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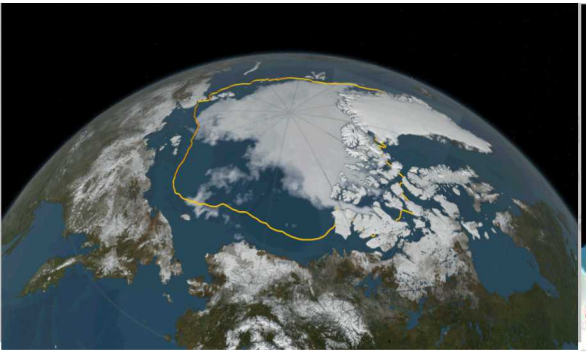

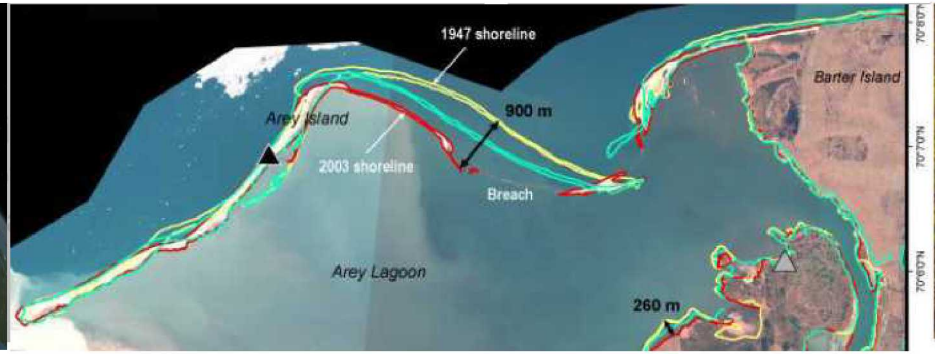


# A Predictive Model for Arctic Coastal Erosion

## University of Alaska Fairbanks. August 6th 2019

PI: Diana Bull, PM: Lori Parrott

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

Jim McClelland, Craig Connolly, Emily Bristol

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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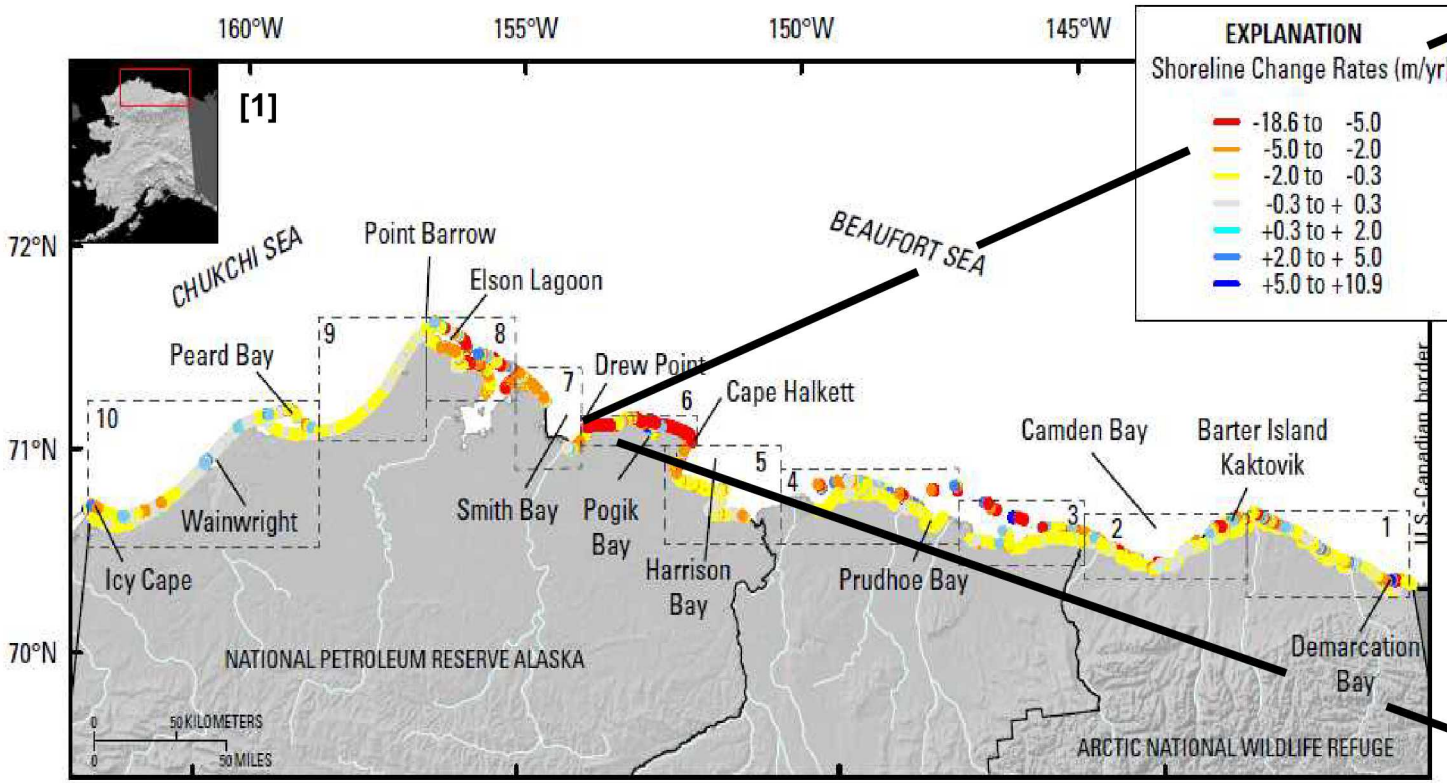
# MOTIVATION

