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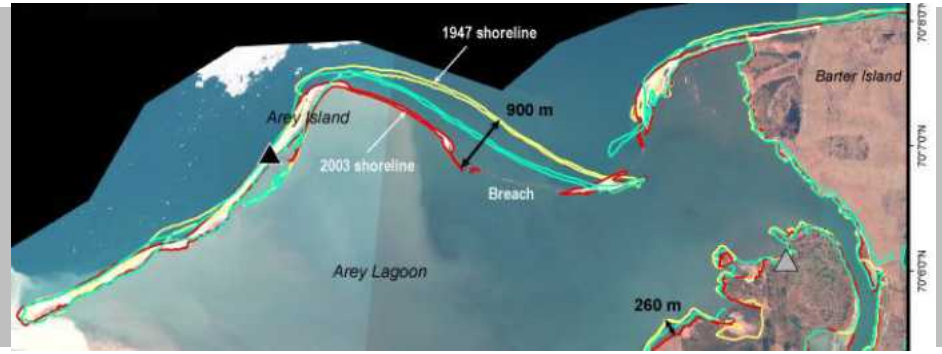

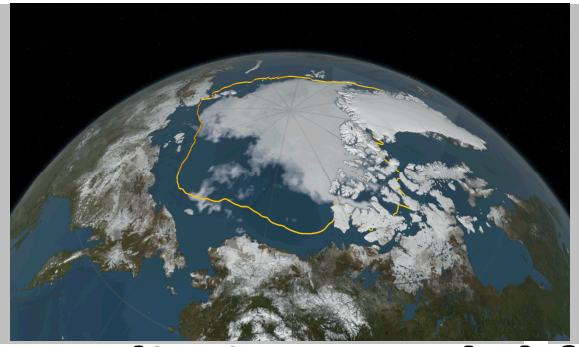

A Predictive Model for Arctic Coastal Erosion Interagency Arctic Research Policy Committee Permafrost & Coastal Resilience Collaborations. February 13th 2018

PI: Diana Bull (00159), PM: Lori Parrott (08863)

Jennifer Frederick, Ben Jones, Craig Jones, Jeremy Kasper, Alejandro Mota, Jesse Roberts, Matt Thomas

Jim McClelland, Craig Connolly, Ken Dunton

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Team & Funding

Team Member	Qualifications and Expertise
Diana L. Bull (PI)	(SNL); Physicist with expertise in ocean wave dynamics, model development, laboratory and field testing, data analysis, and statistics
Kenneth Dunton	(UT Austin); Ecologist with expertise in coastal ecosystem dynamics, food web relationships, and biogeochemical cycling in estuaries
Jennifer M. Frederick	(SNL); Computational geoscientist with expertise in software development, validation and verification, flow and transport modeling in porous media, and permafrost thermal modeling.
Benjamin M. Jones	(USGS); Integrating field studies and remote sensing data in permafrost, research campaigns along remote arctic coastlines, field instrumentation and near-real time data transmissions
Craig Jones	(I.C.); Coastal hydrodynamics and sediment transport data analysis and modeling with expertise in field program and model development.
Jeremy Kasper	(UAF); Physical oceanography of shallow ice covered continental shelves including observations and modeling
James McClelland	(UT Austin); Biogeochemist with expertise in land to sea fluxes, composition, and bioavailability of organic matter in water, soils, and sediments
Alejandro Mota	(SNL); Computational solid mechanics, finite element analysis, numerical methods, constitutive models, large deformation, plasticity, fracture and failure.
Jesse D. Roberts	(SNL); Sediment dynamics measurement and modeling expertise in coastal environments. Extensive experience in managing large projects with multiple partners.
Matthew A. Thomas	(USGS); Experience with slope stability assessment via stochastic Factor of Safety computation, and numerical simulation of coastal slope instability.

Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

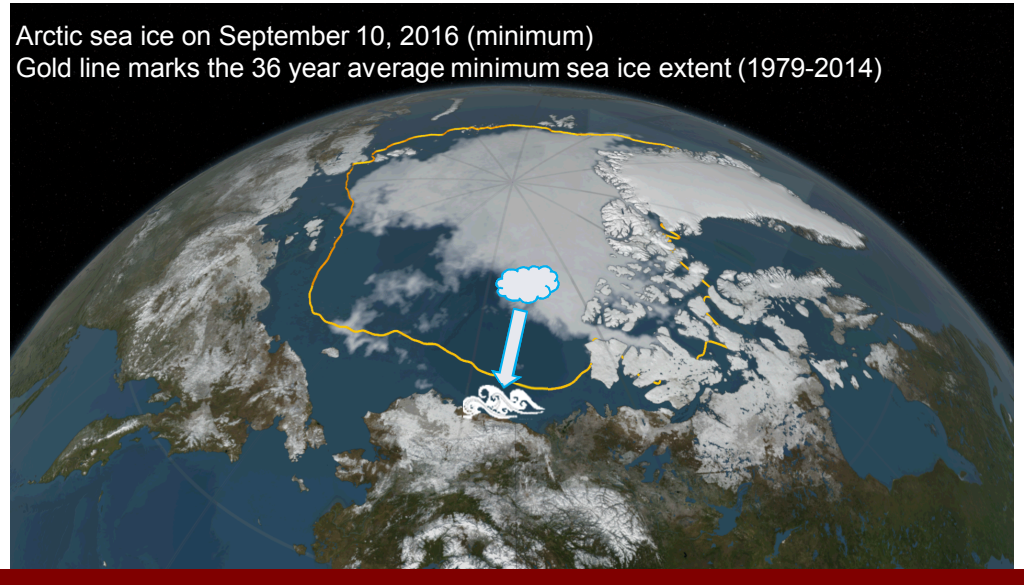
MOTIVATION

Problem Statement

The Arctic is warming at twice the rate of the rest of the US resulting in **accelerated coastal erosion rates** due to:

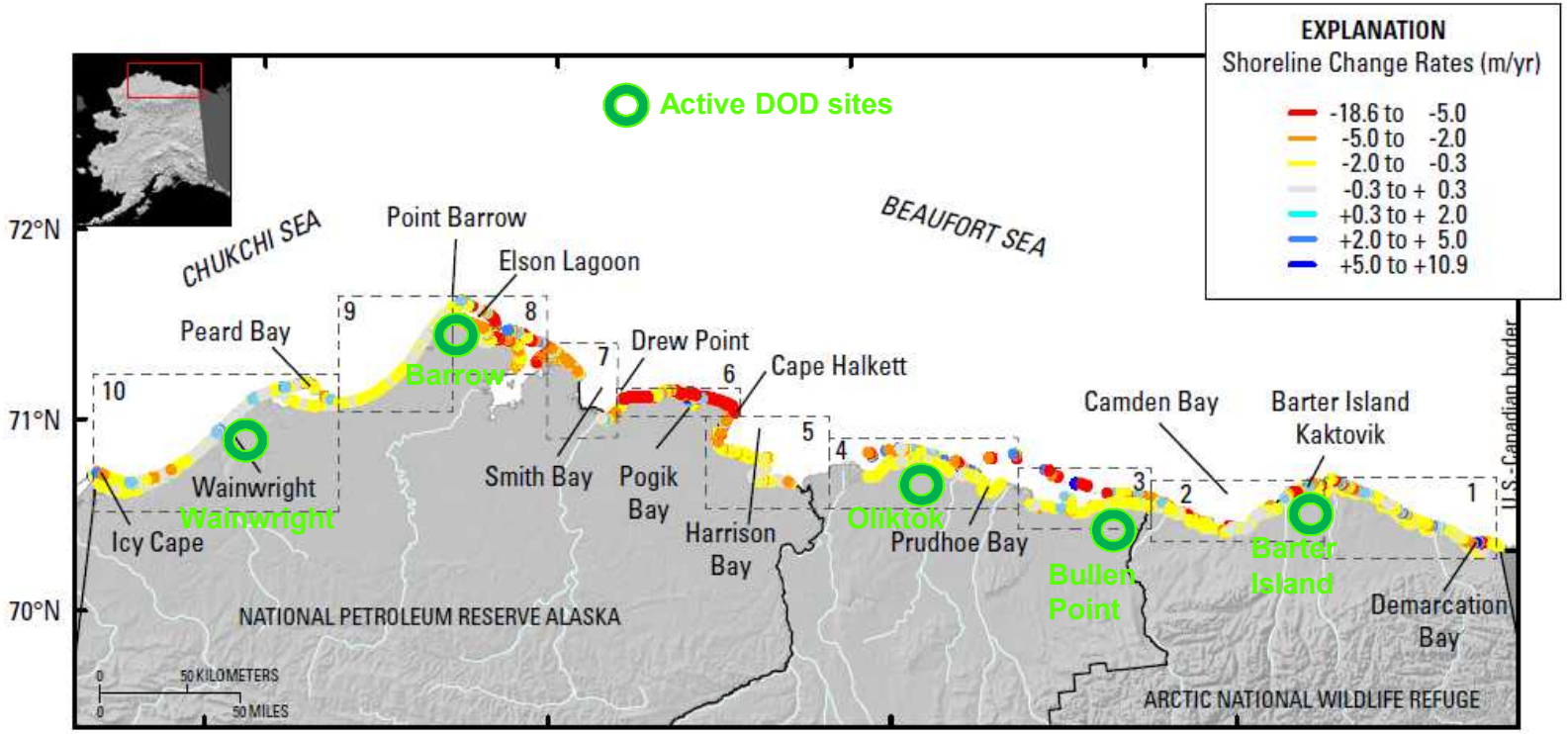
- ~40% decline in sea ice since 1979 resulting in increasingly energetic waves incident upon the Alaskan coast
- increasing sea water temperatures due to ice-albedo positive feedback
- thawing permafrost

