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

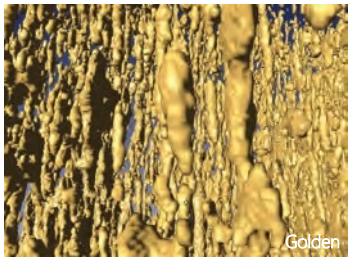
Recommendation for a new paradigm in modeling sea ice, permafrost, and multiscale systems.

Seth Cowall, Saint Mary's College of Maryland
Ken Golden, University of Utah
Tongtong Li, Dartmouth College
Chris Jones, University of North Carolina
Kirk Jordan, IBM Research
Malgorzata Peszynska, Oregon State University

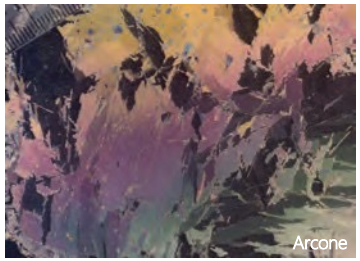
DMS 2227218

From Micro to Macro in the Climate System

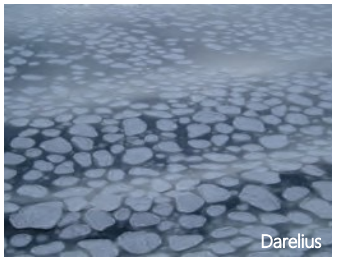
