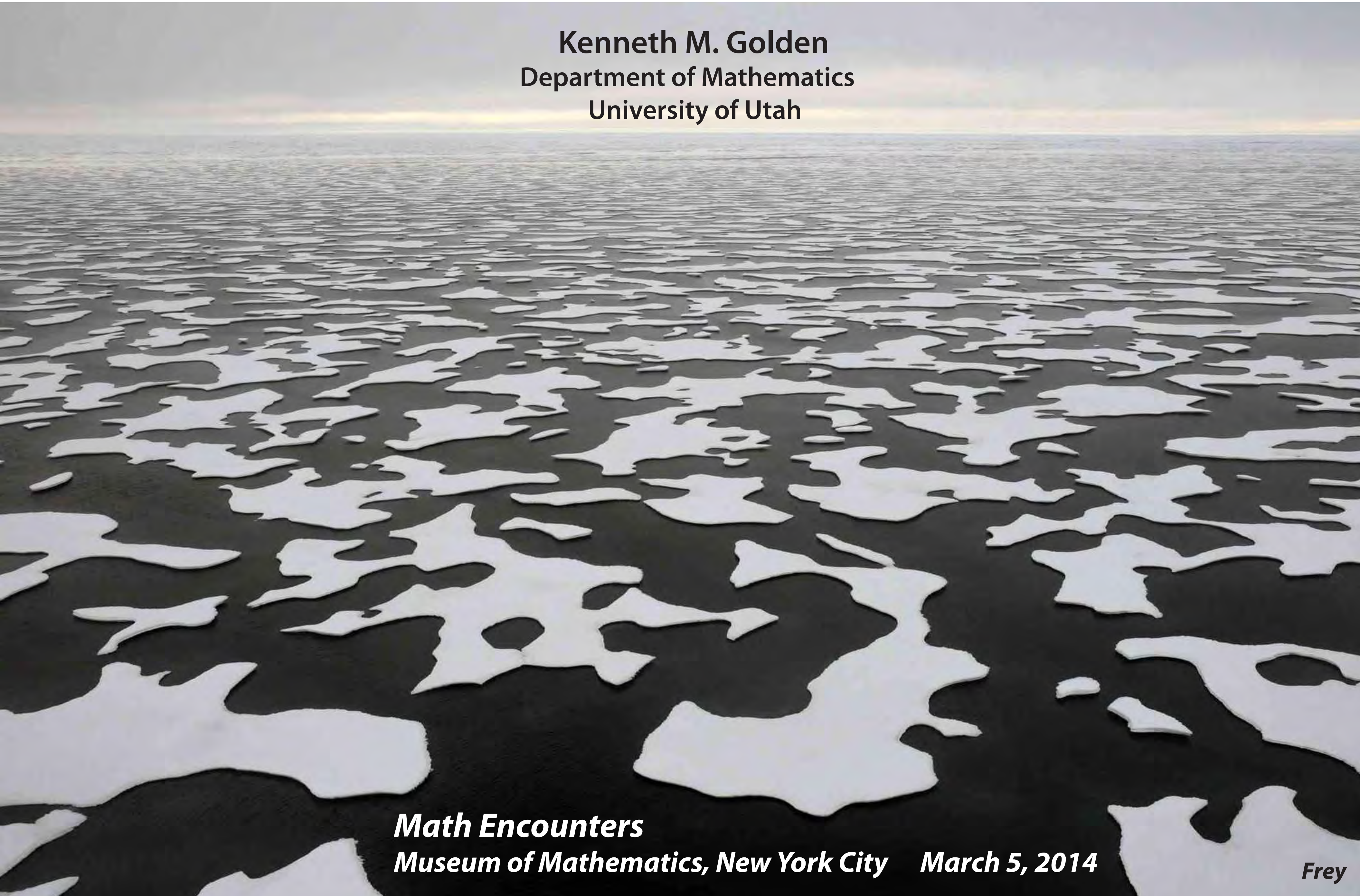
MODELING *the* MELT:
what math tells us about the disappearing polar ice caps



