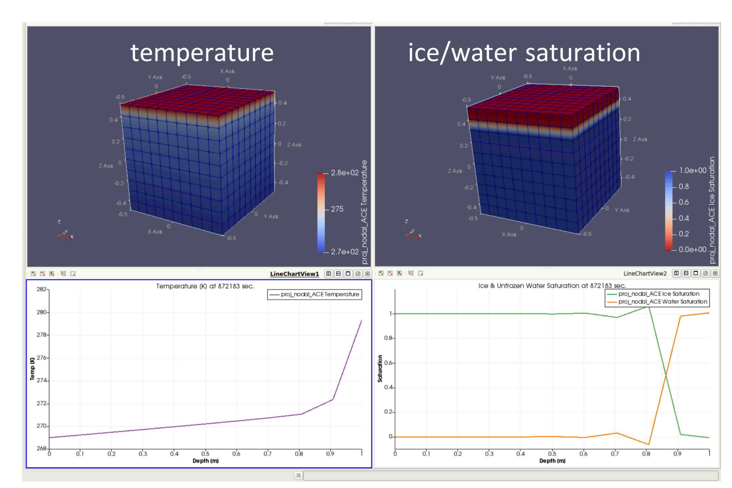
Governing Equations For Thermal Problem

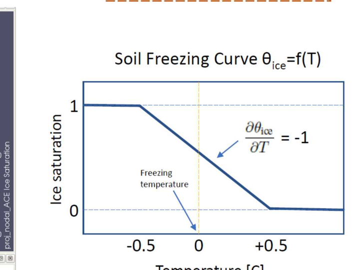
$$\overline{\rho c_p}\frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{K} \cdot \nabla T) + \Theta$$

$$\Theta := \rho_f L_f \frac{\partial f}{\partial t} = \rho_f L_f \frac{\partial f}{\partial T}\frac{\partial T}{\partial t}$$

heat evolution due to conduction and phase change (ignores convection)

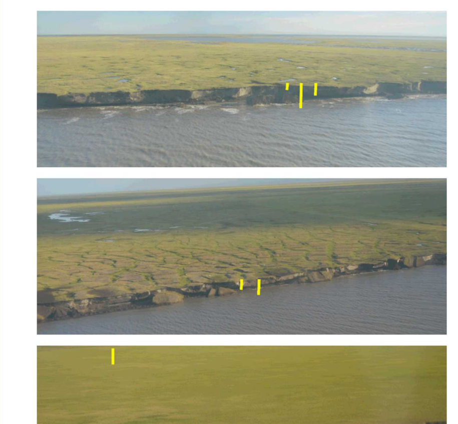






This figure shows a snapshot of permafrost temperature and ice/water saturation after heat was applied to the top of the initially frozen domain.

Drew Point April 2018 Permafrost Coring



PM 1 - Primary Surface – bluff height 6.8 m
- Deep Core: 7.4 m
- Short Core 1: 4.0 m
- Short Core 2: 1.3 m
- Cryopeg from 6.5 to >7.4 m bgs
  - Cryopeg at 0.3 m asl to >0.6 m bsl

DP 1 - Ancient Drained Lake Basin– bluff height 5.2 m
- Deep Core: 7.5 m
- Short Core 1: 3.3 m
- Cryopeg from 5.1 to > 7.5 m bgs
  - Cryopeg at 0.1 m asl to > 2.3 bsl

DP 2 - Young Drained Lake Basin– bluff height 4.0 m
- Deep Core: 4.6 m
- Short Core: 3.0 m
- Cryopeg from 4.1 m to > 4.6 m bgs
  - Cryopeg at 0.1 m bsl to >0.6 m bsl

Total core length retrieved– ~31 m

Fig. 10. Borehole DP-2'-2, silt with reticulate cryostructure, 30-55 cm.

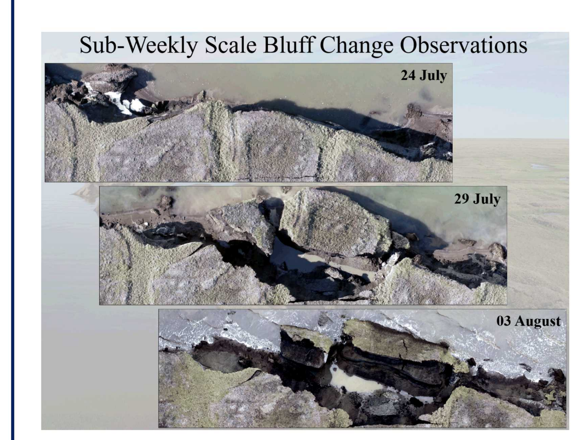
Fig. 5. Borehole PM-1-1, subvertical silt/peat structure: almost no visible ice in peat, extremely ice-rich silt with ataxitic cryostructure, 180-200 cm.