millimeters



centimeters



meters

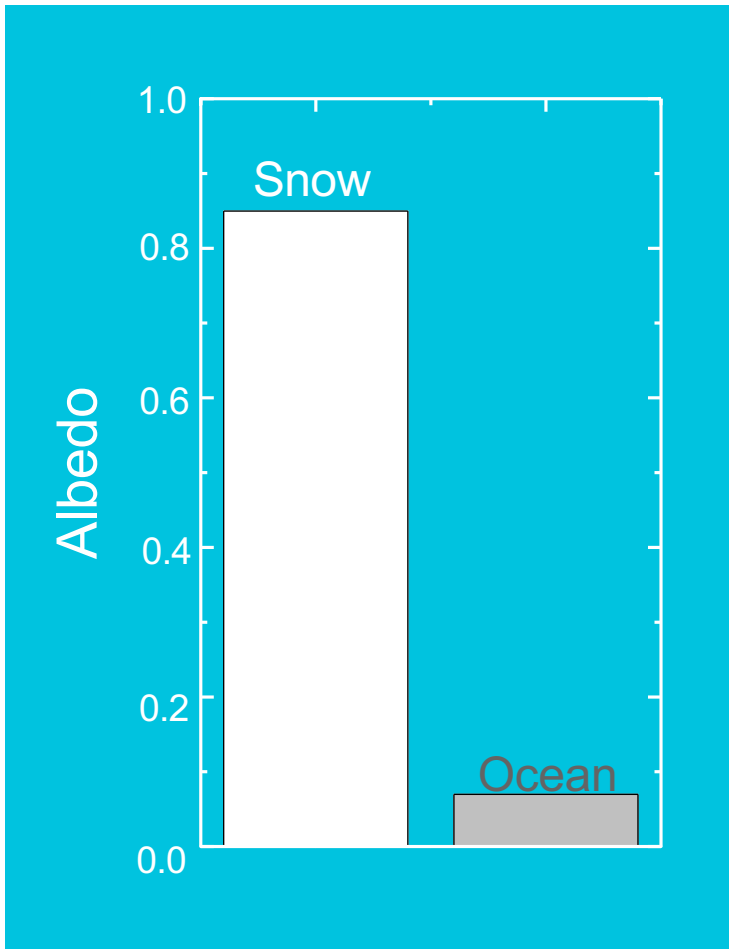


kilometers

10^3 kilometers

polar ice caps critical to global climate in reflecting incoming solar radiation

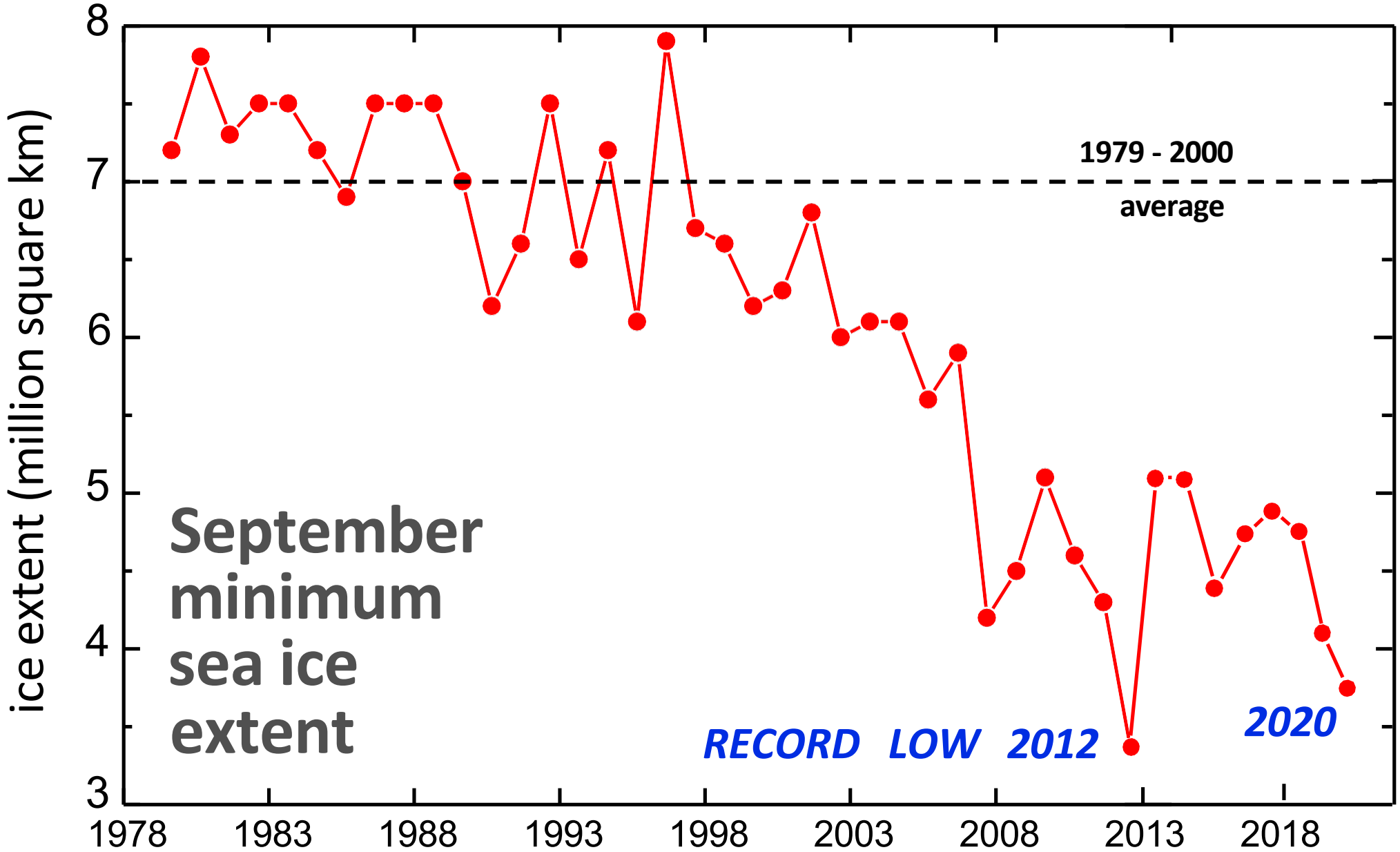
white snow and ice reflect



dark water and land absorb

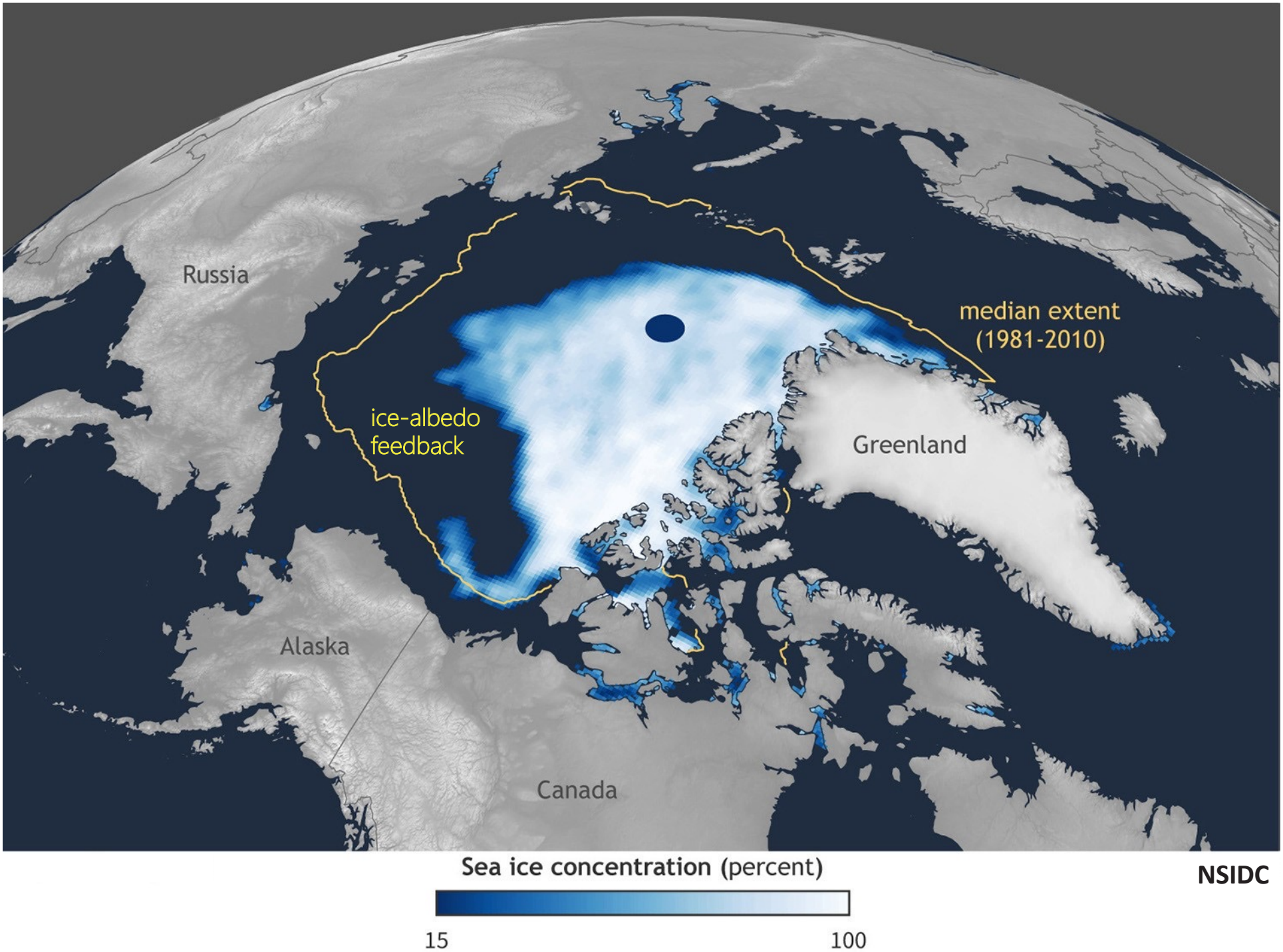
$$\textbf{albedo } \alpha = \frac{\text{Reflected sunlight}}{\text{Incident sunlight}}$$

the summer Arctic sea ice pack is melting



National Snow and Ice Data Center (NSIDC)