Permafrost exposed by coastal erosion along the Beaufort Sea (credit: K. Dunton, UT)



Problem Statement

- Along the northern Alaskan coastline:
  - 7 active DoD sites
  - Over 30 threatened villages
- Potential Economic Impact of Coastal Erosion is ~1Billion
- Further, increasing activity in warming Arctic demands new infrastructure (deep water port, tourism, rescue services)



Erosion: Gibbs, A. E., and B. M. Richmond. 2015. National assessment of shoreline change-Historical shoreline change along the north coast of Alaska, U.S.-Canadian border to Icy Cape. U.S. Geological Survey Open-File Report 2015-1048, 96 p.
DOD Sites: Alaska Department of Environmental Protection. 2016. Department of Defense Sites in Alaska. https://dec.alaska.gov/, accessed 2016.09.20.

Arctic Coastal Erosion Cross-section

T_{atm} f(x,y,t)

surface energy balance

erosion rate

ice wedge (failure surface)

sediment strength f(Temp,t)

permafrost bluff

sum of torques

shear failure plane

permafrost temperature field f(x,z,t)

ice content

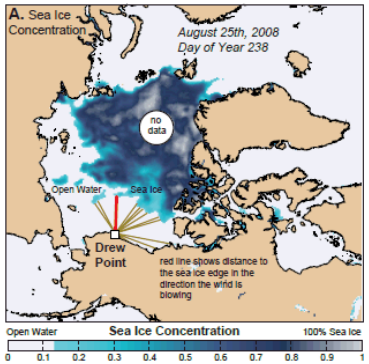
niche growth

z

x

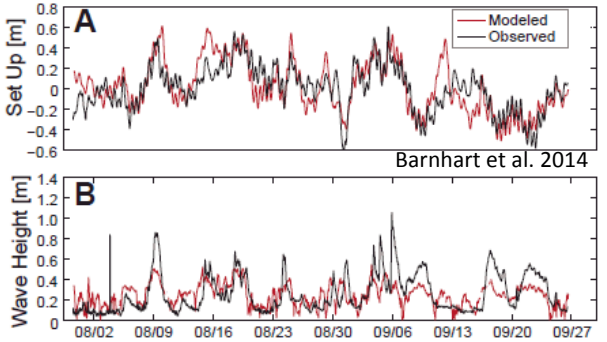
Earth system and sea ice-ocean models

Barnhart et al. 2014



wave energy density spectrum

ocean circulation model



Barnhart et al. 2014

$Temp_{ocean}$ $Salinity_{ocean}$ f(x,y,t)

sediment flux

bathymetry

submarine permafrost

J. M. Frederick, M. A. Thomas, D. Bull, C. Jones, and J. D. Roberts (2016) The Arctic coastal erosion problem, SAND2016-9762, Sandia National Laboratories, NM.

Project Goals

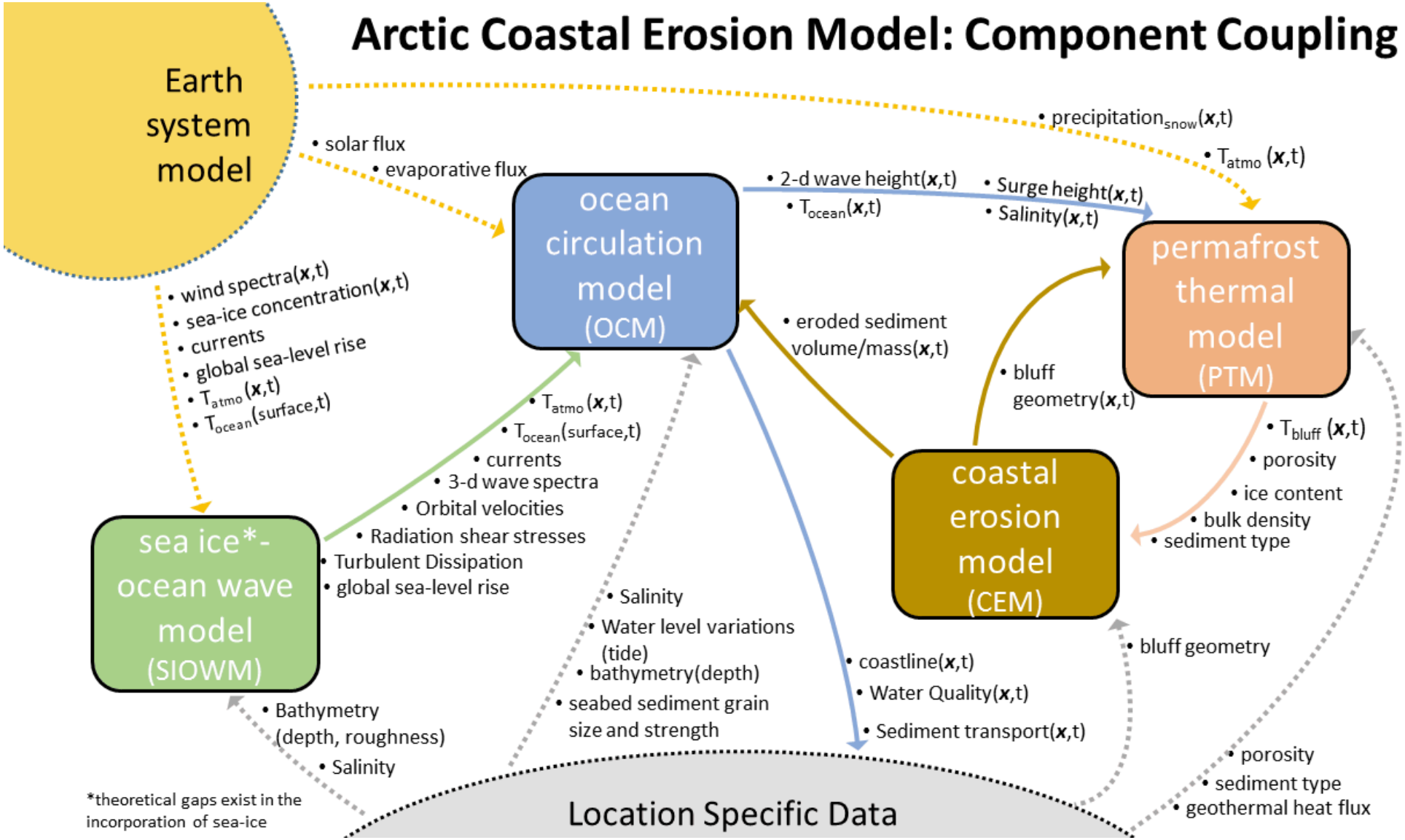
This project will deliver a field-validated predictive model of thermo-abrasive erosion for the permafrost Arctic coastline.