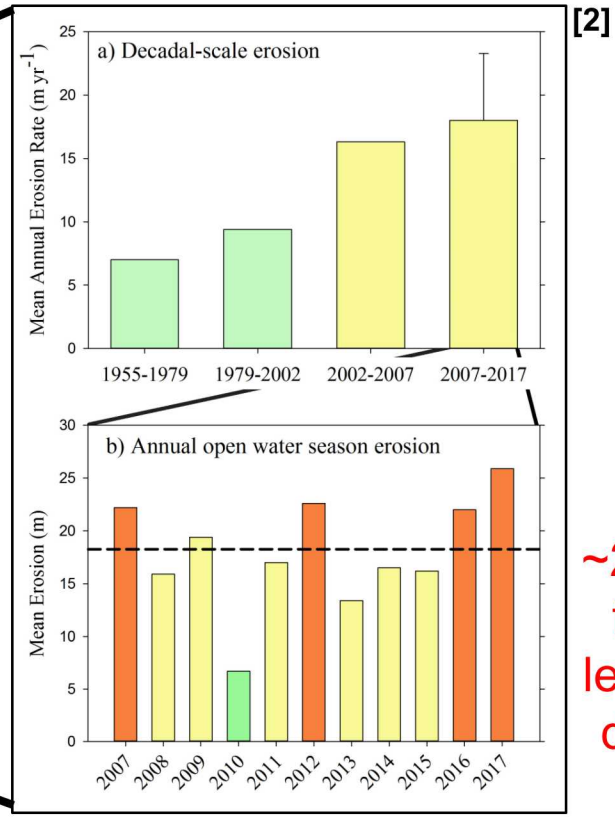
# Problem Statement

The Arctic is warming at 2-3 times the rate of the rest of the US

- 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
- Warming permafrost

There is evidence of accelerating coastal erosion rates



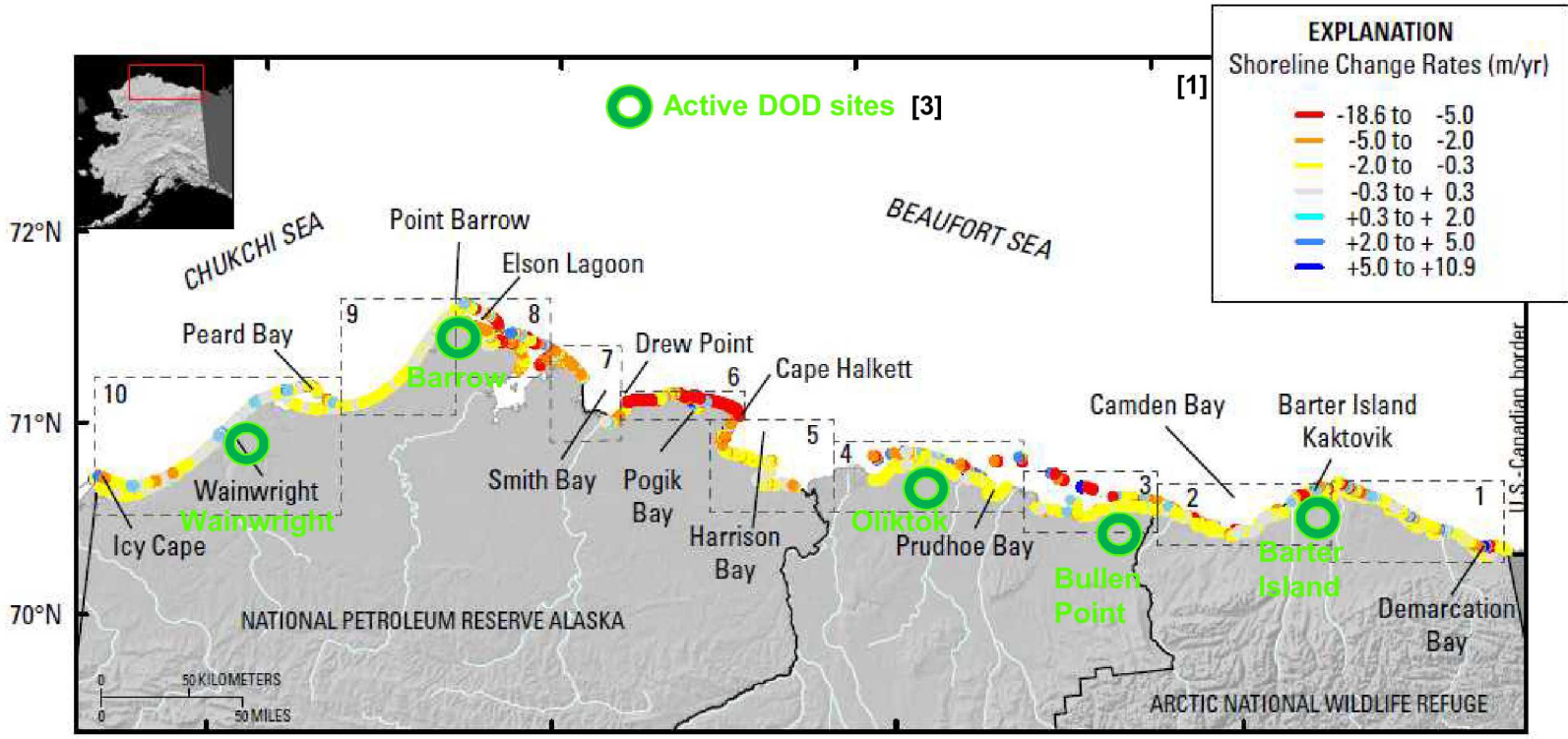

~2 football fields in length in a decade!!

# Impacts

## Infrastructure

- 6 active DOD sites along northern coastline [3,4]
- 30 coastal villages threatened [5]
- Anticipated economic impact is ~1Billion [5,6]

**Anticipated infrastructure development should consider spatially varying erosion *and* deposition rates along Northern Alaska coastline**




## Coastal food webs

- biogeochemical influx into ocean effects  ecological stability of region

## Carbon-climate feedbacks

- Permafrost stores half of all terrestrial organic carbon (1,330-1,580Pg [7], twice the amount in the atmosphere); degrading coastline mobilizes the carbon content

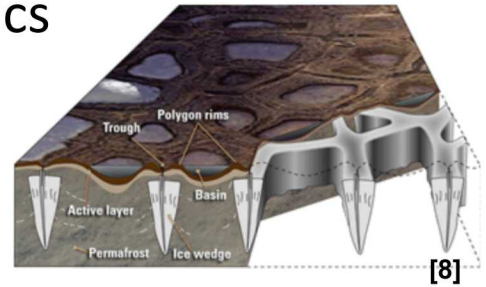
# State of the Technology

## Unique erosion process in Arctic

- Ice acts to bind unconsolidated soils in permafrost
- Melting ice causes failure

## Erosion dependent characteristics

- Geomorphology
- Geophysics
- Boundary Conditions

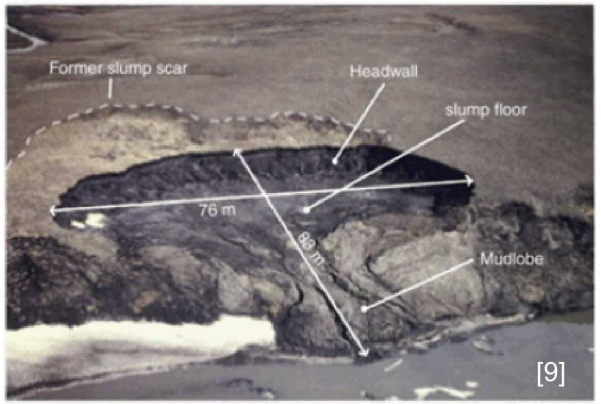


[8]

## State of the art permafrost erosion modeling

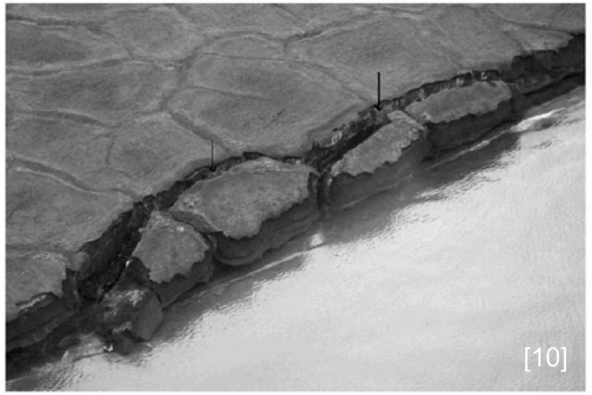
- Trend projection, empirical relationships, 1-D steady state heat flow, …
- Modeling typically estimates boundary conditions and does not account for geomorphologies or geophysics

retrogressive thaw slumping



[9]

block failure


[10]

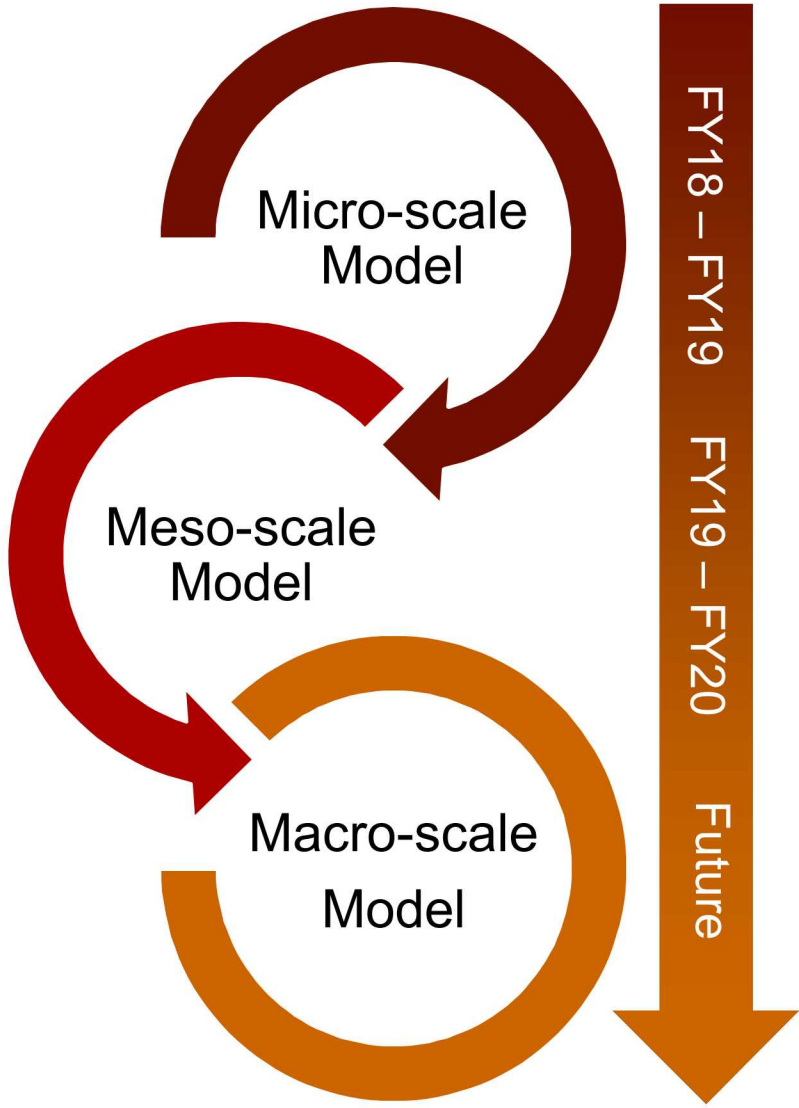
[9]

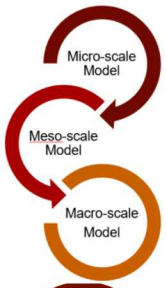

[11]

active layer detachment

FY18 – FY20

# ARCTIC COASTAL EROSION (ACE) MODELING APPROACH



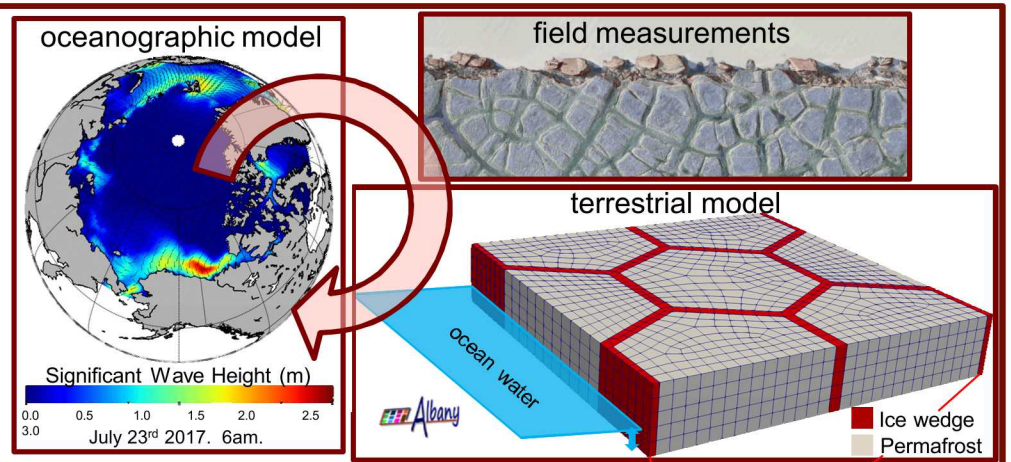



# Proposed Solution

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

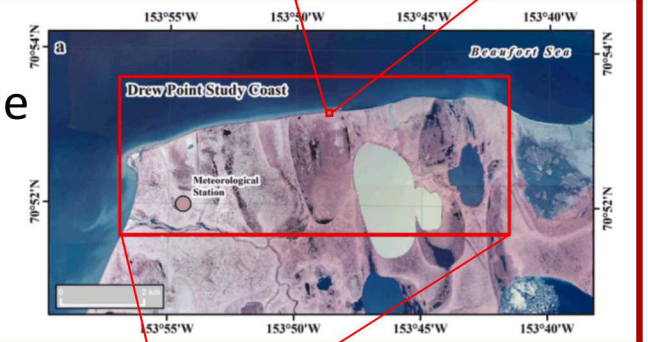
**FY18-FY19 Micro-scale Model**
10's of meters & storm duration

