A thermo-mechanical model of permafrost for the simulation of Arctic coastal erosion

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Motivation

The Arctic is warming at **2-3 times** the rate of the rest of the U.S. 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

**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$_2$).

Gibbs & Richmond, 2015.
Permafrost erosion

**What is permafrost?**

- Ground, comprised of soil, rock, silt, clay and sand, held together by ice, that remains frozen for 2+ consecutive years.
- 24% of ice-free land area in Northern Hemisphere and 85% of Alaska, Greenland, Canada and Siberia sits on top of permafrost.

**Unique coastal permafrost erosion process in Arctic:**

- Predominant geomorphology: **ice-wedge polygons**
  - Ice acts to **bind** unconsolidated soils in permafrost forming ice wedges.
  - Ice wedges **grow/expand** up to ms wide and 10s meters deep.
  - Melting of ice wedges causes permafrost **failure**.

*Left: schematic illustrating formation of ice wedges and ice-wedge polygon landscapes. Right: map of permafrost distribution in Arctic.*

Martin et al. 2009.

Brown et al. 1998.
Permafrost failure mechanisms

- **Retrogressive thaw slumping**: a slope failure characterized by thaw of exposed ground ice and slumping of thawed soil, typically caused by thermo-denundation\(^1\).
- **Active layer detachment**: failures are translational landslides that occur in summer in thawing soil overlying permafrost, typically caused by thermo-denundation\(^1\).
- **Block failure**: a niche (recess at bluff base) progresses landward until the overhanging material fails in a shearing or toppling mode known as block failure, caused by thermo-abrasion\(^2\).

  - Fallen blocks can disintegrate in the near-shore environment **within 1-2 weeks**!

\(^1\)Thawing of permafrost bluffs that proceeds under the influence of gravity.  \(^2\)Undercutting of permafrost bluff by warming ocean.
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State-of-the-art in permafrost modeling

Models and tools to **accurately predict** Arctic coastal erosion are **lacking**!

- Most existing models* (including Earth System Model-, or ESM-, coupled models) are **primitive**:
  - Most models were based on **trend projection** and/or **empirical relationships**
  - **Limited PDE-based models**: primarily **thermal models**, e.g., 1D steady state heat flow (no mechanics/deformation)
  - Most models assumed a **particular type** of erosion (e.g., block failure)
  - Models **did not** include **realistic boundary conditions** and **did not** account for permafrost **geomorphologies** or **geophysics**.

**Premise behind the Arctic Coastal Erosion (ACE) project/model**: an accurate, **predictive** Arctic coastal erosion model must **couple** the influences of evolving **wave dynamics**, **thermodynamics** & **mechanics**.

* See (Frederick et al. 2016), Chapter 5, for extensive overview.
Proposed solution: a multi-scale approach

Goal of the Arctic Coastal Erosion (ACE) project is to deliver a field-validated predictive model of thermo-abrasive erosion for the permafrost Arctic coastline.

**Micro-Scale Model**
10’s of meters & storm duration
One set of input variables defining the geomorphology and geophysics of the terrestrial model.

- **Coupling** of 3D heat transfer + mechanics-based plastic deformation
- **Wave circulation BCs** representing time-varying realizations of individual storm events.

**Meso-Scale Model**
10’s of kilometers & monthly duration
A number of micro-scale models that represent the stochastic distributions of input variables along a confined coastline.

**Macro-Scale Model**
100’s of kilometers & annual (+) durations
A number of meso-scale models representing different coastline types (delta, exposed bluffs, lagoons, etc.) along the AK coastline.

**Longer term vision:** upscale micro-scale model to meso- and macro-scales

Create “catalog” of smaller-scale models for diff. Arctic locations, use catalog to derive (physics-based) statistical parameterizations of things like aggregate retreat rates.
Anatomy of a canonical computational domain

Permafrost

Bluff face (exposed to ocean)

Ice

ocean water

Cryopeg*

* Layer of unfrozen ground that is perennially cryotic (forming part of the permafrost) in which freezing is prevented.
Coupled thermo-mechanical formulation

- Failure modes come from **constitutive relationships** in FEM model (no empirical relationships!)
- Thermal & mechanical problems can use **different time-steppers** (e.g., implicit-explicit coupling)
- Elements are **removed** from the mesh, to simulate **erosion**
- Model takes in **realistic** oceanic, atmospheric & geothermal heat flux **boundary conditions** (BCs) from wave model & observational data
- **Tightly coupled** strength + thermal states: coupling happens at the level of the material model