- The event-based projections will provide a quantitative tool
  - for guiding military and civil infrastructure investments, and
  - understanding coastal food webs and carbon-climate feedbacks.
- Redistributed eroded sediment in the environment enables
  - prediction of deposition locations,
  - tracing of toxic eroded materials, and
  - estimates of biogeochemical fluxes.
- Establish enduring relationships with Arctic invested parties
  - University of Alaska Fairbanks,
  - UT Austin,
  - BLM,
  - Geological Survey of Canada (GSC),
  - USGS,
  - CRREL

FY18 – FY20

ENVISIONED MODEL PROGRESSION

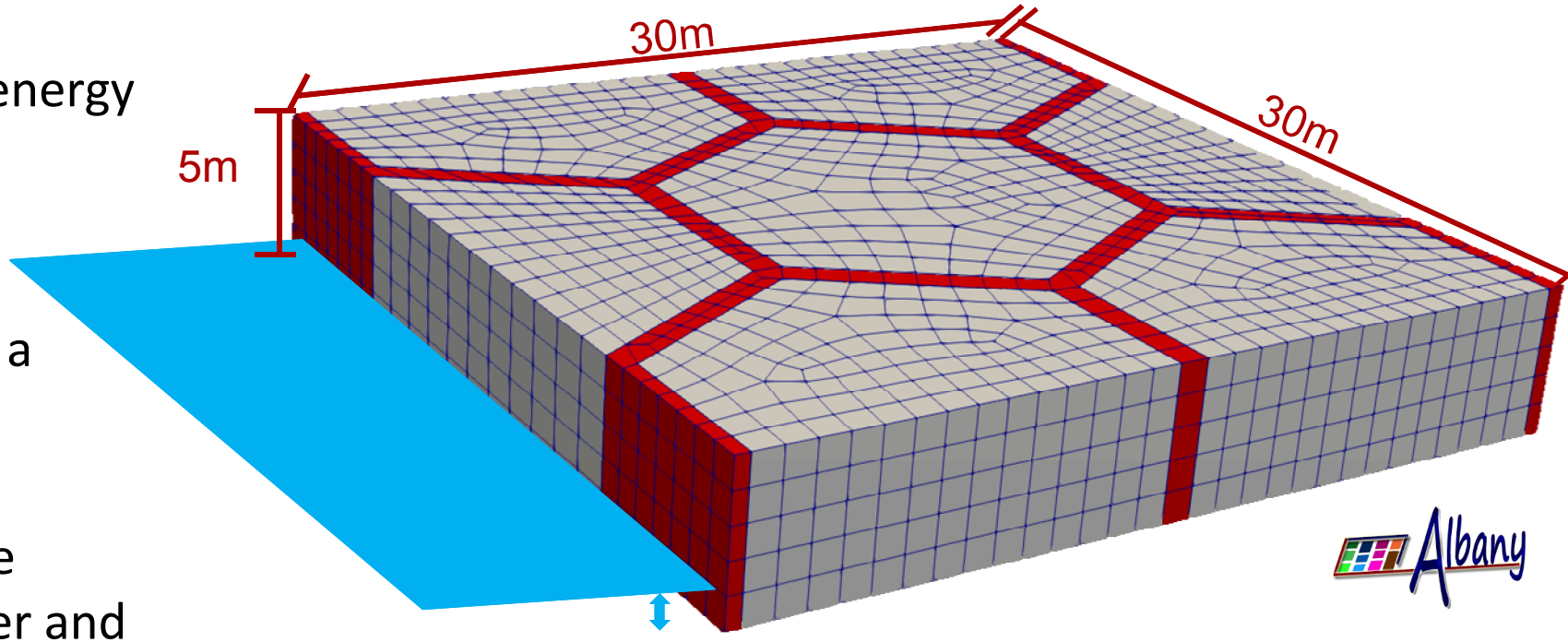
Technical Approach

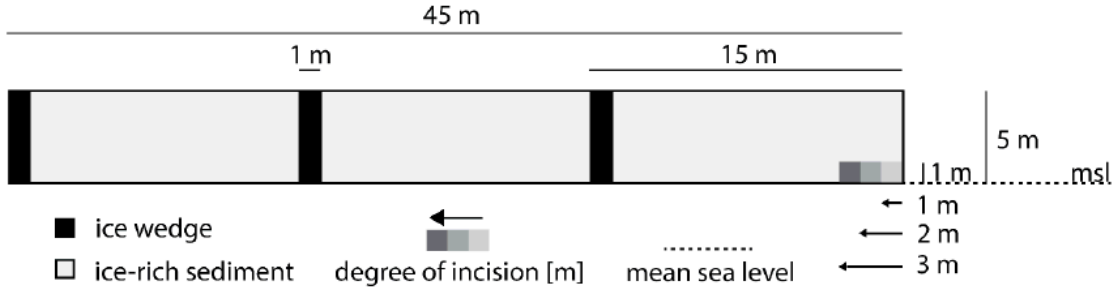


Single Event Mechanistic Modeling

validated, single storm, tightly coupled thermo-structural model

- Tightly coupled wave and circulation model to obtain energy spectra and time averaged inundation heights realized stochastically in multiple time-varying realizations for a ~4-hour long storm event
- Multi-physics finite element model of coastline archetype section with 3-D heat transfer and underlying finite deformation plasticity model
- Validation data provided by experimental campaign (FY18-FY19)

