What happens in the Arctic does NOT stay in the Arctic.

Recommendation for a new paradigm in modeling sea ice, permafrost, and multiscale systems.

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From Micro to Macro in the Climate System

millimeters

centimeters

meters

kilometers

$10^3$ kilometers
polar ice caps critical to global climate in reflecting incoming solar radiation

**Earth’s refrigerator**

white snow and ice reflect

dark water and land absorb

\[
\text{albedo } \alpha = \frac{\text{Reflected sunlight}}{\text{Incident sunlight}}
\]
The summer Arctic sea ice pack is melting.

Ice extent (million square km)

September minimum sea ice extent

1979 - 2000 average

Record low 2012

2020

National Snow and Ice Data Center (NSIDC)
Arctic sea ice extent on September 15, 2020

Sea ice concentration (percent)

[Map showing Arctic sea ice extent with labels: median extent (1981-2010) and ice-albedo feedback.]
Recent losses in comparison to the United States

The Arctic is ground zero for climate change.
Permafrost collapse is accelerating carbon release

**ARCTIC PERMAFROST**
One-fifth of frozen soils at high latitudes are thawing rapidly and becoming unstable, leading to landslides and floods that release carbon into the atmosphere.

**CARBON-RICH SOIL LEVELS**
kilograms of carbon per square metre (% of region vulnerable to type of thawing)

**Rapid thawing**
- >139 (8%)
- 139–105 (10%)
- 104–70 (60%)
- 69–36 (19%)
- 35–0 (3%)

**Gradual thawing**
- >139 (4%)
- 139–105 (3%)
- 104–70 (26%)
- 69–36 (39%)
- 35–0 (28%)

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**1 NORTH SLOPE, ALASKA, USA**
Abrupt thawing is triggering landslides and eroding mountains.

**2 DMITRI LAPTEV STRAIT, NORTHEAST SIBERIA**
Permafrost containing thick layers of ground ice collapses suddenly when the ice melts.

**3 HUDSON BAY LOWLANDS, CANADA**
Thawing peatlands could release a lot of carbon.

**4 TAVVAVUOMA, NORTHERN SWEDEN**
Growing thaw lakes are major sources of methane.

*Source: Turetsky et al, 2019, Nature.com*
Arctic sea ice decline: faster than predicted by climate models

Stroeve et al., GRL, 2007
Stroeve et al., GRL, 2012

September ice extent
Climate Model runs

Modeling of large-scale sea ice dynamics has been dominated for decades by TOP-DOWN coarse-grained numerical models based on a framework developed half a century ago.
Sea Ice is a Multiscale Composite Material

**microscale**
- Brine inclusions
- Polycrystals
- Brine channels

**millimeters**
- Arctic melt ponds
- Antarctic pressure ridges
- Sea ice floes

**centimeters**
- Sea ice pack

**mesoscale**
- Brine inclusions
- Polycrystals
- Brine channels

**macroscale**
- Brine inclusions
- Polycrystals
- Brine channels

**meters**
- Fractals everywhere!

**kilometers**
HOMOGENIZATION for Composite Materials

FORWARD and INVERSE homogenization for composite materials.

LINKING SCALES

MICROSCALE

\[ \sigma_1 \quad \sigma_2 \]

MACROSCALE

\[ \sigma^* \]

\[ \sigma^* \text{ effective conductivity} \]

\[ \homogeneous \text{ medium of conductivity } \sigma^* \]

Maxwell 1873: effective conductivity of a dilute suspension of spheres
Einstein 1906: effective viscosity of a dilute suspension of rigid spheres in a fluid
Wiener 1912: arithmetic and harmonic mean bounds on effective conductivity
Hashin and Shtrikman 1962: variational bounds on effective conductivity

widespread use of composites in late 20th century due in large part to advances in mathematically predicting their effective properties
Multiscale self-similar structure of sea ice at small scales

Brine inclusions are home to ice endemic organisms, e.g., bacteria, diatoms, flagellates, rotifers, nematodes.

The habitability of sea ice for these organisms is inextricably linked to its complex brine geometry.

(A) Many sea ice organisms attach themselves to inclusion walls; inclusions with a higher fractal dimension have greater surface area for colonization.

(B) Narrow channels prevent the passage of larger organisms, leading to refuges where smaller organisms can multiply without being grazed, as in (C).

(D) Ice algae secrete extracellular polymeric substances (EPS) which alter incusion geometry and may further increase the fractal dimension.
Permafrost across the scales as a composite

Permafrost at pore-scale includes grains, water and ice.

Porous media at micro-scale have water and grains (tomographic image).
Permafrost thaw causes infrastructure damage

How microbes in permafrost could trigger a massive carbon bomb

https://www.nature.com/articles/d41586-021-00659-y
Methane seeps from under thawing lakes in permafrost zones

Motivation for the model developments

Dramatic changes in Arctic sea ice and permafrost impact climate, ecology, economics, infrastructure, transportation and human activities in the region, AND have cascading effects in the rest of the world and the U.S. in particular.

weather and precipitation patterns, storm tracks (skiing in Western US, corn fields in Iowa), floods and droughts, ice storms in Texas, ecological communities

Large-scale coarse-grained models built from the TOP - DOWN useful for long-range projections, but have become increasingly complicated as more and more is accounted for, and are not so well suited to studying mesoscale behavior and critical processes where fine-scale structure is essential.