Arctic sea ice extent September 15, 2020



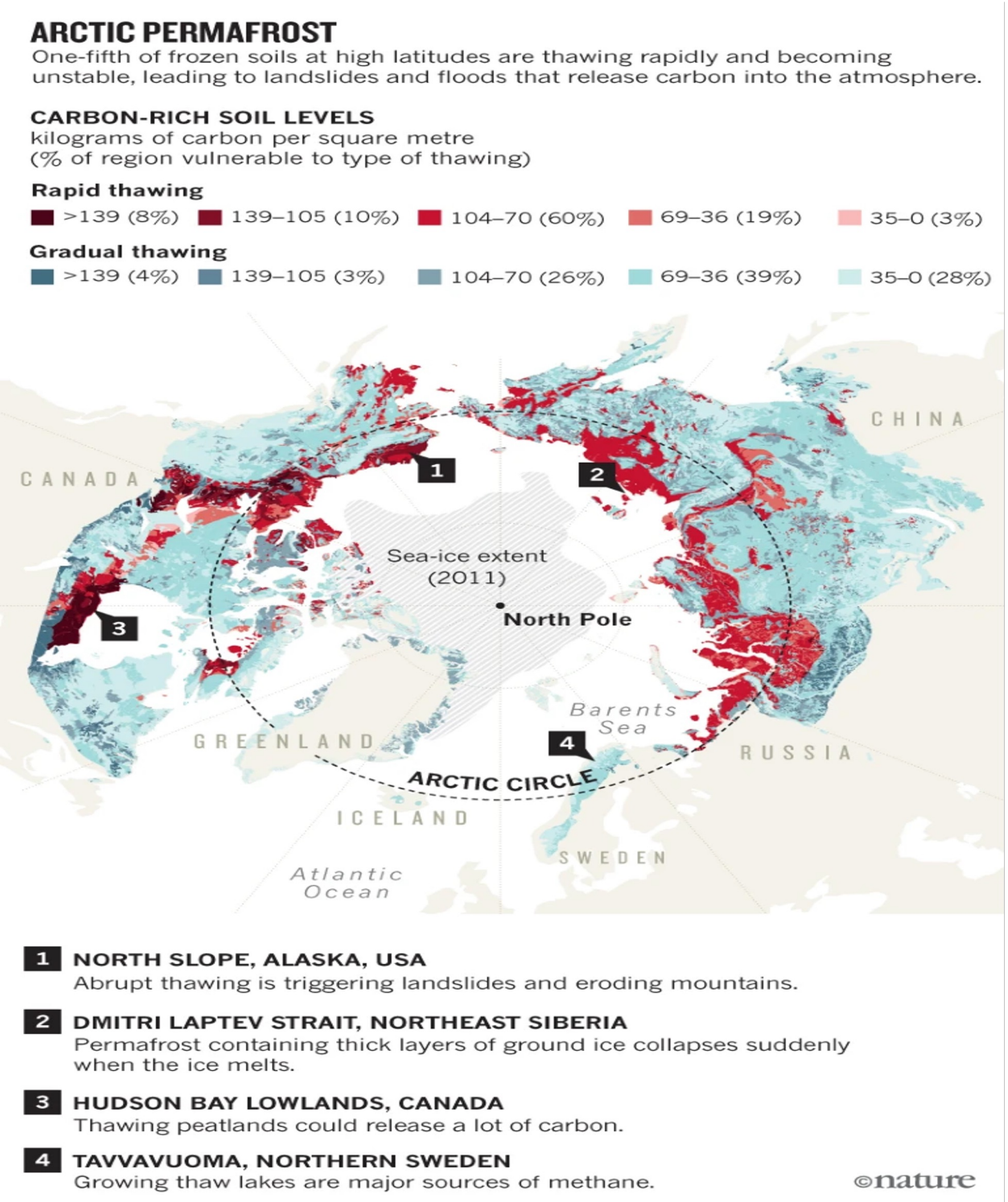
NSIDC

recent losses in comparison to the United States

The Arctic is ground zero for climate change.