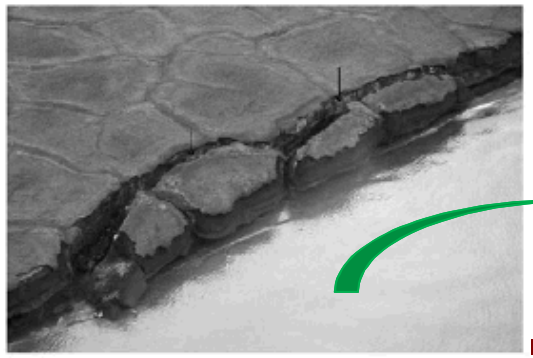




Statistical Modeling

Parameterization enabling coastline view & historical validation

- Model Parameterizations
  - Identify the variable sensitivities that manifest distinct erosional behavior
- Coastline Parameterizations
  - Identify coastline stretches with characteristics that cause unique model parameterizations
- Multiple Archetype Runs
  - Create a “catalog” of coastline archetypes and their overall response to a set of storms
- Historical Validation
  - Using historical data for oceanographic conditions, coastline and model parameterizations, and documented shoreline retreat rates



Predictive Modeling

Parameterizations combined with earth climate models to enable future predictions

- Using IPCC RCP8.5* project oceanographic conditions into the future
- Employ the statistical model and coastline architecture in concert with projected conditions to estimate future levels of erosion
- Use estimates of future erosion levels:
  - infrastructure impact analysis
  - nearshore ecological studies
  - tracing of eroded material

(credit: B. Jones, U.S. Geological Survey)

*The RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in absence of climate change policies.