HUGE GAPS in our knowledge of Arctic climate system
Features of “microstructure” determine large scale dynamics and behavior.
-- sea ice example

brine inclusions
polycrystalline structure
brine channels
floes sizes and shapes / broken ice
ocean surface waves break up the ice
melt ponds
ridges
keels
WANTED: A new PARADIGM for sea ice and permafrost modeling, built from the “ground up”, from MICRO to MACRO.

We recommend that a community be built, with sufficient critical mass and contributions from many disciplines to overcome historical inertia, to develop a new paradigm of sea ice and permafrost models with the goal to incorporate multiscale and complex components of the climate system.

- Look to successes of statistical mechanics, solid state physics, materials science, mathematical homogenization, ...
- Build a modeling approach that reflects actual structure!
- Can rigorously analyze key phenomena over all scales, not just scales that exceed resolutions of 10s of kilometers.
- Approach applies to other multiscale and complex systems.
Resources needed - what is required to accomplish this?

BUILD a community with sufficient critical mass and contributions from many disciplines to overcome historical inertia, to develop a new paradigm for sea ice and permafrost modeling, from MICRO to MACRO.

- Various types of **interdisciplinary teams of researchers, engineers, and stakeholders**, depending on the type of project, its scale, the relative levels of theory, computation and experiment, etc.

  mathematical and computational scientists, data scientists, software engineers, geophysicists, physicists, materials scientists, experimentalists, atmospheric and climate scientists, physical and biological oceanographers, electrical, mechanical and civil engineers, remote sensing scientists, local stakeholders in Arctic regions, industrial partners and stakeholders in the US such as representatives from policy making bodies, and the agricultural, energy and snow sports industries, ...

- **Center** coordinating the various types of theoretical, computational, and experimental efforts.

  **Data:** vast amounts of historical and new, dynamically changing data; remote sensing, field campaigns
  **Methods:** from various theoretical disciplines and powerful computational tools to derive macroscopic behavior from microscopic laws and information
  **Lab and Field Experiments:** designed over a broad range of scales to dovetail with the modeling efforts
RESOURCES NEEDED

- Funding on the scale of $10M per year for 10 years (2-3 cycles of 3-5 year awards) for smaller and larger interdisciplinary and multi-institutional teams for pilot/exploratory as well as full research projects.

- Establishing a $10M center/institute to coordinate research efforts from theory to experiment, and support a large scale distributed research infrastructure of cryo labs, imaging and computational research, and field work to engage the best expertise from across the US and abroad.

- $10M for 2 dedicated expeditions to the Arctic region over the course of the 10 years to inform and validate models, and to “piggy-back” opportunistically on many other expeditions around the world.
Fundamentally new mathematical ideas on multiscale methods and computational tools.

Improving data collection, storage, and imaging technologies for complex Arctic systems.

The ability to improve projections of the cascading effects of sea ice loss and permafrost thaw on the precipitation patterns, freshwater availability and more broadly weather and climate situations in the US; predicting effects on socioeconomics, geopolitics, energy policy, national security, food security.

The center and research projects will be part of the action to mitigate and effectively respond to sea ice loss and permafrost thawing.

Educational impacts, interdisciplinary experience; get math and theoretical students into the ARCTIC!
Why now?

- New data from recent expeditions (MOSAiC)
- Early successes in micro to macro at the material level
- Ice is melting and permafrost is thawing -- let’s get to work!
Let’s finally build models of sea ice, permafrost and other multiscale components of the climate system.

FROM MICRO to MACRO

THANK YOU!
THANKS TO NSF and SIAM!

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Who cares if Arctic sea ice disappears?
Use of sea ice as a platform

- Walrus life cycle tied to sea-ice cycle
- Ice floes as diving platforms for feeding over shallow shelf
Sea-ice loss: impacts beyond the Arctic

changes in precipitation and temperature patterns, storm tracks, ...

- One climate model projects reduced precipitation in American West (Sewall & Sloan, 2005)
  
  *Utah - greatest snow on Earth?*

- Analysis of 2007 ice minimum suggests above normal snow deposition in NW North America (Orsolini et al., 2011)

- Colder weather in SE Asia, possibly in Eastern US (Hondo et al., 2009)
SEA ICE covers ~12% of Earth's ocean surface

- boundary between ocean and atmosphere
- mediates exchange of heat, gases, momentum
- global ocean circulation
- hosts rich ecosystem
- indicator of climate change
Marginal Ice Zone (MIZ)

- biologically active region
- intense ocean-sea ice-atmosphere interactions
- region of significant wave-ice interactions

Transitional region between dense interior pack ($c > 80\%$) and sparse outer fringes ($c < 15\%$)

**MIZ WIDTH**

Fundamental length scale of ecological and climate dynamics

Strong, *Climate Dynamics* 2012
Strong and Rigor, *GRL* 2013

How to objectively measure the “width” of this complex, non-convex region?