**Thermal:**

**Inputs:** geometry, sediment type, ice volume, water volume, pore size, salinity  
**Outputs:** temperature field, ice saturation

**Mechanical:**

**Inputs:** ice saturation, strength relationship as function of thermal state, stress-strain relationships of permafrost and ice  
**Outputs:** displacements, eroded geometry
Thermal model

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

\[
(\tilde{\rho}c_p + \tilde{\Theta}) \frac{\partial T}{\partial t} = \nabla \cdot (K \cdot \nabla T)
\]

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

- Computes **temperature** \(T\) and **ice saturation** \(f\) (needed by mechanical model)

- **Boundary conditions** (from wave model/data)
  - Local geothermal heat flux from below\(^1\)
  - Mean annual air temp from above\(^2\)
  - Air\(^2\)/ocean\(^3\) temp at bluff face

\(^1\) Data from borehole at Barrow, AK. \(^2\) USGS weather station data. \(^3\) From WaveWatch3+SWAN+Delft3D model.
Mechanical model

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

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

‌ 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, plastic flow and creep of polycrystalline materials like ice
  ➢ Minimal calibration parameters\(^1\)
  ➢ Simplest material model with plastic behavior
  ➢ Modified to be a function of **ice saturation** \(f\) (from thermal model)

• **Boundary conditions:**

  ➢ **Symmetry BCs** on lateral sides
  ➢ **Wave pressure Neumann BC** on bluff face\(^2\) (from wave model).

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\(^1\) Determined by laboratory tests on frozen soil samples from targeted location.  \(^2\) Partensky, 1988.
Erosion failure criteria

- **Sub-grid scale erosion criterion**: when material is exposed to water, thermal parameters are modified proportional to water force.
- **Stress criterion**: removes material when it reaches a critical value of the yield stress
  \[ \sigma_0(T) := S_s \sigma_Y^{\text{soil}} + S_f f(T) \sigma_Y^{\text{ice}} \]
- **Kinematic criterion**: when material has tilted excessively, it is assumed to have fallen as part of block erosion.

Once failure criterion is reached, “failed” elements are removed from mesh.
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Erosion happens in the mechanics problem but is influenced by the thermal problem.
Finite element implementation within *Albany*

The *thermo-mechanical Arctic Coastal Erosion (ACE)* model is implemented within the *LCM project* in Sandia’s open-source parallel, C++, multi-physics, finite element code, *Albany*.

- **Component-based** design for rapid development.
- Contains a wide variety of **constitutive models**.
- Extensive use of libraries from the open-source *Trilinos* project.
  - Use of the *Phalanx* package to decompose complex problem into simpler problems with managed dependencies.
  - Use of the *Sacado* package for **automatic differentiation**.
- Coupled to the *DOE’s Energy Exascale Earth System Model (E3SM)* through Albany Land-Ice (ALI) component.
- All software available on *GitHub*. 
2.5D slice at Drew Point, Alaska*

- Computational domain is **2.5D cross-section** of archetypal 3D bluff geometry discretized using a uniform hex grid.
  - Slice of permafrost is exposed to **realistic BC data** occurring at Drew Point, Alaska in July 2018 (pseudorealistic problem)

- **Initial temperature field** obtained from vertical thermistor string placed into DP1-1 ice core at Drew Point.

- **Material properties** determined from laboratory experiments on frozen soil samples from Drew Point, Alaska

- **Implicit** Newmark for mechanical, **explicit** forward Euler for thermal (stable $\Delta t = 1$ hour)

2.5D slice at Drew Point, Alaska*

Once niche advanced far enough, tension crack development in response to niche formation is observed. Simulation showing niche progression beginning at the bluff toe and block failure/collapse event.*

- ~3m deep niche forms before a block collapse event similar to observed collapse at Drew Point, Alaska in early fall 2018.

- Thermal denudation simultaneously with realistic niche geometry development.

Summary

• We have developed a thermo-mechanical coupled FEM model, ACE, that can simulate transient niche development and permafrost erosion within Albany.

• The model was calibrated using data from a series of experiments on frozen soil samples from Drew Point, Alaska that were performed at Sandia’s Geomechanics Laboratory, as well as observational data collected at the same location.