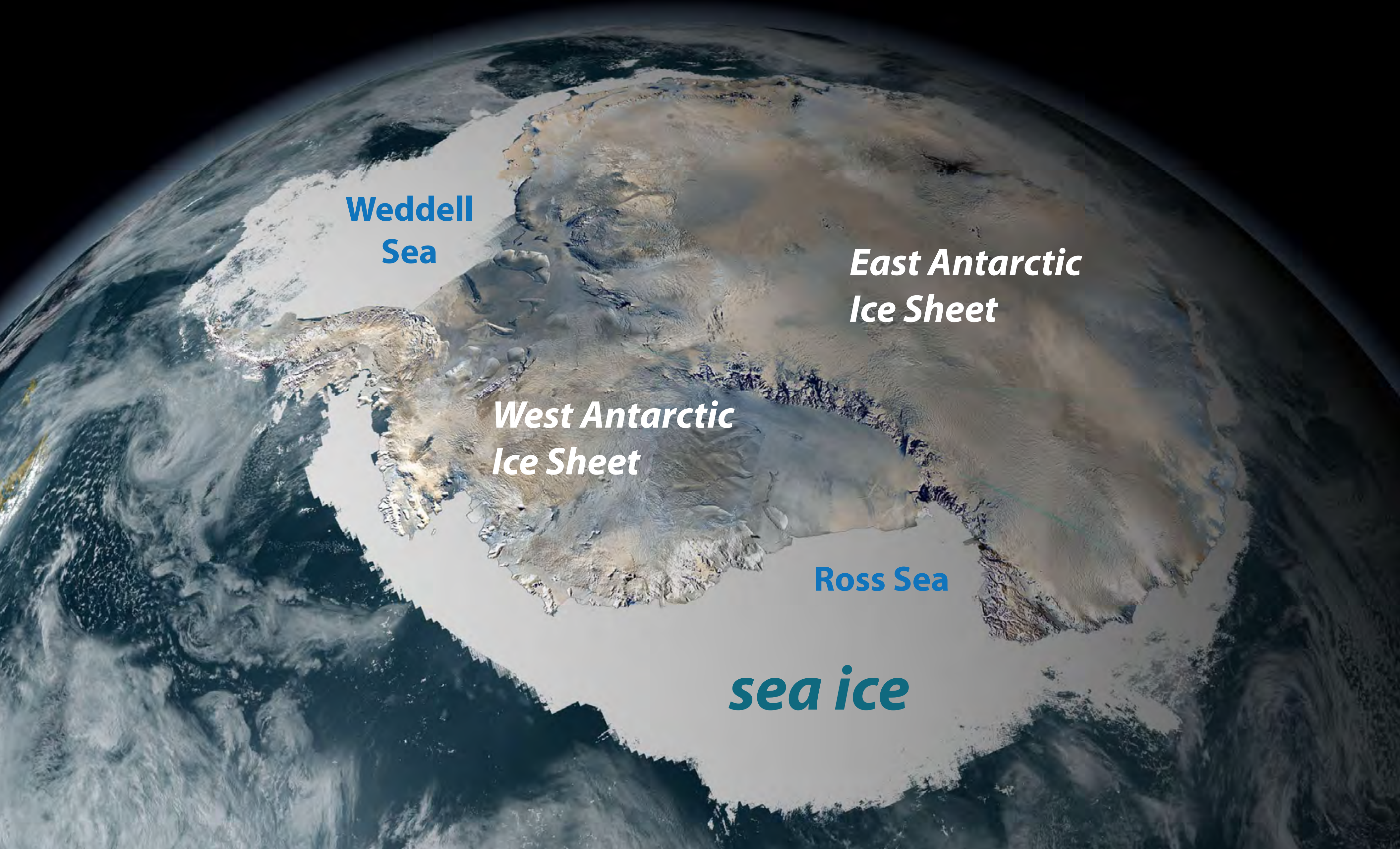
Kenneth M. Golden
Department of Mathematics
University of Utah