- Multi-physics finite element terrestrial model coupled with high-fidelity model of water levels along a coastline
  - 3-D thermo-chemo-mechanical constitutive relationships allowing any terrestrial deformation
  - Time-varying boundary conditions of same fidelity and resolution as terrestrial model



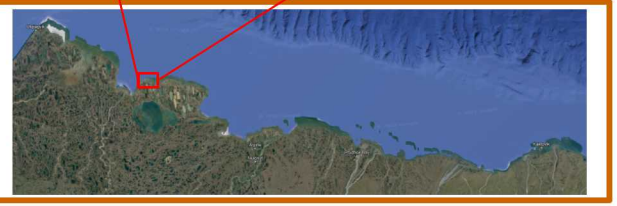

**FY19-FY20 Meso-scale Model**
10's of km's & seasonal duration

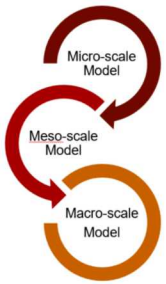
- A weighted combination of micro-scale models representing a stochastic distribution of terrestrial configurations along a coastline
  - Site specific probability distribution functions of geomorphology and geophysics used to weight erosion output
  - Evaluating ocean "exposure metrics" to represent time-varying ocean




**future Macro-scale Model**
North Slope & annual

- A weighted combination of meso-scale models to capture circum-Arctic terrestrial and oceanographic variation
  - Fidelity built-upon a series of archetypes at micro- and meso-scales






# Boundary Conditions

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## Atmospheric, Terrestrial, Oceanographic

### Historical

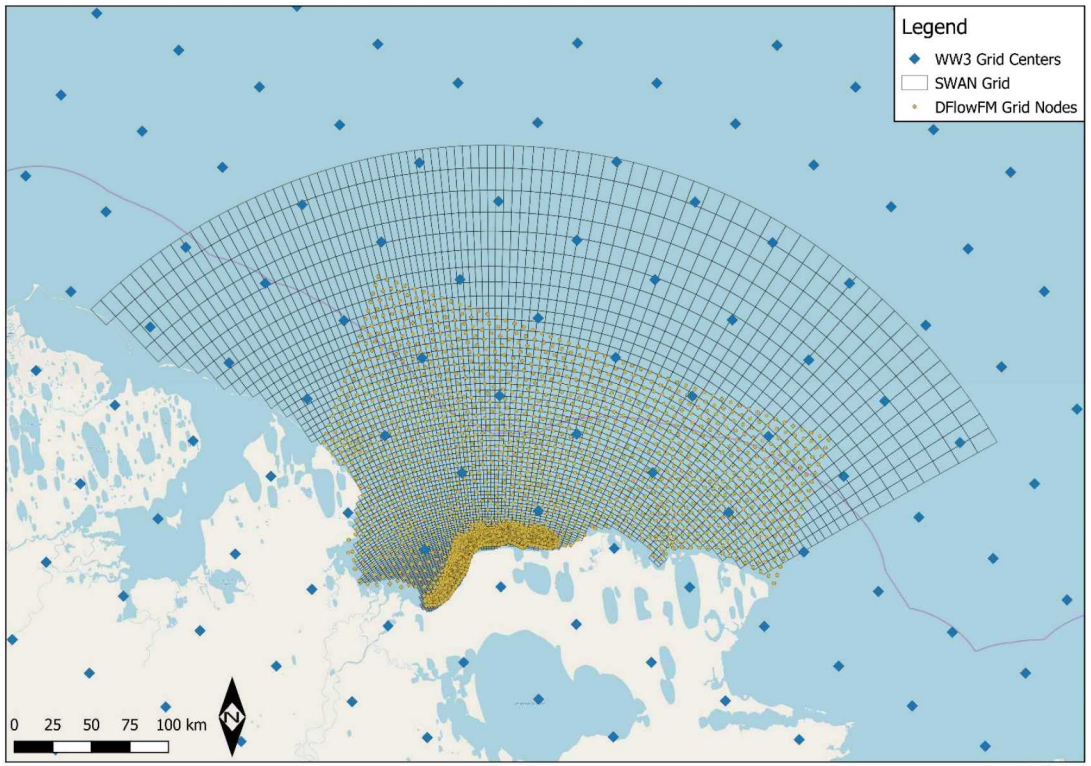
- Arctic system reanalysis (ASR) v2 & HYCOM

### Present Day

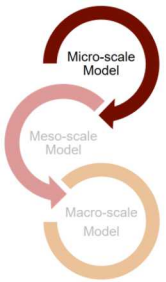
- Field work

### Projections

- Downscaled earth system model predictions under IPCC RCP8.5*




*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 & FY19

# Micro-Scale Modeling

validated, single storm, tightly coupled thermo-chemo-mechanical model

## Time-varying boundary conditions

- Water level, temperature, & salinity defined through coupled, bathymetry dependent oceanographic models
- Air temperature, permafrost temperature, & radiative flux (potential)

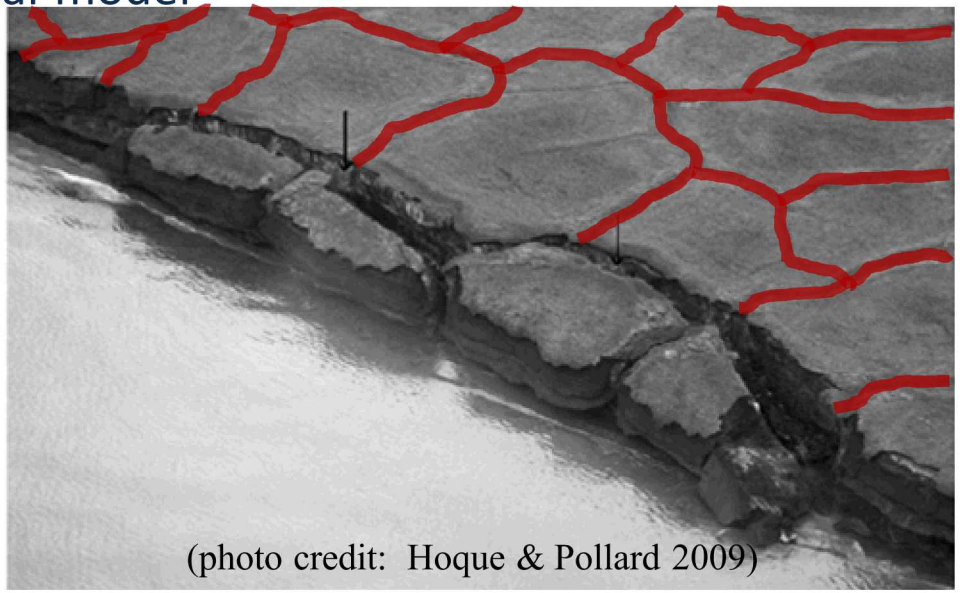
## Terrestrial coastline

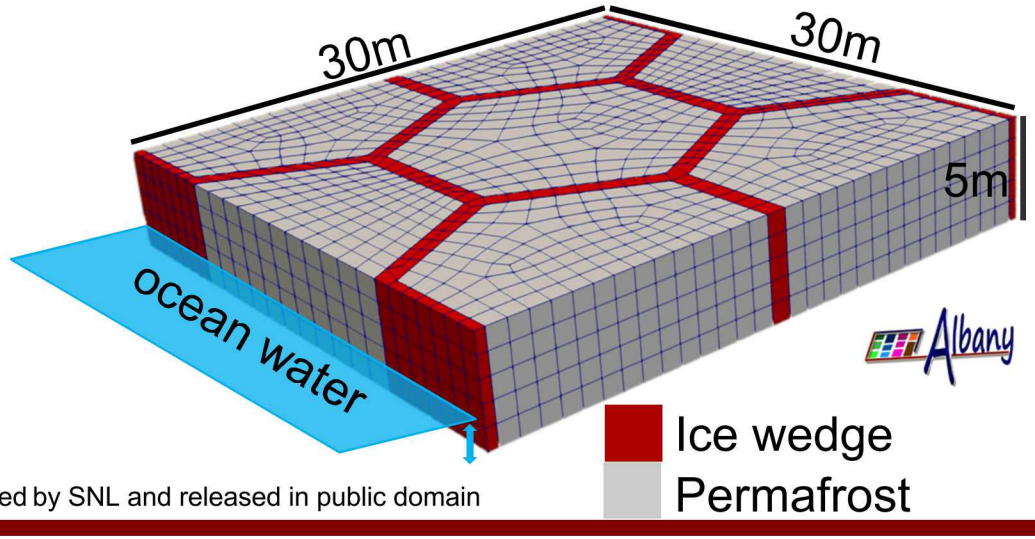
- Multi-physics finite element model developed in Albany*
- Geomechanical testing to determine coupled thermal-mechanical strength characteristics

## Site-specific geomorphology & geophysics

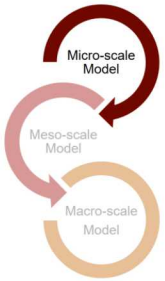
- 3-D stress in terrestrial model evolves based on these characteristics