Perovich

Permafrost collapse is accelerating carbon release

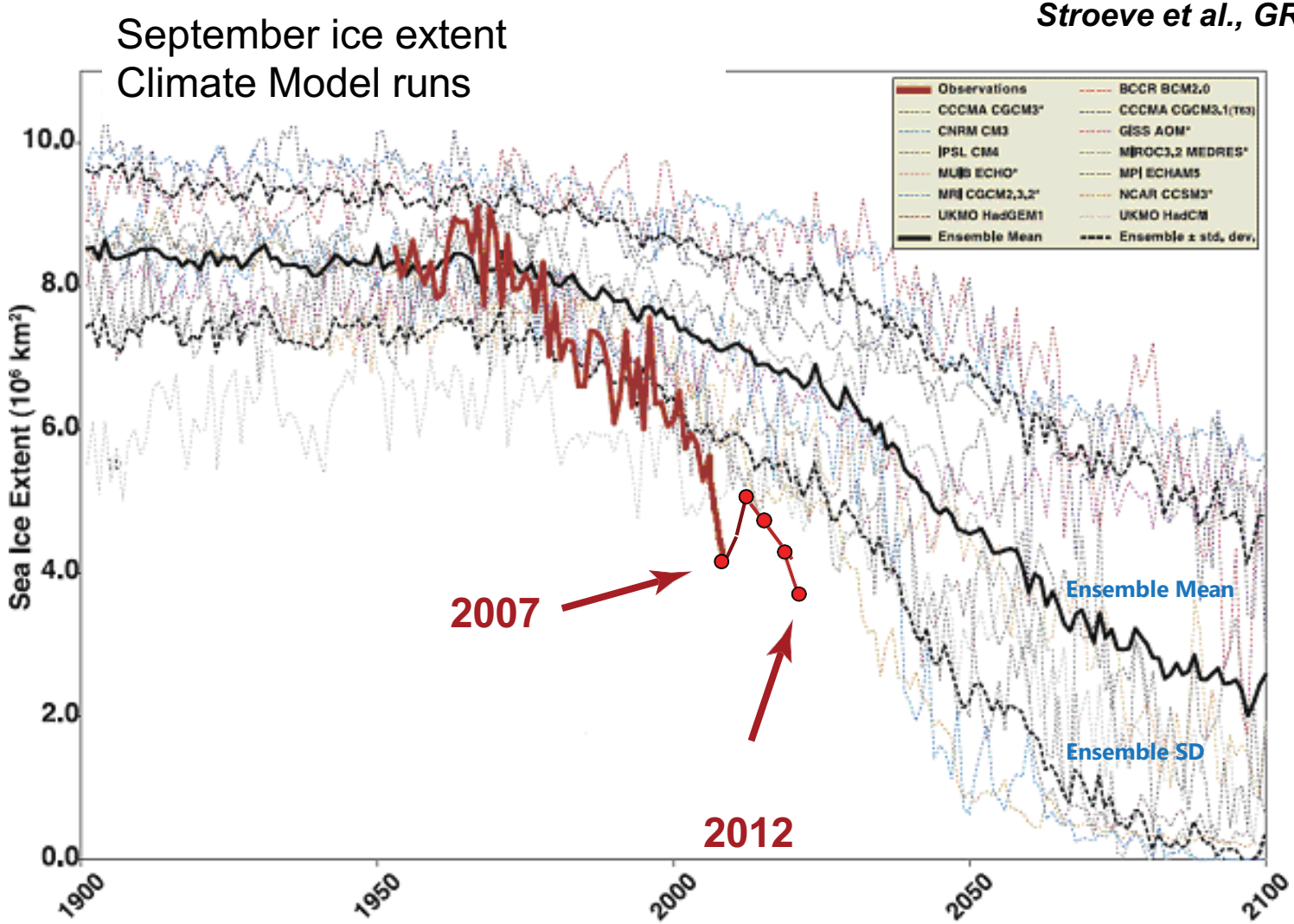


Source: Turetsky et al, 2019, Nature.com

Arctic sea ice decline: faster than predicted by climate models

Stroeve et al., GRL, 2007

Stroeve et al., GRL, 2012



IPCC AR4 Models

Intergovernmental Panel on Climate Change (IPCC)

Fourth Assessment AR4, 2007

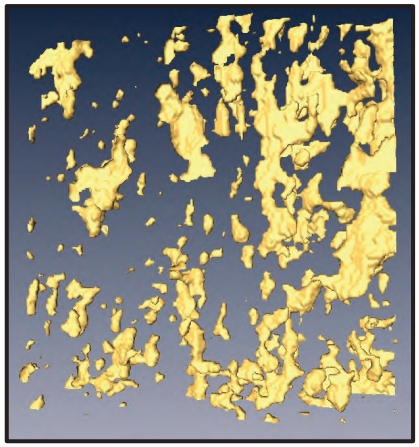
Modeling of large-scale sea ice dynamics has been dominated for decades by TOP-DOWN coarse-grained numerical models based on a framework developed half a century ago.