• The model incorporates boundary conditions from the WW3+SWAN+Delft3D wave models and observational data from field campaigns at Drew Point, Alaska.
Ongoing/future work

Near term:

- **Quantitative validation study** in which the ACE model predictions are compared to available observational data collected during the 2018-2019 summer seasons at Drew Point, Alaska (2.5D slice + 3D).
- Further **calibration** and **sensitivity studies** using a range of environmental, geomorphological and numerical parameters.

Longer term:

- Integrate **chemical transport** into thermal model.
- Infer **statistical meso-/macro-scale models** and relevant **physics-based parameterizations** from ACE micro-model, towards integration into ESMs.
  - ACE is member of the newly-funded DOE sponsored **InteRFACE project*** focused on coastal processes in Arctic.
References


Research Team

**SNL:** D. Bull (PI), J. Frederick, A. Mota, C. Choens, I. Tezaur, L. Criscenti

**USGS:** M. Thomas, B. Jones

**UAF:** J. Kasper, E. Brown

**Integral Consulting:** C. Jones, C. Flanary

**U Texas:** J. McClelland, E. Bristol, C. Connolly

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Start of Backup Slides
Potential impacts

- **3D 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
  - An improved understanding of **coastal food web impacts** and **carbon-climate feedbacks**

- **Redistributed eroded sediment** in the environment enables:
  - Prediction of deposition locations
  - Estimates of fluxes (biogeochemical, toxins, etc.)

Approach for moving from mechanistic micro-scale to stochastic meso-scale model sets stage for **integration** into **global climate models** built upon parametric analyses of input variables
Example of bluff erosion during 2019 UAV surveys*

Fallen blocks can disintegrate in near-shore environment within 1-2 weeks!

*Images courtesy of Ben Jones, UAF
ACE Model Component Coupling

**ACE project has many pieces!**

- **Terrestrial model**: thermo-mechanical coupled FEM model that can simulate transient niche development.
- **Oceanographic model**: WW3 + SWAN + Delft3D wave models for providing oceanic BCs (ocean temp/height) to terrestrial model.
- **Geomechanical testing**: for characterization of permafrost parameters in terrestrial model.
- **Field campaign**: offshore oceanographic measurements, bathymetric survey, niche measurements, etc.
ACE project has many pieces!

- **Terrestrial model**: thermo-mechanical coupled FEM model that can simulate transient niche development. *This talk*

- **Oceanographic model**: WW3 + SWAN + Delft3D wave models for providing oceanic BCs (ocean temp/height) to terrestrial model.

- **Geomechanical testing**: for characterization of permafrost parameters in terrestrial model.

- **Field campaign**: offshore oceanographic measurements, bathymetric survey, niche measurements, etc.
Oceanography in Mechanistic Model

## WW3
- Development of wave field in the Arctic to develop nearshore BCs
  - 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

WW3 polar stereographic model initially developed by NRL (Erick Rogers) and NOAA (Arun Chawla)
Goal of the Arctic Coastal Erosion (ACE) project is to deliver a field-validated predictive model of thermo-abrasive erosion for the permafrost Arctic coastline.

- Multi-physics finite element model of an archetype of the coastline coupled with high-fidelity model of storm intensities
  - Input variables define geomorphology & geophysics
  - Plastic deformation model of material (J2 class)
  - Geomechanical testing to determine coupled thermal-mechanical strength characteristics
  - Time-varying ocean BCs (water level, temp, salinity)
  - Eroded sediment and biogeochemical flux tracking

- A “catalog” of micro-scale models that represent the statistical distributions of input variables along a ~10km stretch of coastline.
  - Probability distribution functions of geomorphology and geophysics used to weight erosion output
    - Will validate approach with decade long annual measurements at Drew Point.
    - Evaluating ocean “exposure metrics” to represent time-varying ocean

This talk

- Oceanographic model
- Thermo-chemical-mechanical terrestrial model
- Significant Wave Height (m)
- July 23rd 2017, 6am.
Multi-scale approach

Micro-Scale Model
10’s of meters & storm duration
One set of input variables defining the geomorphology and geophysics of the terrestrial model.

Meso-Scale Model
10’s of kilometers & monthly duration
A number of micro-scale models that represent the stochastic distributions of input variables along a confined coastline.

Macro-Scale Model
100’s of kilometers & annual (+) durations
A number of meso-scale models that represent the diversity of coastline types (delta, exposed bluffs, lagoons, etc.) along the AK coastline.