## Validation campaign


(photo credit: Hoque & Pollard 2009)




*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




# Oceanographic Modeling

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

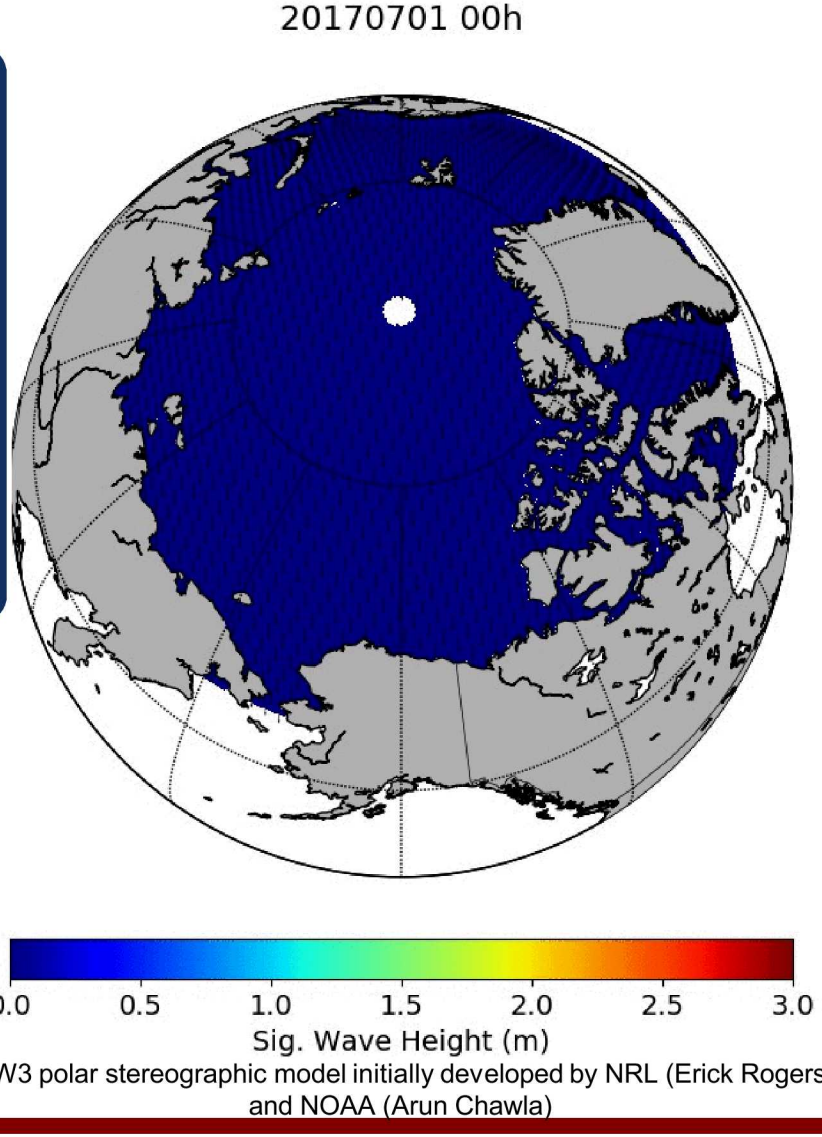
- surface winds
- ice cover

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

- high resolution near shore environment
- wave energy inclusive of induced current effects

**Delft3D** Circulation and thermal conditions 2-way coupled with waves

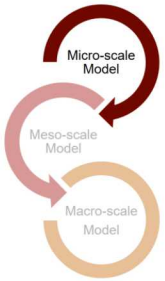
- capture induced currents in nearshore
- capture set-up (storm surge and runup)



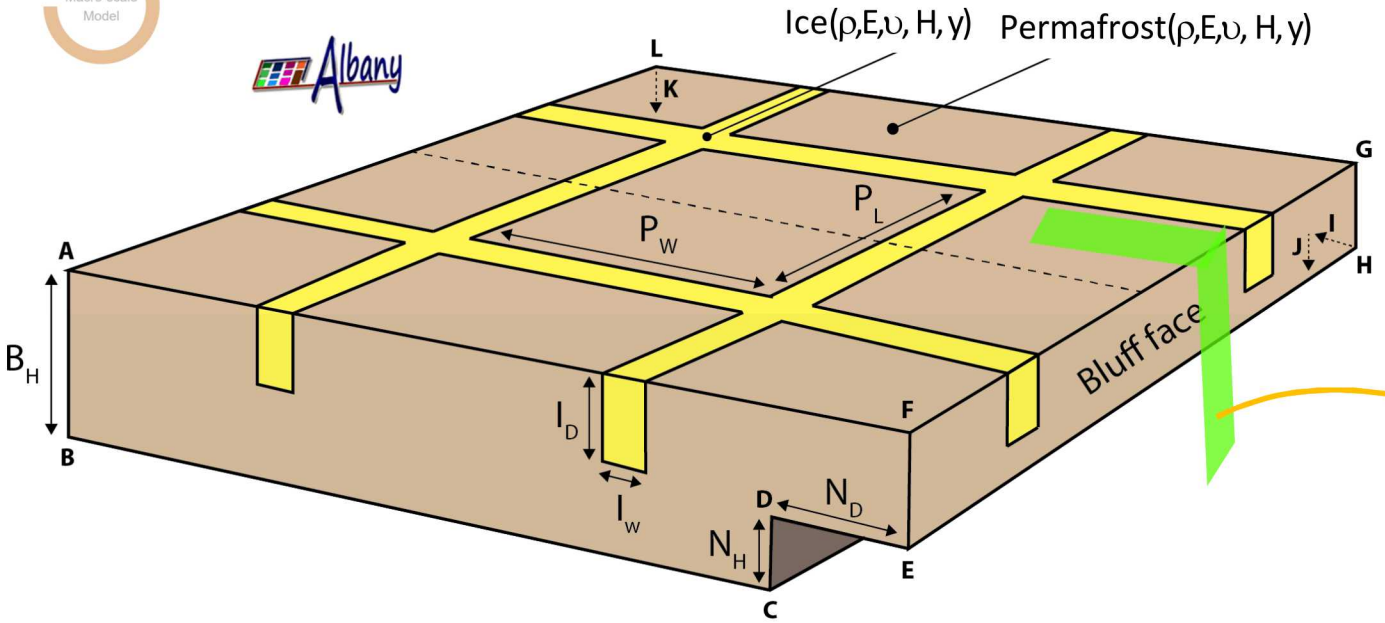

WW3 polar stereographic model initially developed by NRL (Erick Rogers) and NOAA (Arun Chawla)

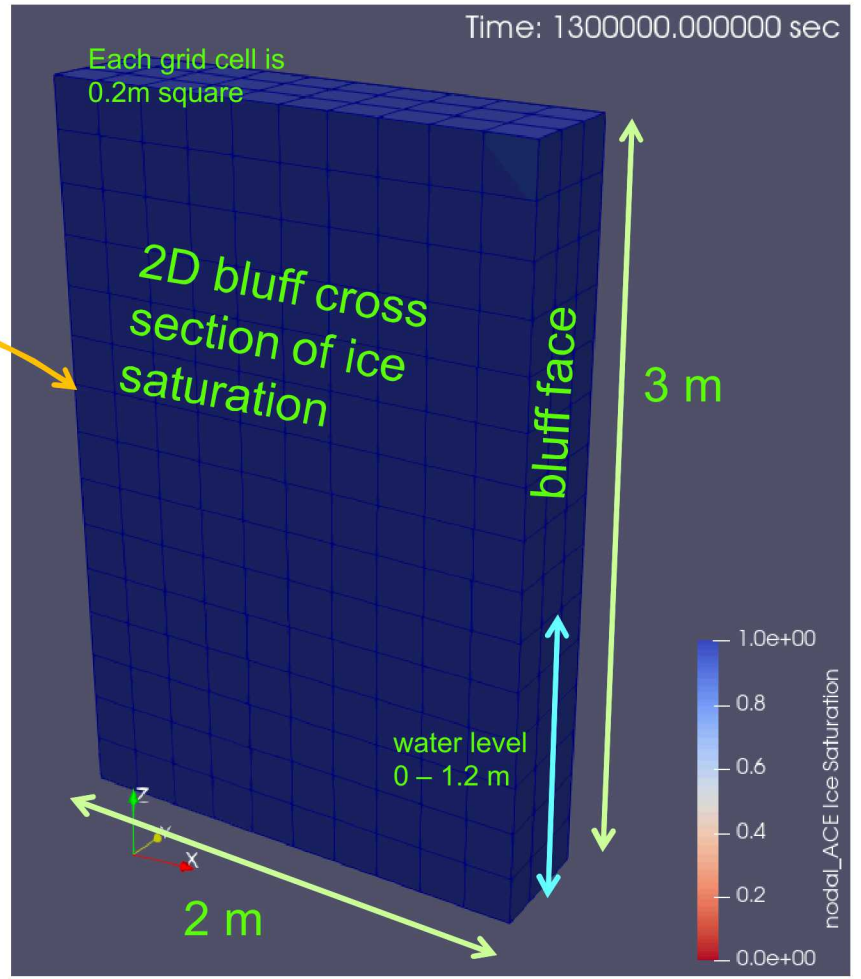
## Key Advances

- High-fidelity development of oceanographic B.C.'s
- 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 conditions



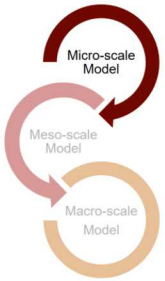

# Terrestrial Modeling




## Key Advances

- 3-D unsteady thermal flow and chemical characteristics
- Tightly coupled strength and thermo-chemical states
- Failure modes develop from constitutive relationships in Finite Element Model (no empirical relationships!)
- Material removed as failure strength surpassed