FY18 MODELING WORK

Oceanographic

WW3 Development of wave field in the Arctic to develop nearshore BC's

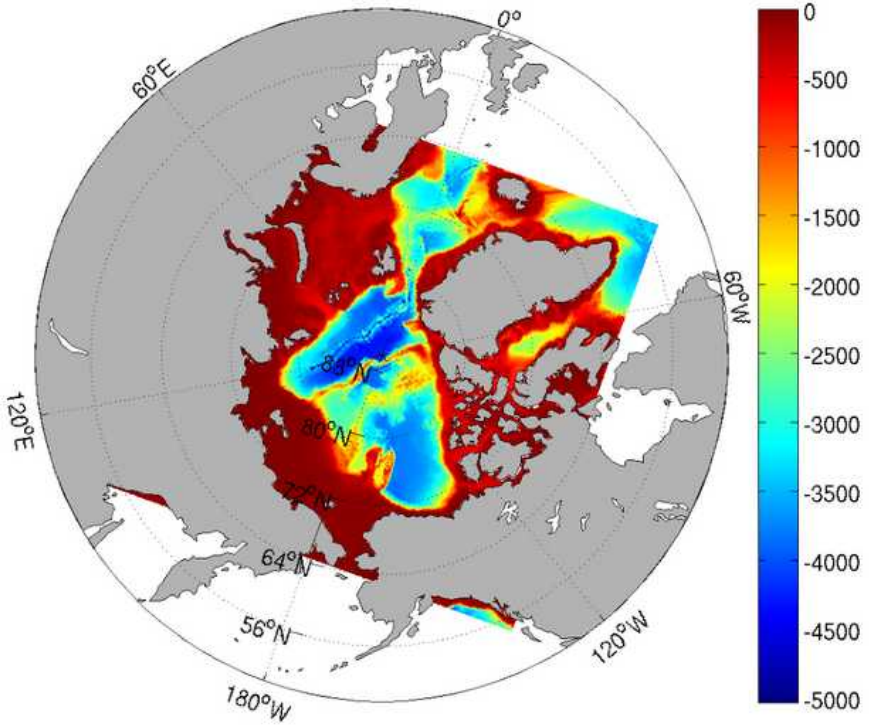
- surface winds
- ice cover
- temperature (surface and ocean)
- solar radiation
- persistent currents

SWAN Wave set-up conditions 2-way coupled with circulation

- high resolution near shore environment
- capture set-up (storm surge and runup)
- wave energy inclusive of induced current effects

Delft3D Circulation and thermodynamic mixing 2-way coupled with waves

- ability to model mixing of temperature and salinity clines
- capture induced currents in nearshore



- Potential Key Advances
  - Inclusion of ice coverage for fetch limited wave growth
  - Knowledge of wave energy along broad coastline
  - Set-up determination inclusive of bathymetry and wave energy
  - Ability to accurately predict temperature at bluff face through mixing of clines in the ocean

Thermo-chemical-structural

Thermo-chemical

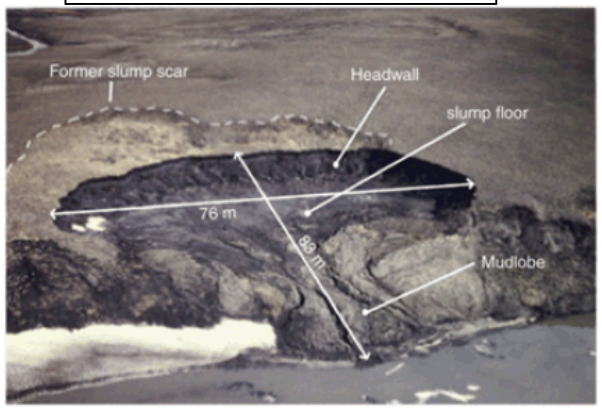
- Sediment type
- Ice volume
- Water volume
- Pore size
- Salinity
- Temperature field

Structural

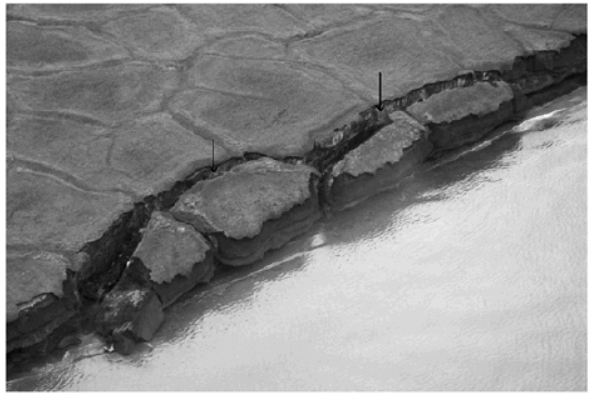
- Strength relationships as a function of thermo-chemical state
- Morphology of coastline
- Cohesion of permafrost
- Bulk and shear moduli

- Potential Key Advances
  - Failure modes develop from constitutive relationships in FEM model
  - 3-D unsteady heat flow inclusive of the chemistry (salinity)