• Working towards a series of fully coupled studies to determine terrestrial model sensitivities to:
  ➢ Height of water on bluff face
  ➢ Exposure time of bluff face to water
  ➢ Temperature of water
  ➢ Salinity of water
Parameters & inputs

**Parameters estimated from lab experiments:**
- Elastic modulus, Poisson’s ratio, yield strength
- Sand/silt/clay fractions with depth
- Porosity with depth

**Parameters from literature:**
- Ice/water/sediment densities, thermal conductivities, heat capacities
- Freezing curve/width as function of sediment type
- Bluff salinity with depth

**Parameters estimated from observational data at Drew Point, AK:**
- Air temp w/ time, initial bluff temp (USGS weather station data)
- Geothermal heat flux (borehole at Barrow, AK)
- Polygon dimension, ice wedge thickness and depth, bluff height, living organic layer thickness (Aug. 2019 field campaign)

**Parameters from wave model (WW3+SWAN+Delft3D):**
- Ocean temperature, salinity and sea-level w/ time (for thermal and wave pressure mechanical BCs)
Parameters & inputs

- Permafrost properties depend on *ice content, unfrozen water content* and *frost susceptibility*.

- *Few mathematical relationships exist* that describe changes in tensile strength, shear strength and cohesion of ice/permafrost with changes in temperature.

- Series of *experiments* (UCS\(^1\), BTS\(^2\), DT\(^3\)) on frozen soil samples at different temps (-6C, -3C, -1C) and ice content from Drew Point, AK were performed at SNL’s Geomechanics Laboratory to estimate:
  
  - Strength: 1-3 MPa
  - Young’s modulus: 0.01-0.16 GPa
  - Poisson’s ratio: 0.1-0.35
  - Porosity values: 40-95%

\(^1\) Unconfined compressive test. \(^2\) Brazilian tensile tests. \(^3\) Direct tensile tests. 

\[y = -1.872x\]

\[R^2 = 0.3908\]

Lots of noise in data!
Mechanics-only simulation*

From 2020 article published in special issue of Frontiers in Earth Science.

Mechanics-only simulation*

- **3D elastic mechanics-only** simulations assessed impact of **bluff geometry** and **material variability** on stress states leading up to bluff failure
  
  ➢ Only load is gravitational.

- Simulations facilitated examination of **stress patterns** within bluff and identification of **location** and **magnitude** of **max tensile stress** ($\sigma_{T_{\text{max}}}$)

Mechanics-only simulation*: main takeaways

Niche dimension affects location and magnitude of simulated max tensile stress ($\sigma_{T_{\text{max}}}$) more than the bluff height, ice wedge polygon size, ice wedge geometry, bulk density and Poisson’s ratio.

- Inland extent of niche was advanced for 6 erosional niche heights from 0.1-3 m.

Taller and narrower erosional niches promote smaller failure masses compared to those with shorter and deeper niches.

- Lower bound for tensile strength from lab measurements: 100 kPa.
- Orange/green shading highlights potential failure areas.

Mechanics-only simulation*: main takeaways

Taller and narrower erosional niches promote smaller failure masses compared to those with shorter and deeper niches.

As niche advances into the block, the overhanging section in the block acts as cantilever.

Highest tensile stresses develop on top surface where cantilever meets rest of block.

Mechanics-only simulation*: main takeaways

- It has been observed that failure can occur along tension cracks in ice wedge polygon centers.

- Simulations suggest tension cracks can form within the range of niche depths/heights considered here.

- Even relatively shallow vertical cracks can concentrate strain within ice-bonded permafrost bluffs.

$$F_D: \text{fracture depth}$$

Thermo-mechanical coupling: cuboid problem

- Cuboid is comprised of block of ice material, wedged between two blocks of permafrost material.
- Cuboid subjected to simultaneous heating and stretching from the top.
- Cuboid is affixed to the bottom and with symmetry boundary conditions on the sides.
- Temperature is initialized to 265K.
Thermo-mechanical coupling: cuboid problem

Plots (right) show quantities along vertical line as a function of $z$ in the ice block.
Thermo-mechanical coupling: cuboid problem

Plot (right) shows quantities along vertical line as a function of $z$ in the ice block.
Thermo-mechanical coupling: cuboid problem

Plots (right) show quantities along vertical line as a function of $z$ in the ice block.

- Ice Saturation
- Water Saturation
- Temperature

Temp = 280 K
Disp = 0.2 m

24 days

3.2 m
<1.0 m
Thermo-mechanical coupling: cuboid problem

Plots (right) show quantities along vertical line as a function of $z$ in the ice block.
As cuboid is heated and stretched at top, heat propagates down, *melting ice* and causing *failure*. 