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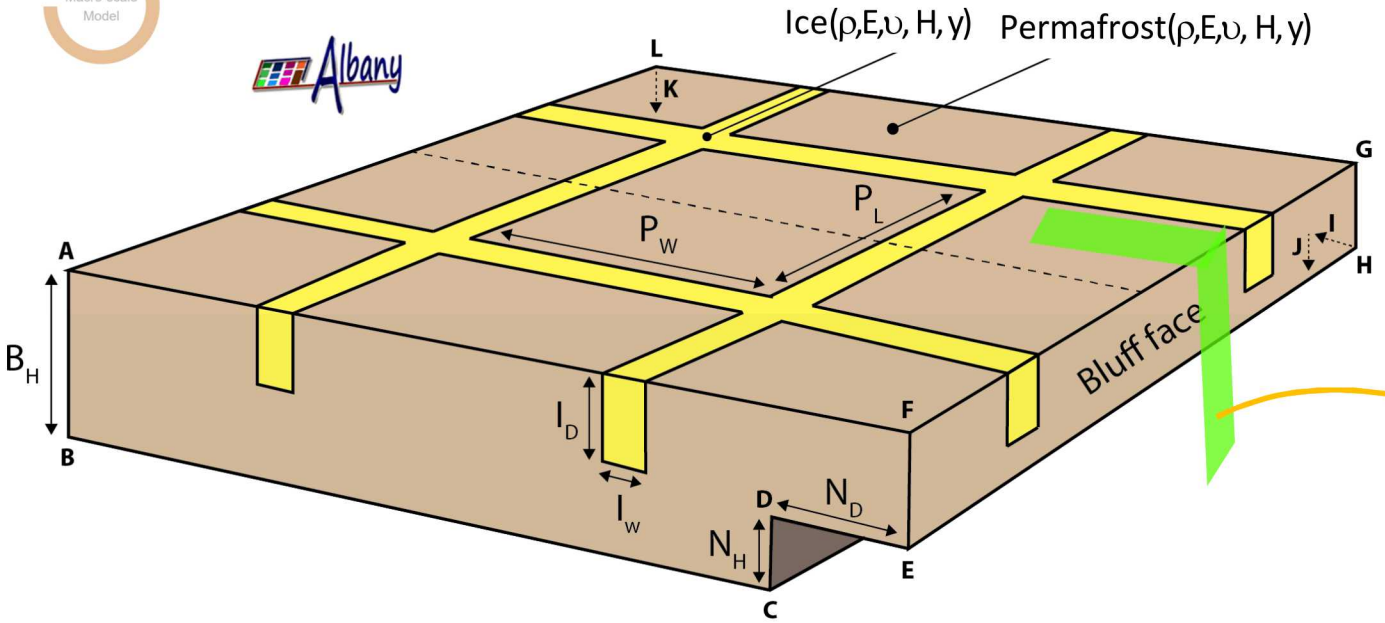


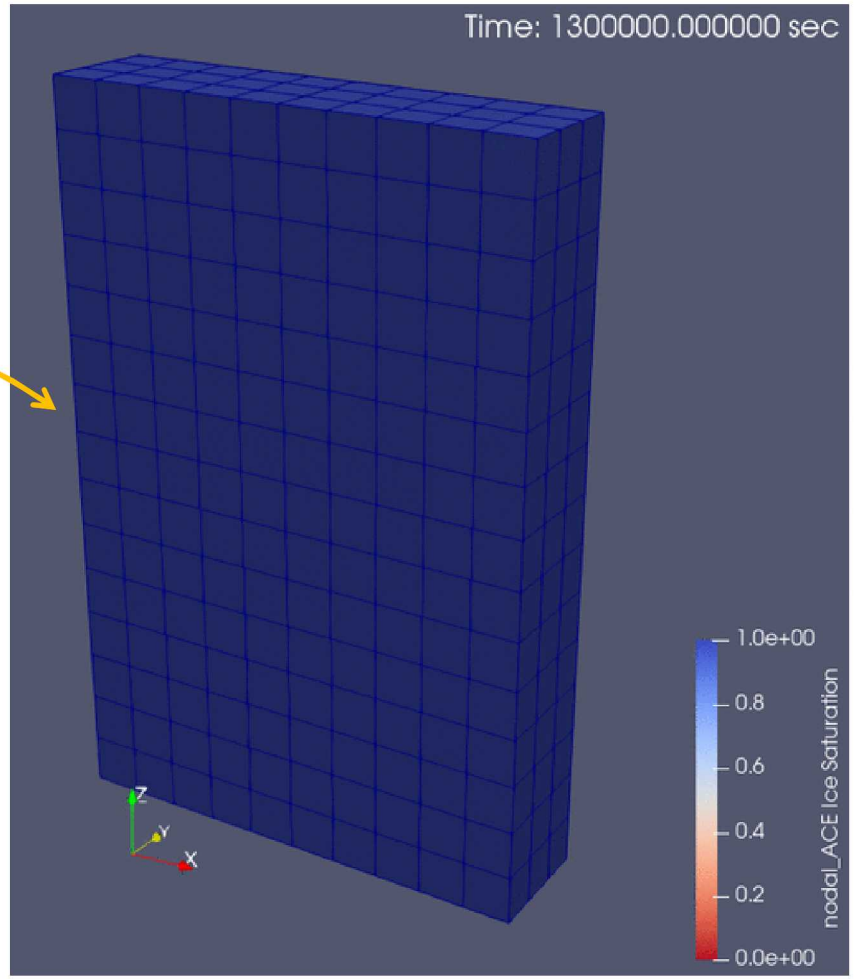


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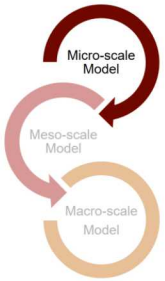
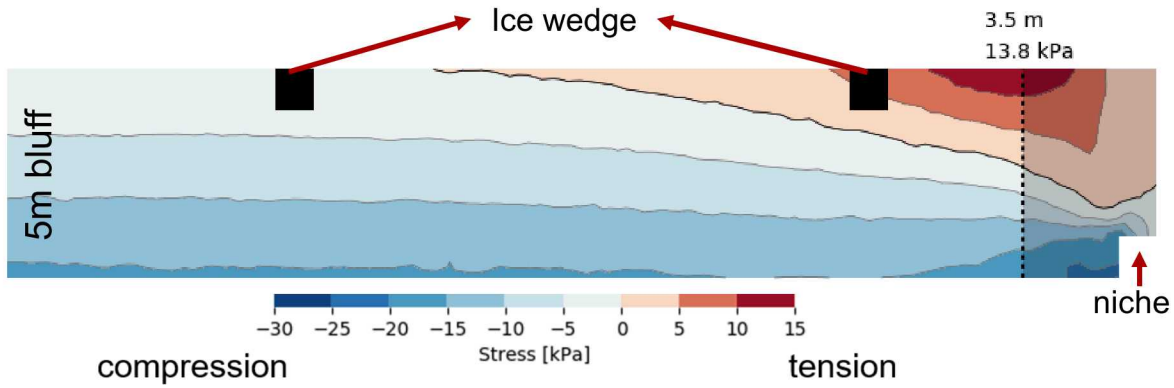
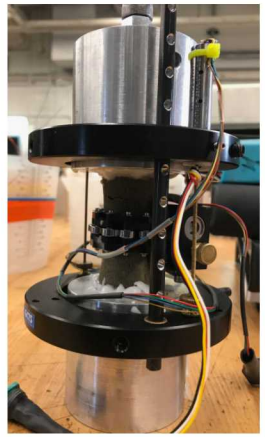



# Coupled Thermal-Mechanical Response



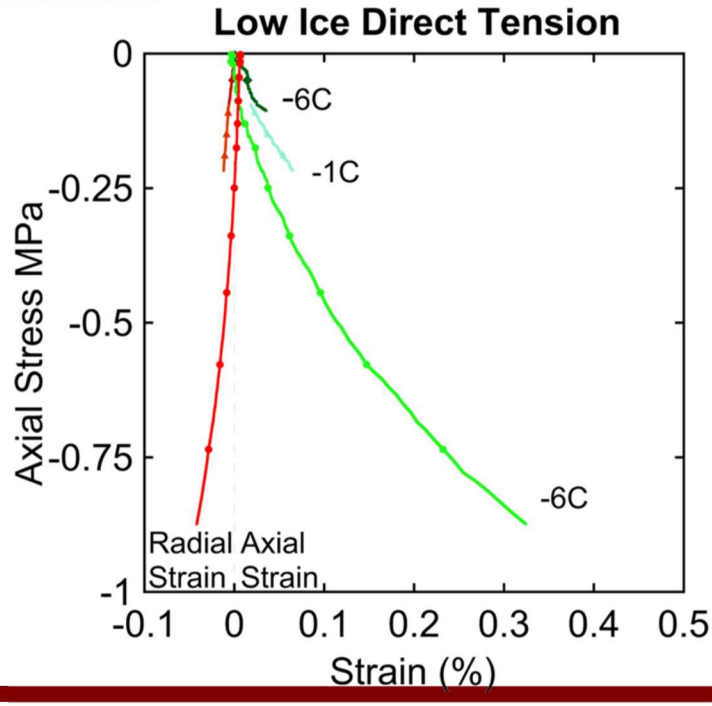



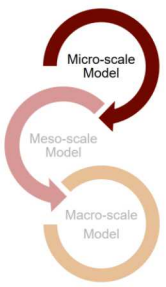
Albany is a finite deformation plasticity model