Sea Ice is a Multiscale Composite Material

microscale

brine inclusions

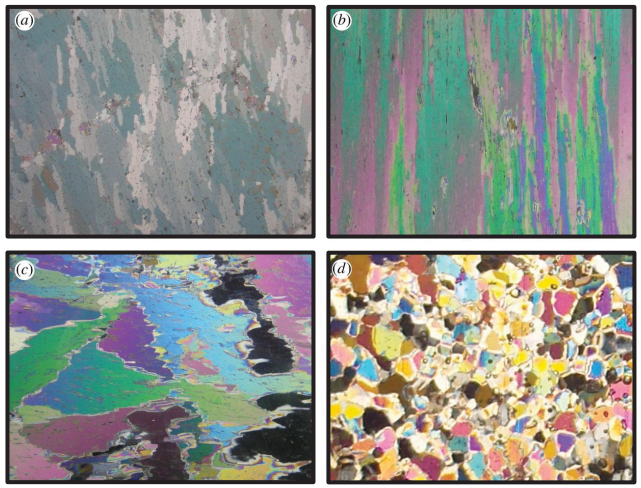
Weeks & Assur 1969



H. Eicken

Golden *et al. GRL* 2007

polycrystals



Gully *et al. Proc. Roy. Soc. A* 2015

brine channels

D. Cole

K. Golden

millimeters

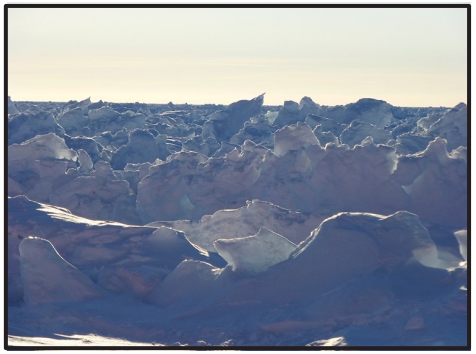
centimeters

mesoscale

Arctic melt ponds

K. Frey

Antarctic pressure ridges



K. Golden

macroscale

sea ice floes

J. Weller

sea ice pack

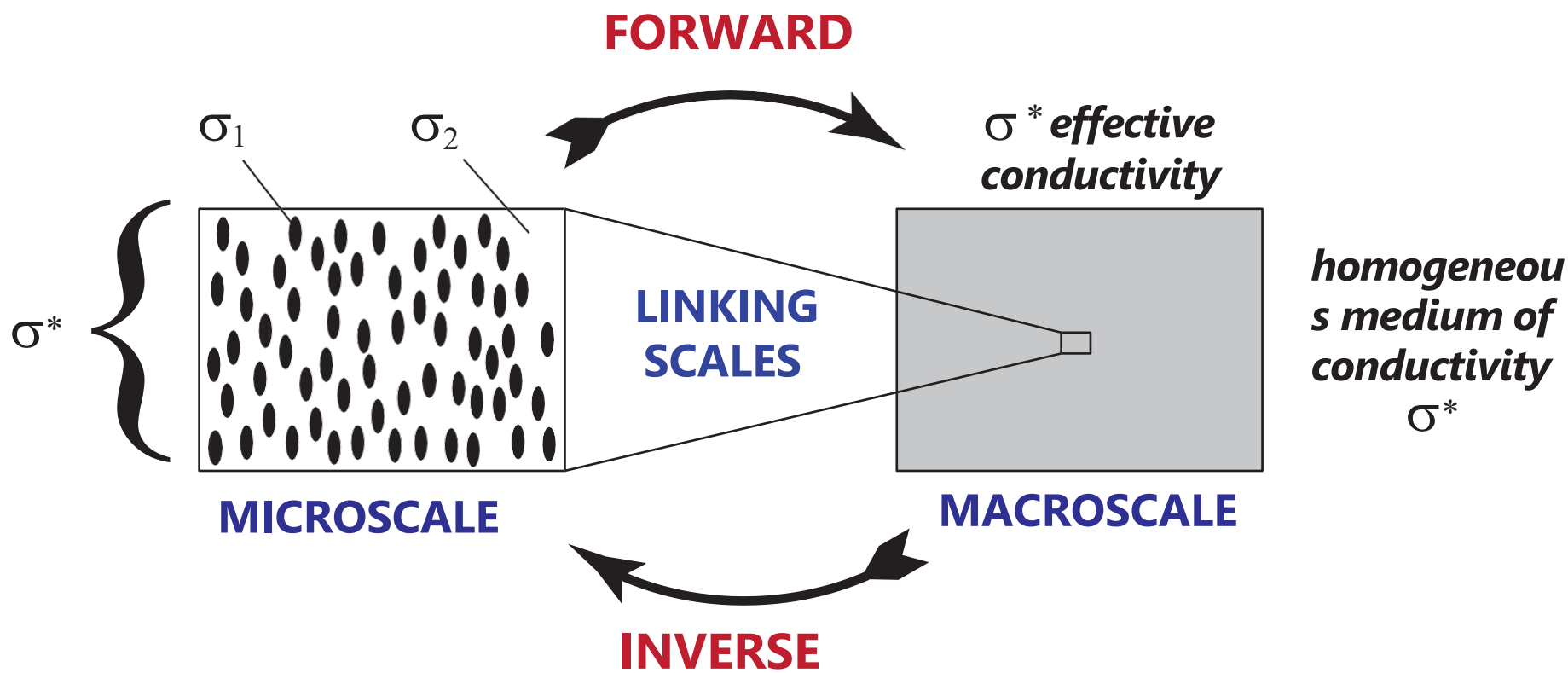
NASA

meters

fractals everywhere!