Math Encounters
Museum of Mathematics, New York City   March 5, 2014

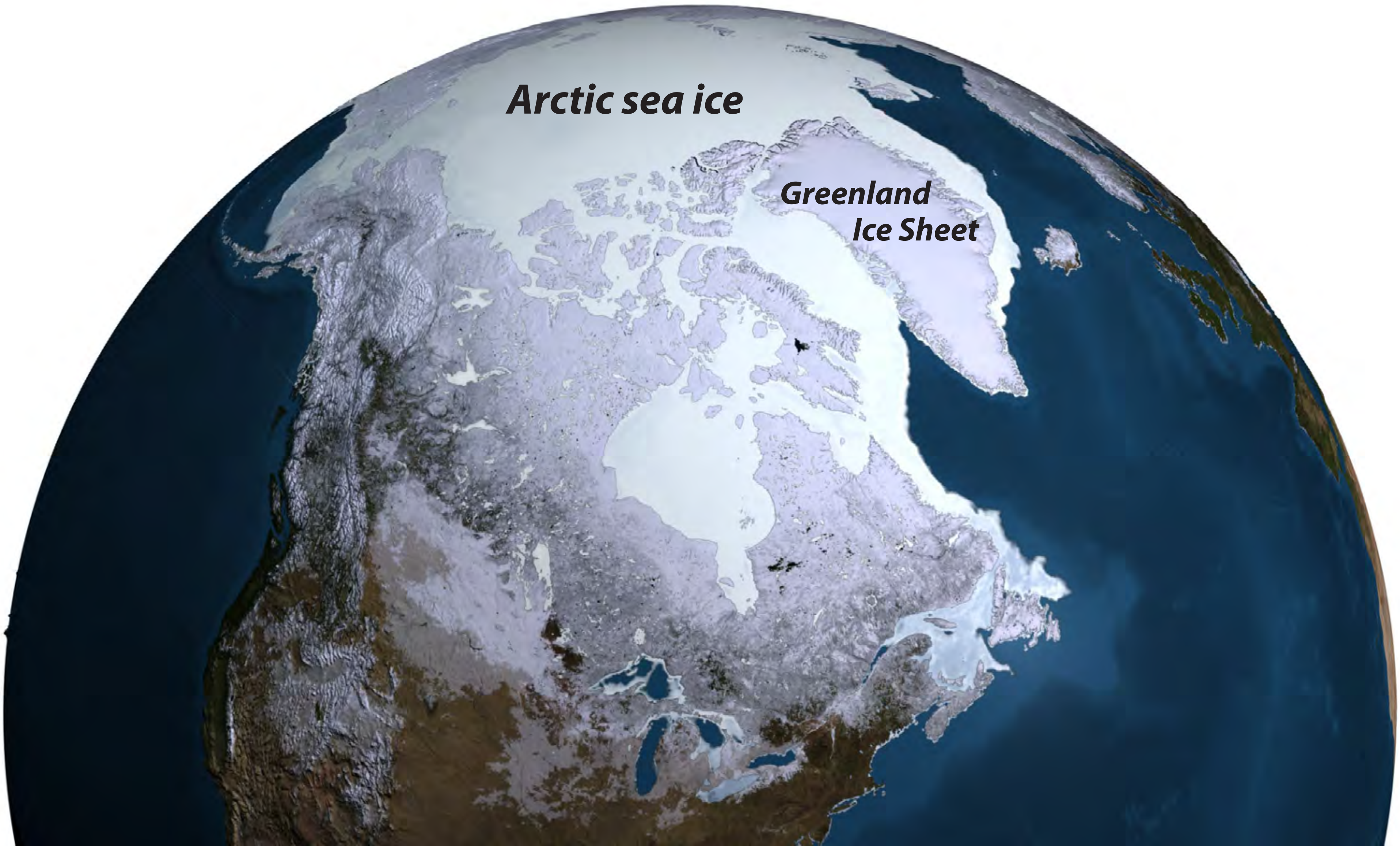
Frey

ANTARCTICA

southern cryosphere



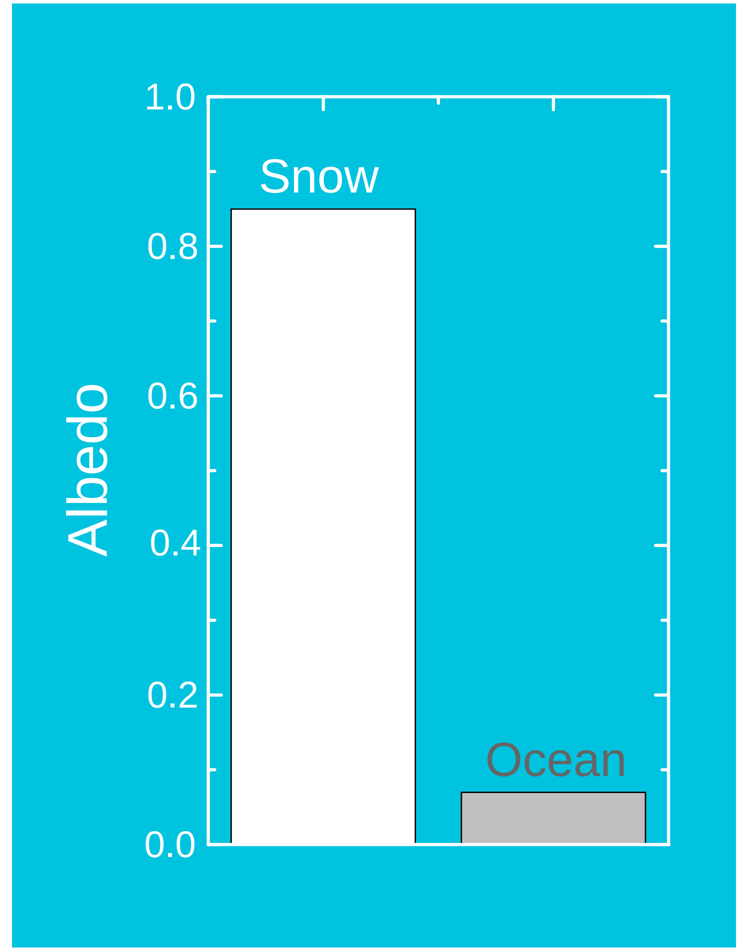
northern cryosphere




SEA ICE covers 7 - 10% of earth's ocean surface
• boundary between ocean and atmosphere
• mediates exchange of heat, gases, momentum