retroactive slumping



block failure



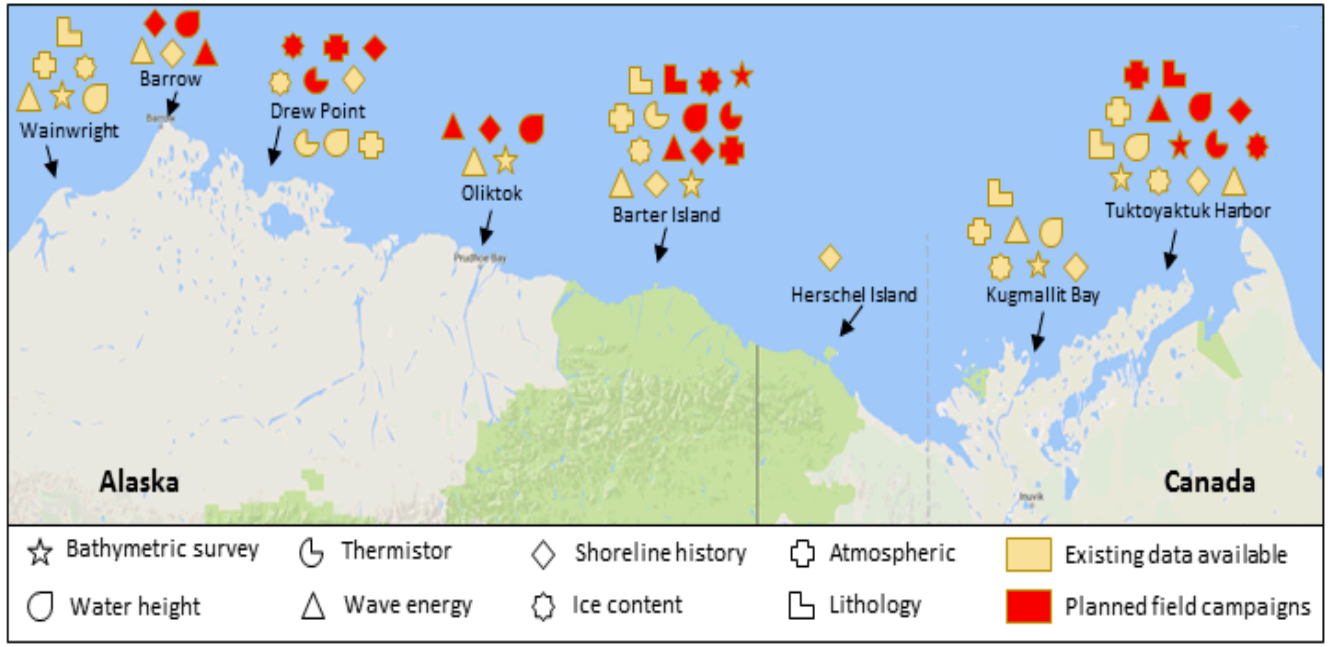
active layer detachment

*Albany is an implicit, unstructured grid, finite element code for the solution and analysis of multiphysics problems developed by SNL and released in public domain

FY18 FIELD CAMPAIGN

Landscape of field work

- **Known Campaigns**
  - Multiple historical and active experimental campaigns with relevant data to validate our models
  - Project will **augment the Drew Point database** to establish a more complete data set
    - Will complement strong data sets at Barter and Tuk harbor



- **Project Connections**
  - **Beaufort Lagoon Ecosystems (BLE) Long Term Ecological Research (LTER) program**
    - Determine **impacts to water quality** by focusing on **biogeochemical characterization** of eroding soil and hence **ecological stability** in the region
  - **Bureau of Ocean Energy Management: Wave and Hydrodynamic Modeling in Beaufort Sea**
    - **Evaluate wave and storm surge** for the Beaufort Sea (past, present and future) with **verification of coupled wave, sediment, hydrodynamic model** of Foggy Island Bay.