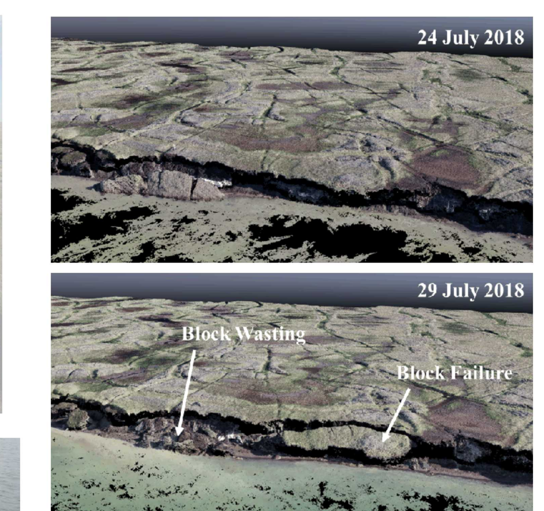
The Coring Team:

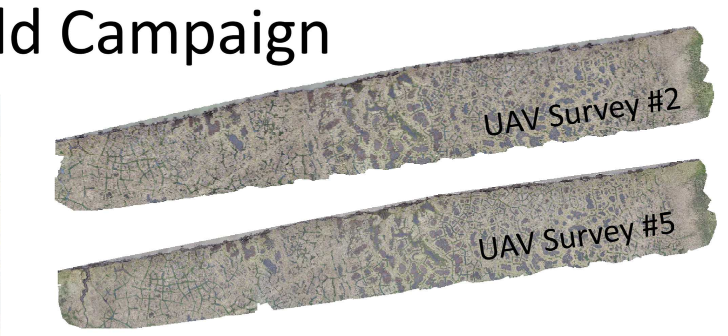
Fig. 9. Borehole DP-1-1, unfrozen silty clay, 650-670 cm.

In April, a small team braved the frozen tundra to take several core samples of the permafrost at Drew Point. The team discovered a cryopeg while coring which is located at and below today's sea level. *Does the cryopeg contribute to Drew Pt's elevated erosion rates?*

Drew Point July 2018 Field Campaign

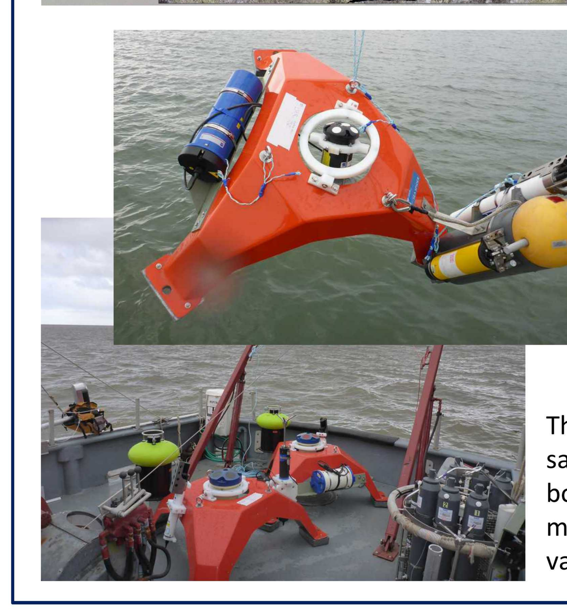






UAV surveys can tell us how the coast changes between surveys. It can also help characterize tundra morphology, such as polygon size and spacing.

In late July and early August 2018, another small team lead by Ben Jones went back to Drew Point to collect field data on land and sea. The summary of observations and measurements made are shown below:

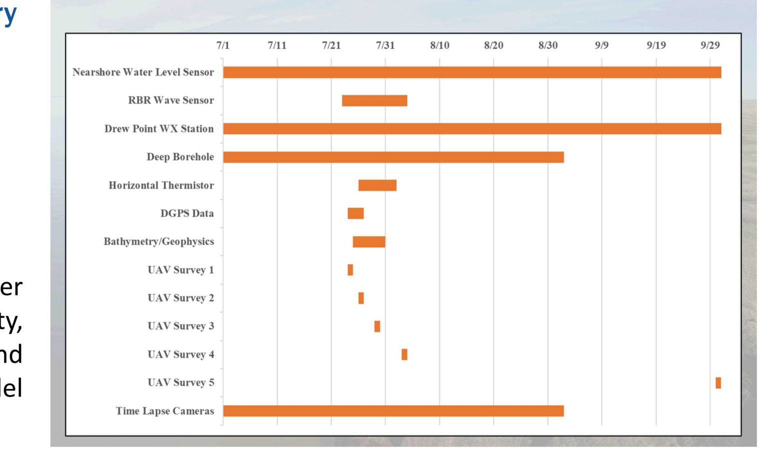


Drew Point Measurement Summary

- 8 x 3 water samples (nuts, TSS, delO18)
- 8 CTD casts (LISST, PAR, OBS, chl. A)
- 8 bottom grabs (grain size)
- Multibeam bathymetric mapping
- 1 year-round mooring
  - ADCP: Directional wave spectra, water velocity
  - CTD: water level, sal., temp.

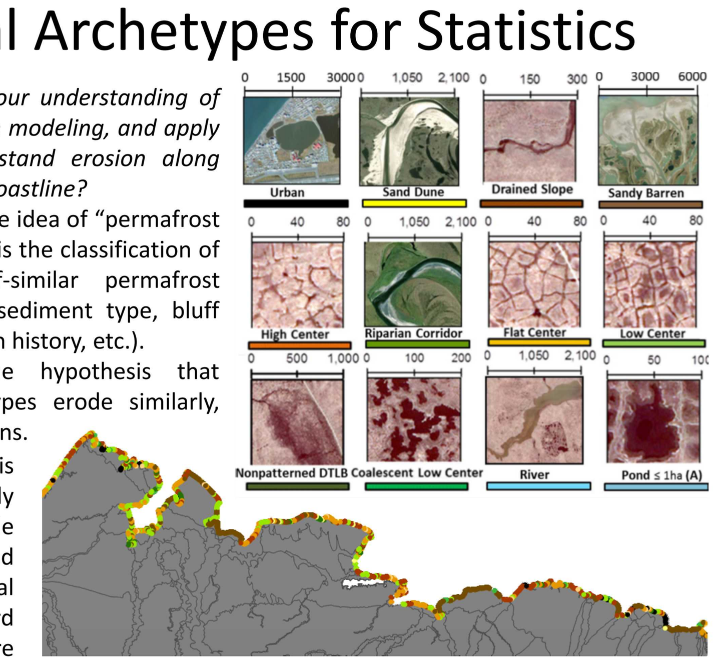
The oceanographic data collected (water samples, conductivity, temperature, density, bottom grabs for grain size, bathymetry, and mooring data) will aid the oceanographic model validation.

Summary of Terrestrial Observations in 2018 Season



Coastal Archetypes for Statistics

- *How can we take our understanding of event-based erosion modeling, and apply it to better understand erosion along entire stretches of coastline?*
- We are exploring the idea of "permafrost archetypes," which is the classification of regions with self-similar permafrost morphology (e.g., sediment type, bluff geometry, formation history, etc.).
- We will test the hypothesis that permafrost archetypes erode similarly, given same conditions.
- If this hypothesis is true, we can apply predictions made with event-based modeling to regional scales, for hazard and infrastructure risk analysis.



References & Further Reading

This work was supported by a Laboratory Directed Research and Development project at Sandia National Laboratories. For further information, please contact the Principle Investigator, Diana L. Bull, dlbull@sandia.gov, or the project manager and Sandia's Arctic Science and Security Initiative point of contact, Lori Parrott, lkparro@sandia.gov.

Frederick, J.M., M.A. Thomas, D.L. Bull, C. Jones, and J. Roberts. 2016. The Coastal Erosion Problem. SAND2016-9762, Sandia National Laboratories, Albuquerque, NM.

Jones, B. M., C. D. Arp, M. T. Jorgenson, K. M. Hinkel, J. A. Schmutz, and P. L. Flint. 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. Geophysical Research Letters, 36, L03503.

Jones, B. M., L. M. Farquharson, C. A. Baughman, R. M. Buzard, C. D. Arp, G. Grosse, D. L. Bull, F. Gunther, I. Nitze, F. Urban, J. L. Kasper, J. M. Frederick, M. A. Thomas, C. Jones, A. Mota, S. Dallimore, C. Tweedie, C. Maio, D. H. Mann, B. Richmond, A. Gibbs, M. Xiao, T. Sachs, G. Iwahana, M. Kanevskiy, and V. E. Romanovsky (2018), A decade of remotely sensed observations highlight complex processes linked to coastal permafrost bluff erosion in the Arctic, Environmental Research Letters, vol. 13, no. 11, doi:10.1088/1748-9326/aae471.