• global ocean circulation
• indicator and agent of climate change

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

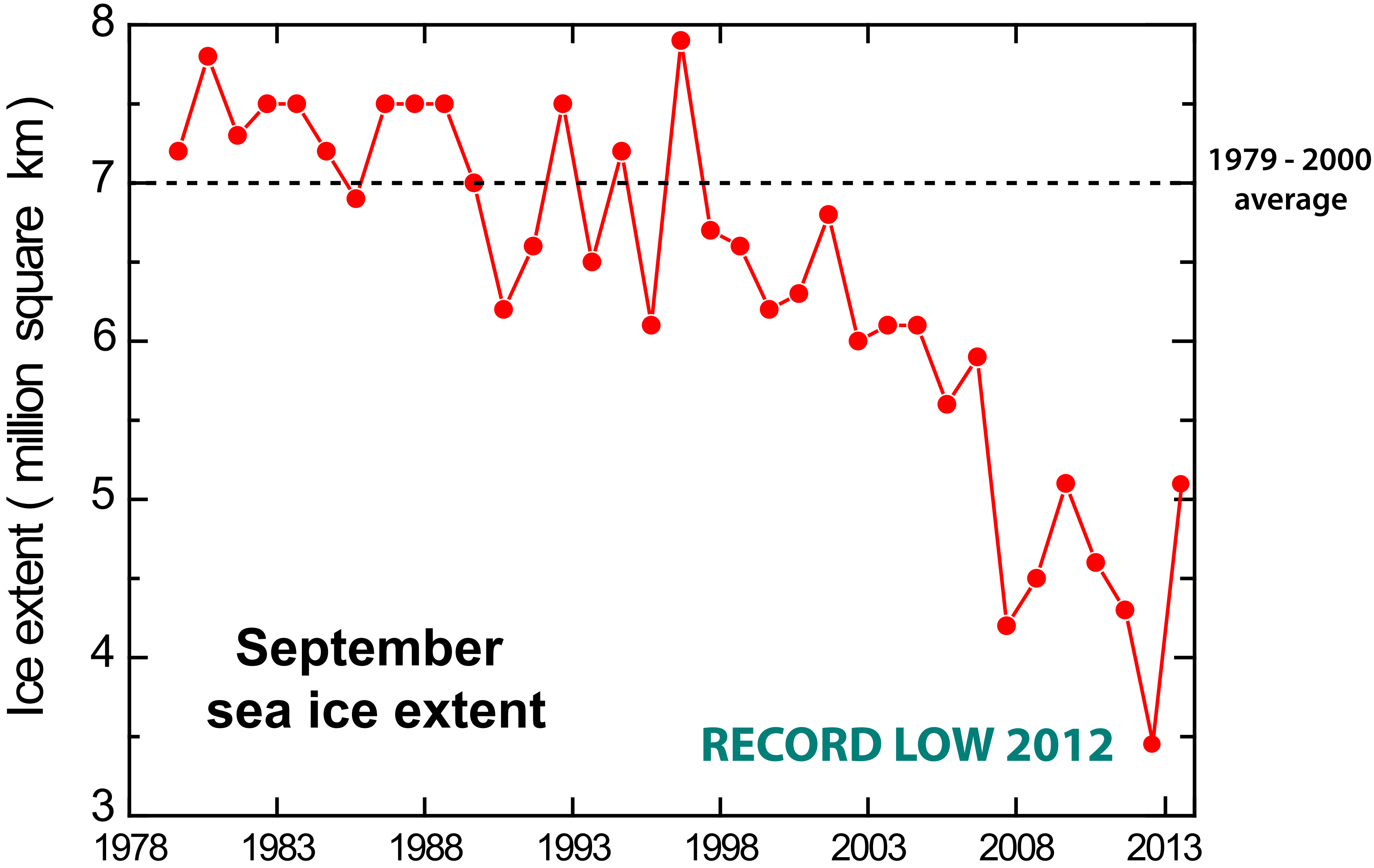
white snow and ice reflect



dark water and land absorb

$$\textbf{\textit{albedo}}\ \alpha = \frac{\text{reflected sunlight}}{\text{incident sunlight}}$$