kilometers

HOMOGENIZATION for Composite Materials

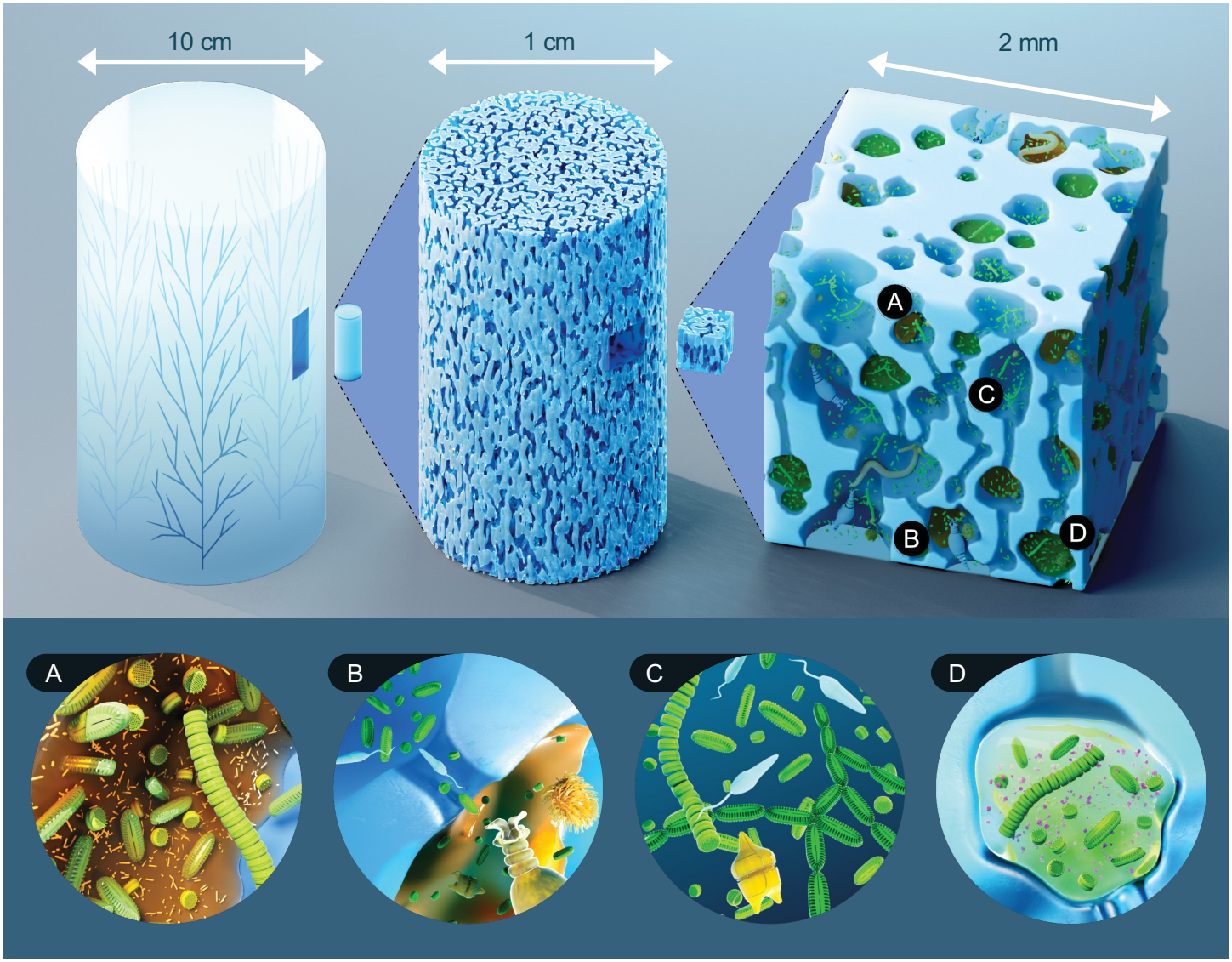


Maxwell 1873 : effective conductivity of a dilute suspension of spheres
Einstein 1906 : effective viscosity of a dilute suspension of rigid spheres in a fluid

*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 fractal geometry and sea ice ecology

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.

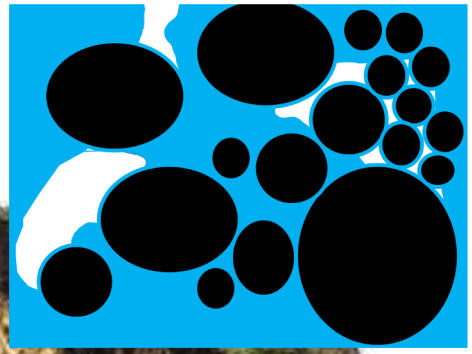
(A) Many sea ice organisms attach themselves to inclusion walls; inclusions with a higher fractal dimension have greater surface area for colonization.

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

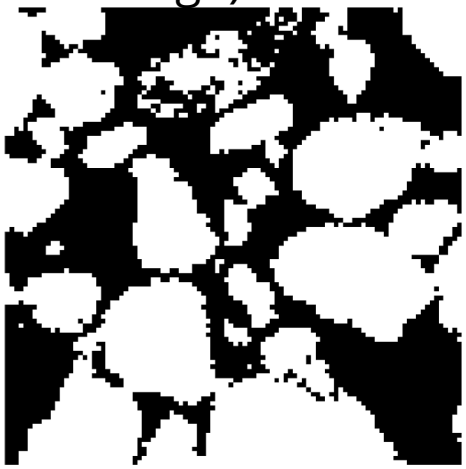
(D) Ice algae secrete extracellular polymeric substances (EPS) which alter incusion geometry and may further increase the fractal dimension.

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)



Credits: NPS.gov

Permafrost thaw causes infrastructure damage

Credit: newsweek.com

- **NEWS FEATURE (credit Moira Hough)**
- 17 March 2021

How microbes in permafrost could trigger a massive carbon bomb

https://www.nature.com/articles/d41586-021-00659-y

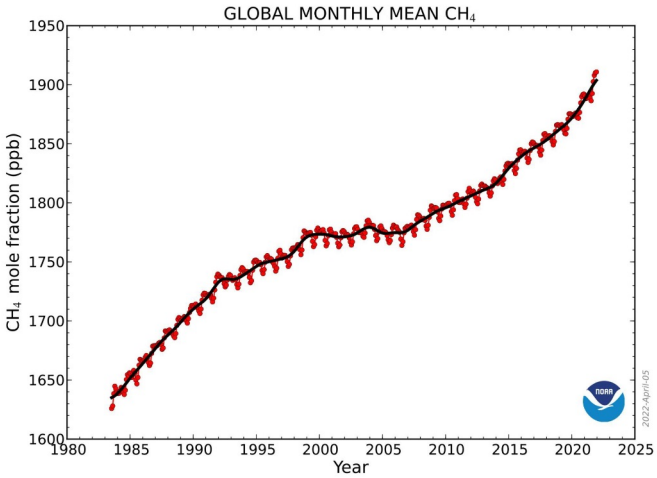
Methane seeps from under thawing lakes in permafrost zones