- 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 temperature and ice volume for local permafrost samples

SNL's Geomechanics Laboratory

- Environmental chamber to control temperature whilst performing unconfined compressive tests & direct tensile tests






# Field-Work

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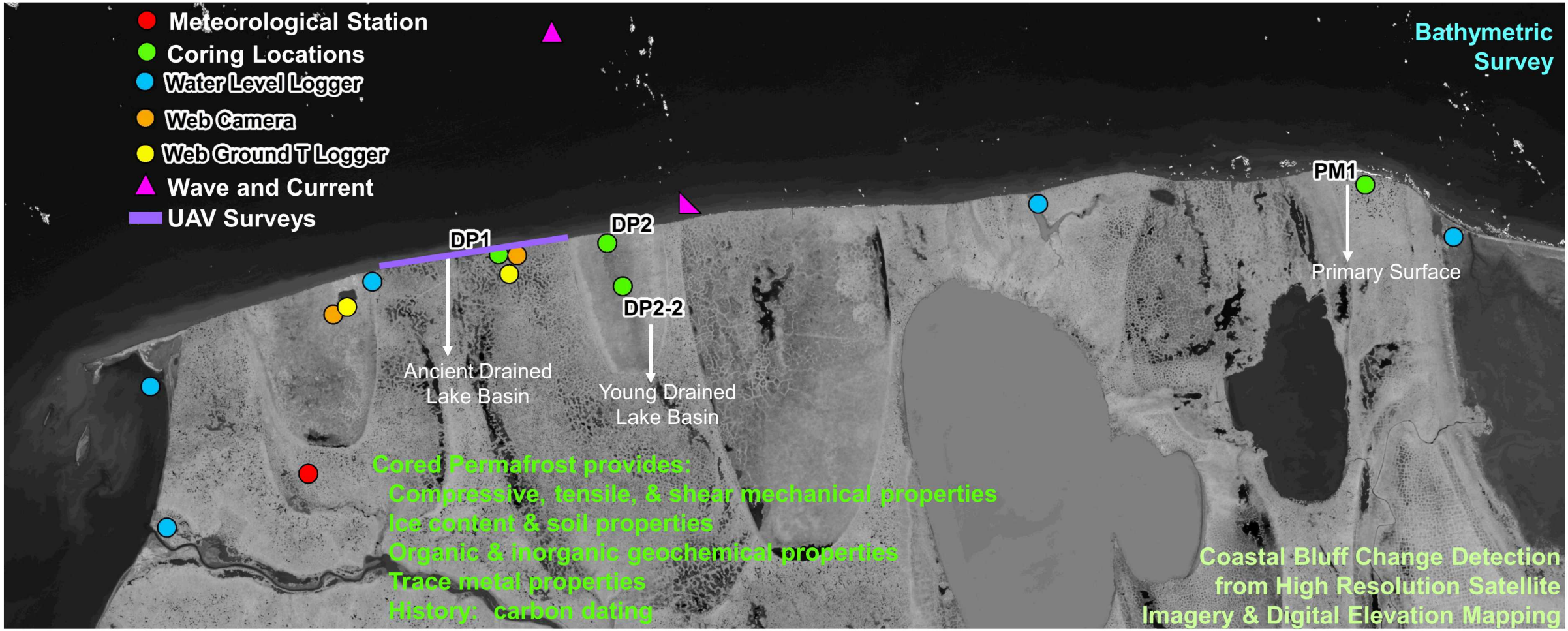
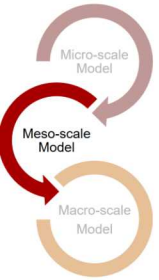





FY19 & FY20

# Meso-Scale Modeling

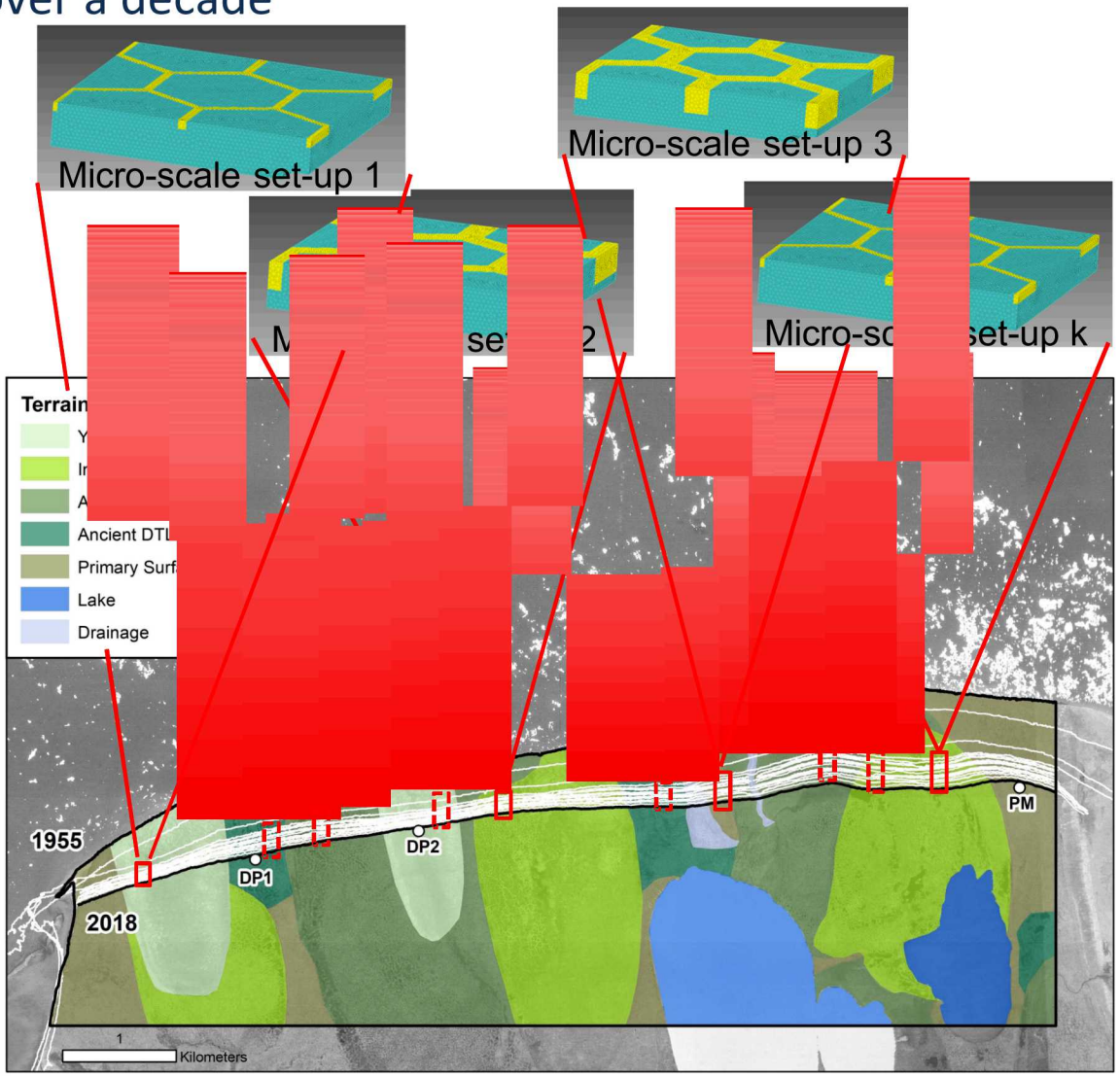
## Weighted combination of micro-scale models verified over a decade

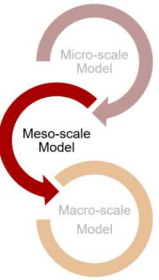
### Micro-scale simulations

- Most terrestrial input variables treated as invariant over a decade
- Establish validity of independent & discrete storm modeling
- Apply historical and projected boundary conditions

### Determining weight magnitudes

- Determine input variables' probability distribution functions
- Understand bluff stress state sensitivity to input variables
- Optimize erosion weighting schemes to match annual retreat rates over a decade