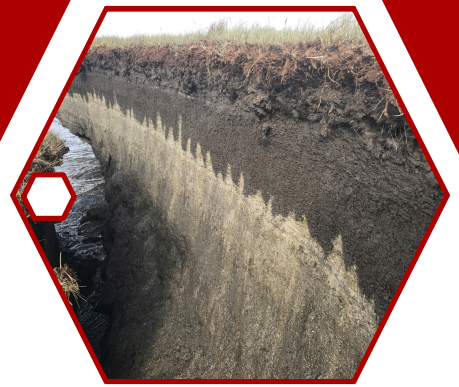
Project Field Campaign

Oceanography

Coastal Morphology

Permafrost

Biogeochemical



Atmosphere

Validation Data Set

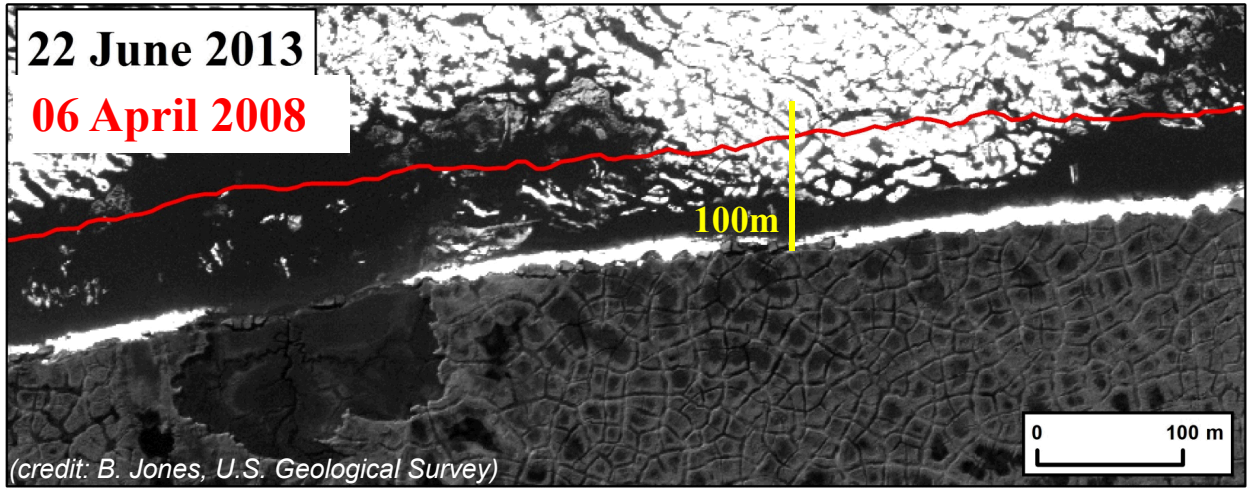
Obtaining data at resolution needed to validate mechanistic model

- Oceanographic
  - Wave Spectra (Significant wave height, direction and period); Water Temperature; Water Salinity; Water Depth; Water Currents; Bathymetry; Ice Thickness and Velocity
- Atmospheric
  - Air Temperature; Incident / reflected solar flux; Wind speed / direction @ 3 m above ground; Snow depth; Atmospheric pressure; Ground temperature (10 depths: 5-120cm); Soil Moisture; Rainfall
- Permafrost
  - Ice content (cryostructure & unfrozen content); Salinity content; Grain size characteristics; Silt / sand fraction; Stress-Strain Analysis (soil strength testing) as a function of temperature (up to thawing); Permafrost Temperature; Active Layer Depth
- Coastal Morphology
  - Ice Wedge Geometry; Shoreline positions; 3-D bluff mapping; Niche Geometry

IMPACTS

Technological/Scientific Impact

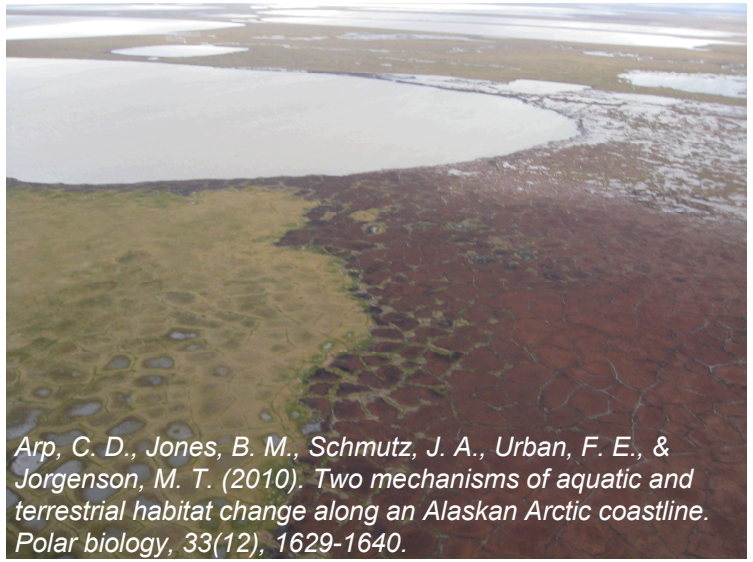
- Chief technical advancements in this model
  - modeling time-dependent ocean inundation upon the coast,
  - accounting for ocean temperature variations,
  - simulating transient multi-dimensional permafrost thermodynamics including ice content evolution,
  - assessing the permafrost stress state through constitutive relationships
  - providing inputs to assess impact on water quality
  - experimental validation



Technological/Scientific Impact

- Chief impacts of this model
  - predicted erosion rates over time (given climatic input data or weather forecasts)
  - designed to coupled with infrastructure impact models
  - facilitates ecological impact studies key to understanding food-webs
  - aids in tracking eroded sediment for deposition or toxic tracing studies
  - enables informed and sustainable risk management decisions with respect to infrastructure

(credit: B. Jones, U.S. Geological Survey)



Arp, C. D., Jones, B. M., Schmutz, J. A., Urban, F. E., & Jorgenson, M. T. (2010). Two mechanisms of aquatic and terrestrial habitat change along an Alaskan Arctic coastline. Polar biology, 33(12), 1629-1640.

DISCUSSION

Uncertainties

- Variability in permafrost is high, it is poorly characterized along the coastline, and it must be considered to develop widely applicable predictive capabilities.
  - How can we best incorporate uncertainty surrounding permafrost properties?
  - How can we best incorporate uncertainty surrounding the geomorphology of coastlines?

- Given all this variability, the need for high quality and broadly representative data sets is high.
  - Is there additional data available?
  - Is there a particular measurement we should consider?
  - Is there a widely used repository we should consider to upload our data to?