Credits: NASA's Earth Science News Team

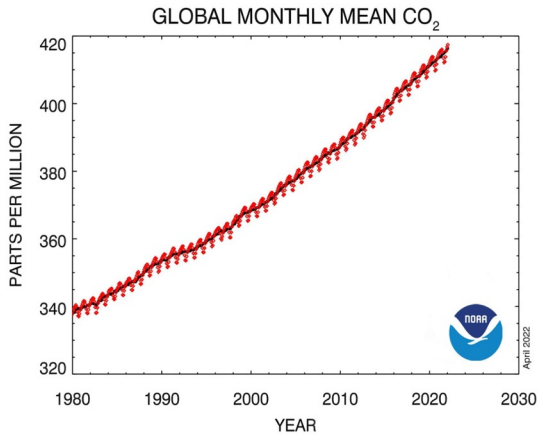
Image Credit: Katey Walter Anthony/ University of Alaska Fairbanks

Credit: Yuri Kozyrev/NOOR/eyevine

credits: NOAA



https://www.noaa.gov/news-release/increase-in-atmospheric-methane-set-another-record-during-2021



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 channnels

MICRO

floes sizes and shapes / broken ice
ocean surface waves break up the ice
melt ponds
ridges
keels

MESO

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.

IMPACTS

- 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!

Society for Industrial and Applied Mathematics

DMS 2227218

Who cares if Arctic sea ice disappears?

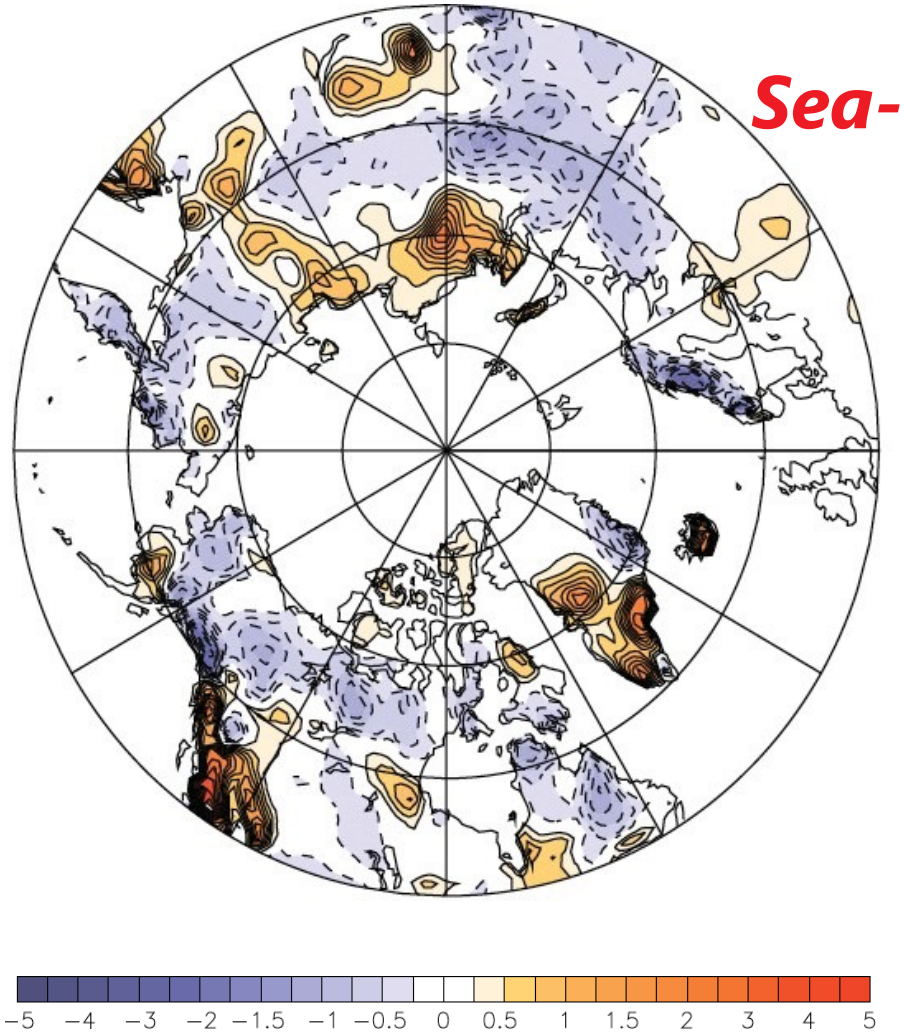
Use of sea ice as a platform

- Walrus life cycle tied to sea-ice cycle
- Ice floes as diving platforms for feeding over shallow shelf