# Variabilities

## Oceanographic B.C.'s

- Inundation height
- Water temperature
- Water salinity
- Storm duration

## Geomorphological Features

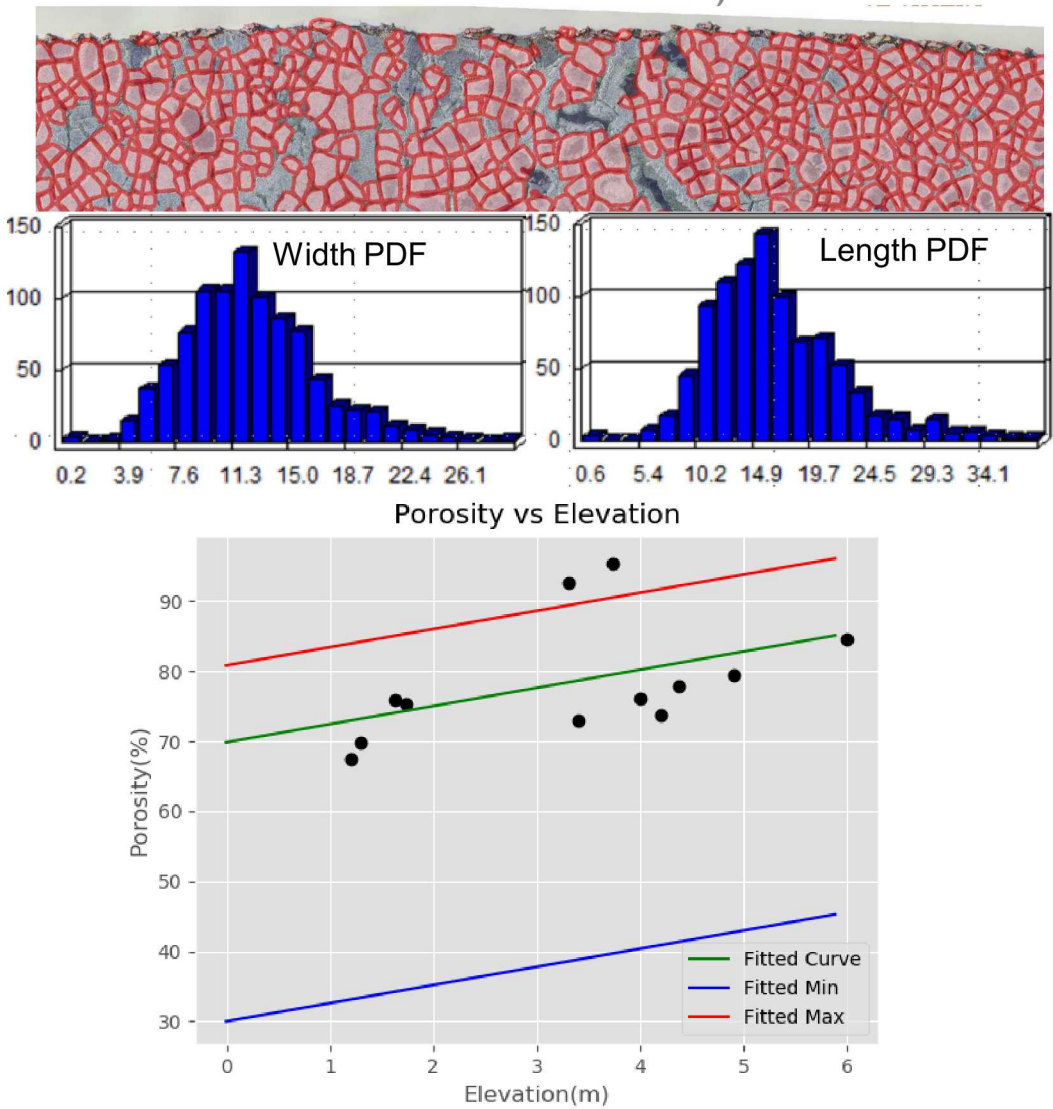
- Ice wedge
- Permafrost polygons
- Niche
- Bluff height

## Geophyscial Features

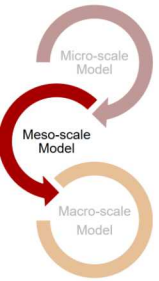
- Sediment
- Porosity
- Ice fraction
- Salinity

## Geomechanical Features

- Poisson's Ratio
- Youngs Modulus
- Yield Strength
- Hardening Modulus




Porosity is air and water volume fraction




# Flux Estimation

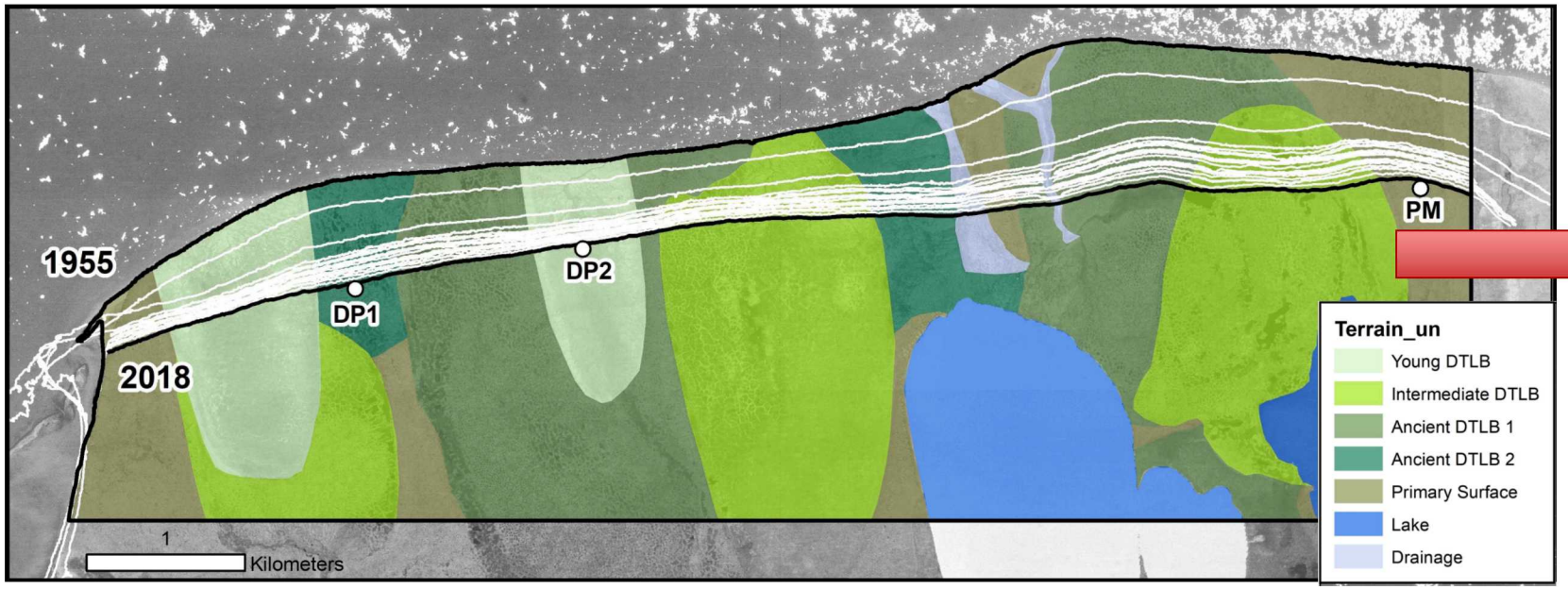
Estimate infrastructure impact due to linear land losses

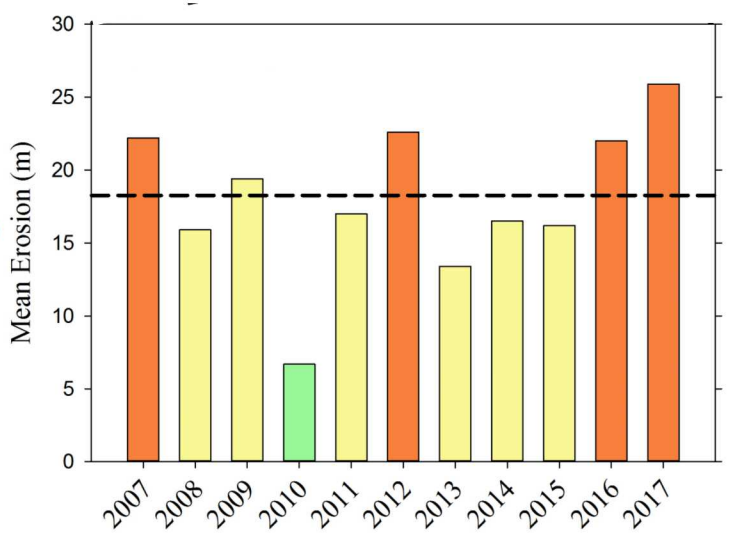
Verify erosion amounts over decade period to determine near-shore inputs of:

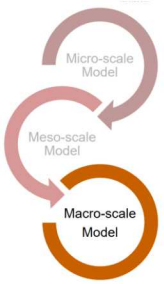
- Sediments
- Nutrients
- Toxins

Determine recirculation of eroded materials

Partner to evaluate near-shore ecological stability






future

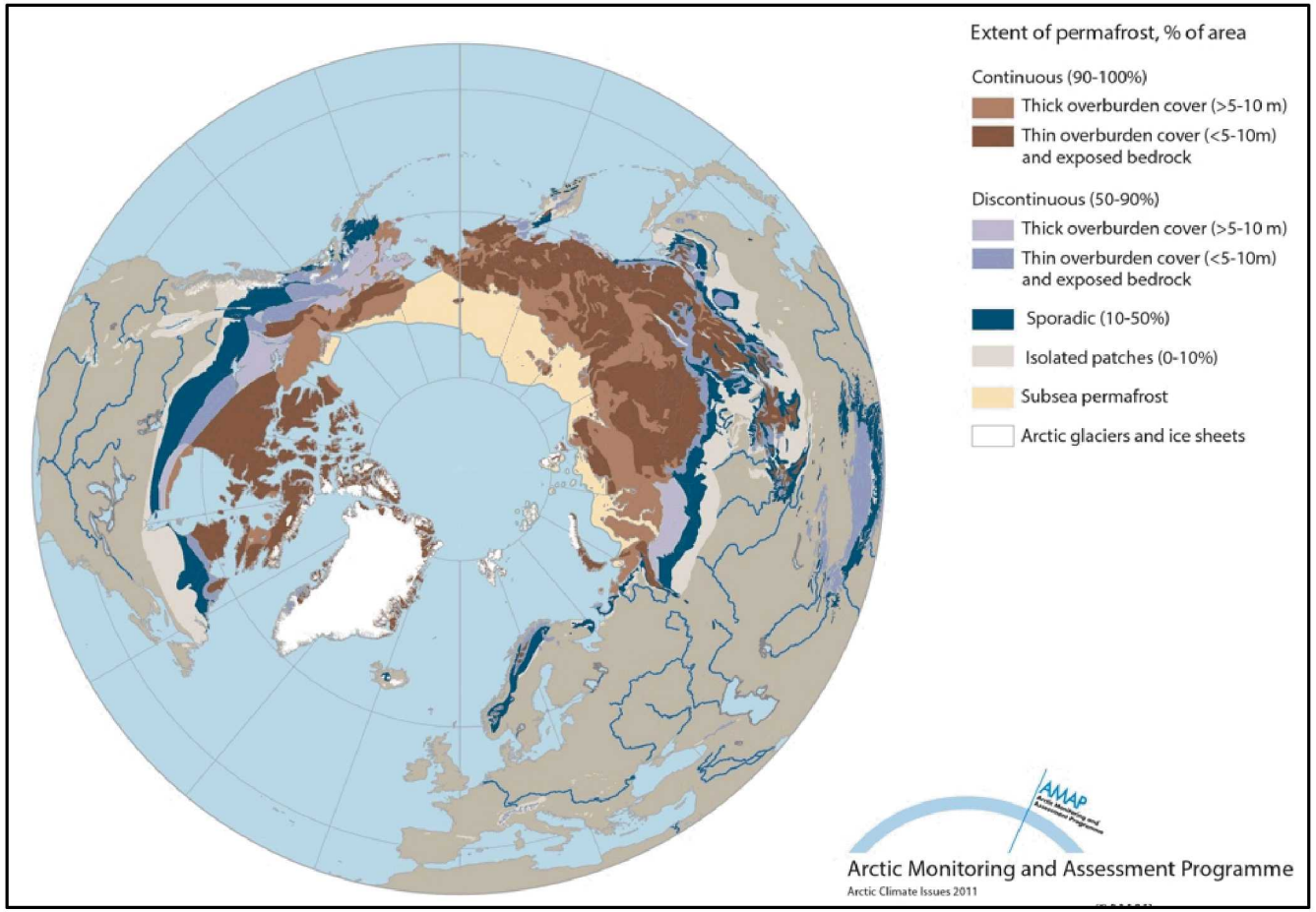
# Macro-Scale Modeling

## Weighted combination of meso-scale models

Classify circum-Arctic terrestrial and oceanographic typologies

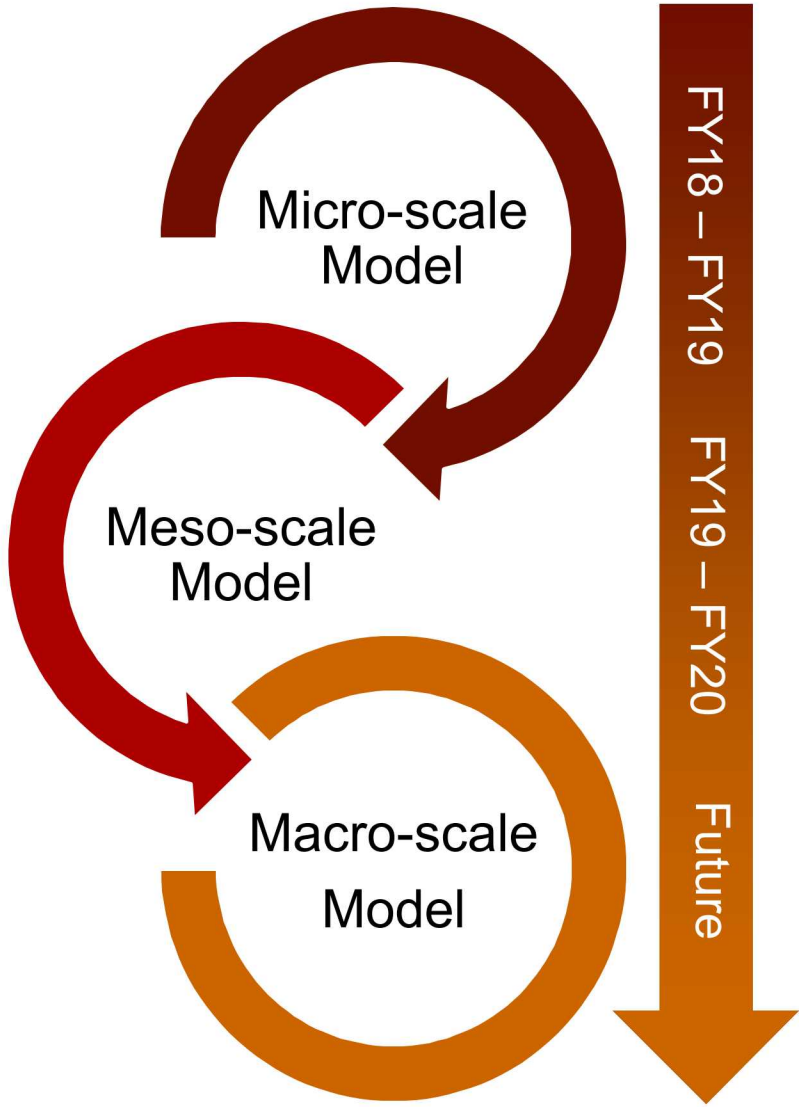
Use historic and projected meso-scale simulations representative of the typologies in order to:

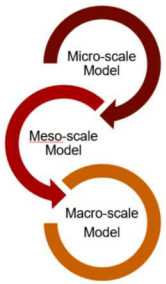
- Establish skill of the parameterized representation
- Identify most erosion-vulnerable locations
- Determine total sediment, nutrient, and toxin flux into the Arctic ocean



FY18 – FY20

# SUMMARY






# Advancements

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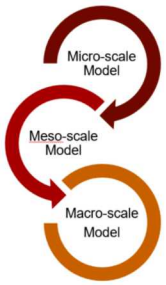
Establishing enduring relationships with Arctic invested parties

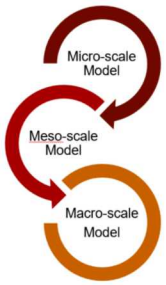
- University of Alaska Fairbanks,
- UT Austin
- USGS
- University of Alaska Anchorage,
- USAF
- DOE
- CRREL,
- Geological Survey of Canada (GSC),
- BLM
- ….




# Advancements

Redistributed eroded sediment in the environment enables

- prediction of deposition locations, and
- ecological stability analyses.

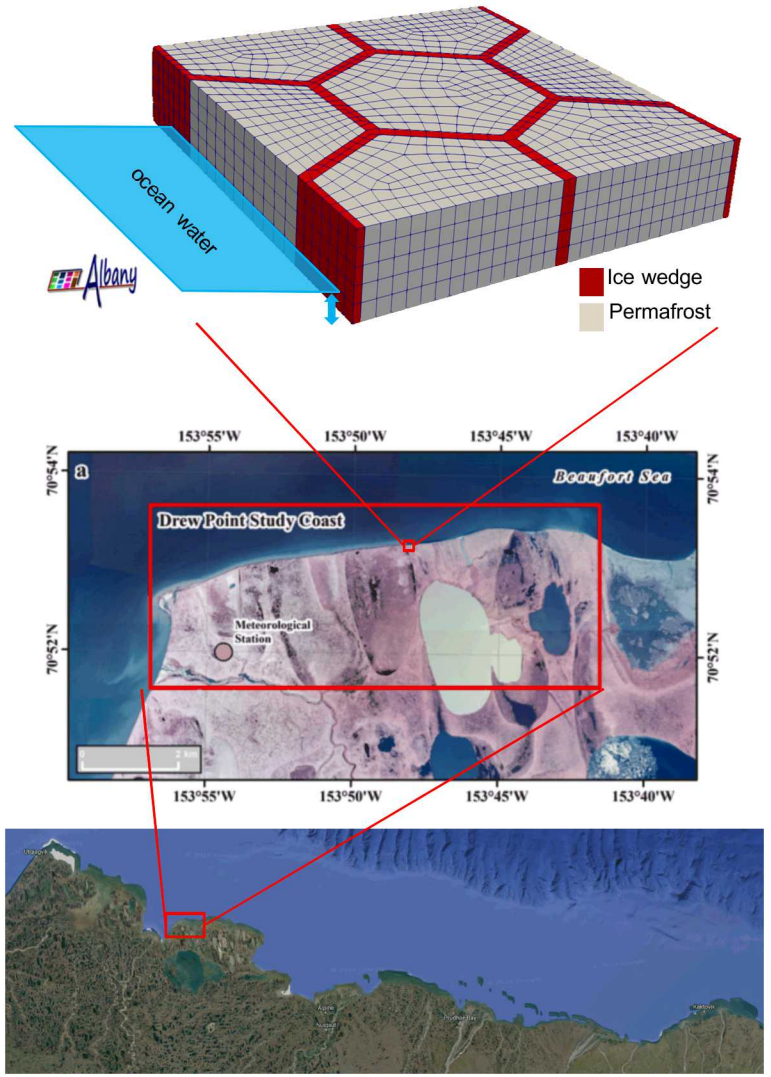


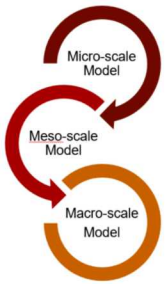

# Advancements

Approach for moving from mechanistic micro-scale to stochastic meso-scale model sets stage for integration into global climate models (macro-stage) built upon parametric analyses of input variables

- Member of the newly proposed DOE sponsored InteRFACE project focused on coastal processes in the Arctic

INTERFACE






# Advancements

3-D model capable of predicting erosion from the material's constitutive relationships capturing all types of deformation (block & denudation) leading to

- data driven understanding of the characteristics that cause erosion
- a tool to guide military and civil infrastructure investments, and
- an improved understanding of coastal food web impacts and carbon-climate feedbacks.



Sandia National Laboratories

USGS science for a changing world

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The University of Texas at Austin

# QUESTIONS

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# POSTDOCTORAL APPOINTEE - MODELING AND SIMULATION OF CLIMATE PROCESSES IN THE ARCTIC

Posting # 668493

Open through August 29th 2019.

# References


**Title slide photos (in order)**

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