Photo: Marc Webber, US Fish & Wildlife Service

BMCM Tim Sullivan

Sea-ice loss: impacts beyond the Arctic



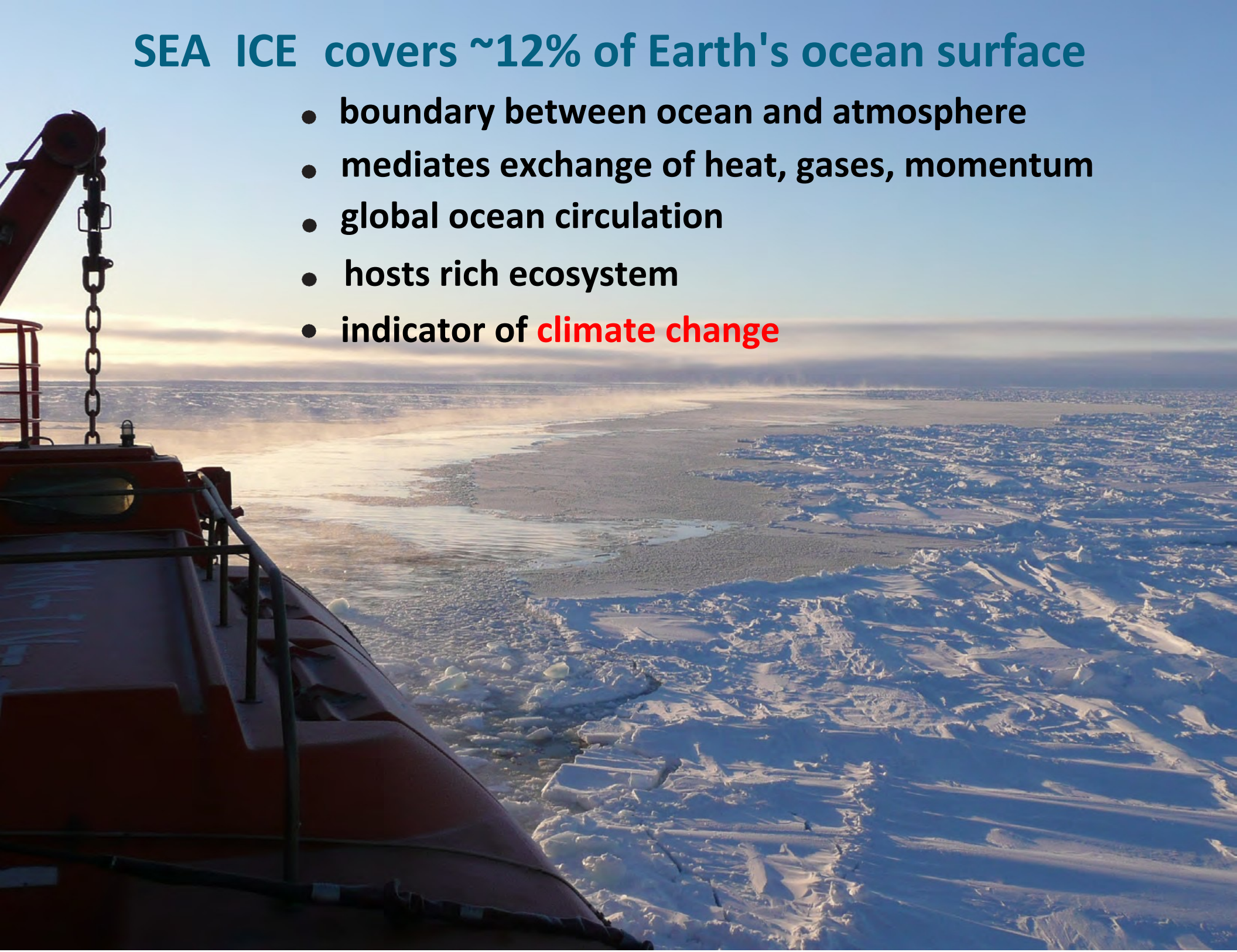
Orsolini et al., 2011

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

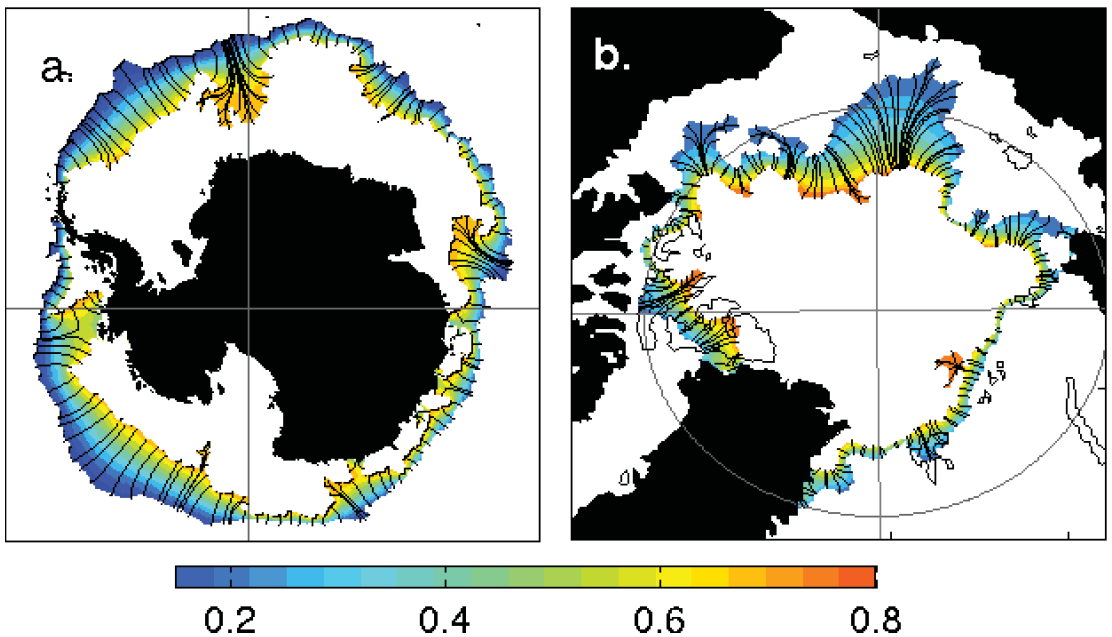
- boundary between ocean and atmosphere
- mediates exchange of heat, gases, momentum
- global ocean circulation
- hosts rich ecosystem
- indicator of climate change



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 ($c > 80\%$)
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?