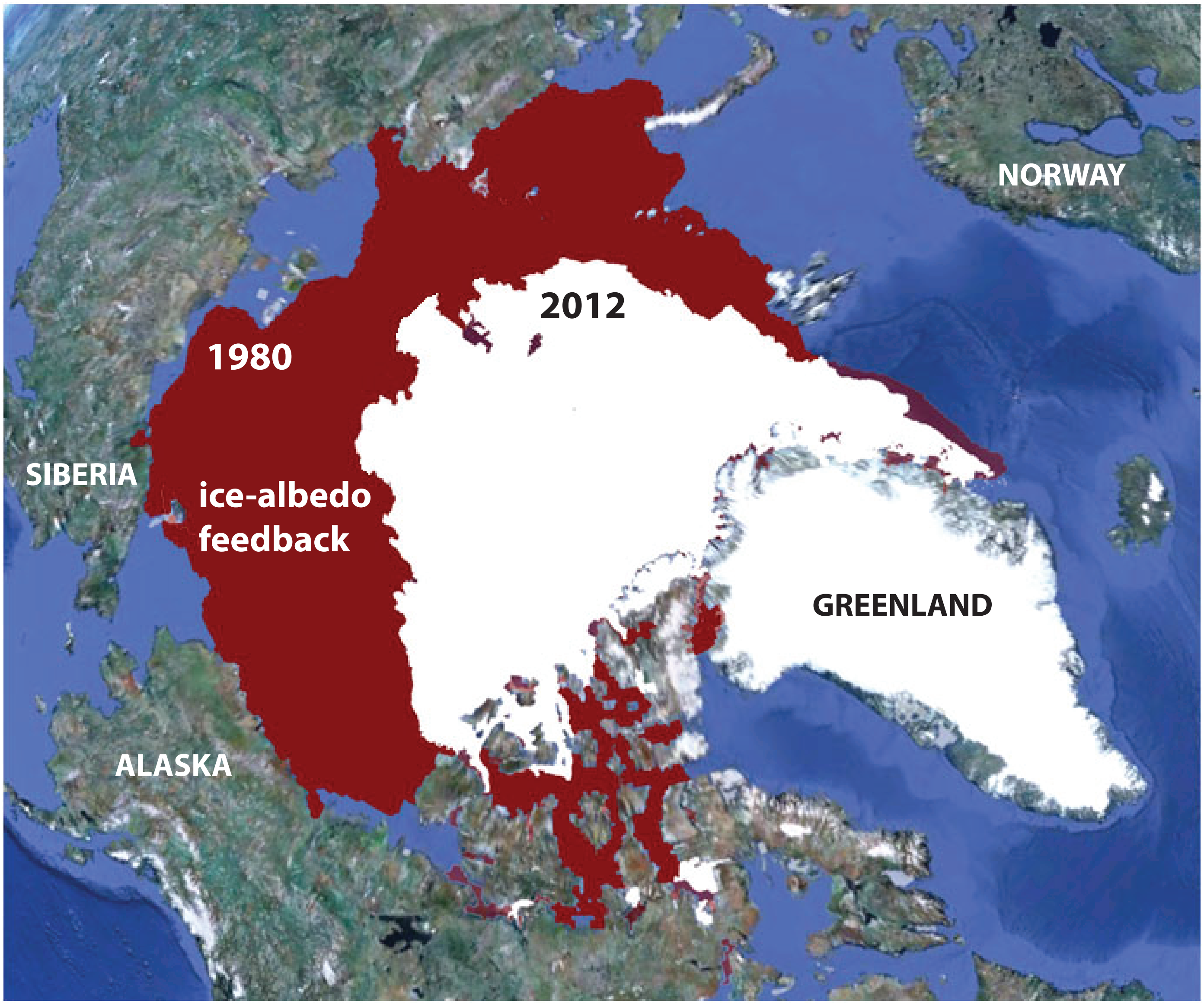
the summer Arctic sea ice pack is melting



National Snow and Ice Data Center

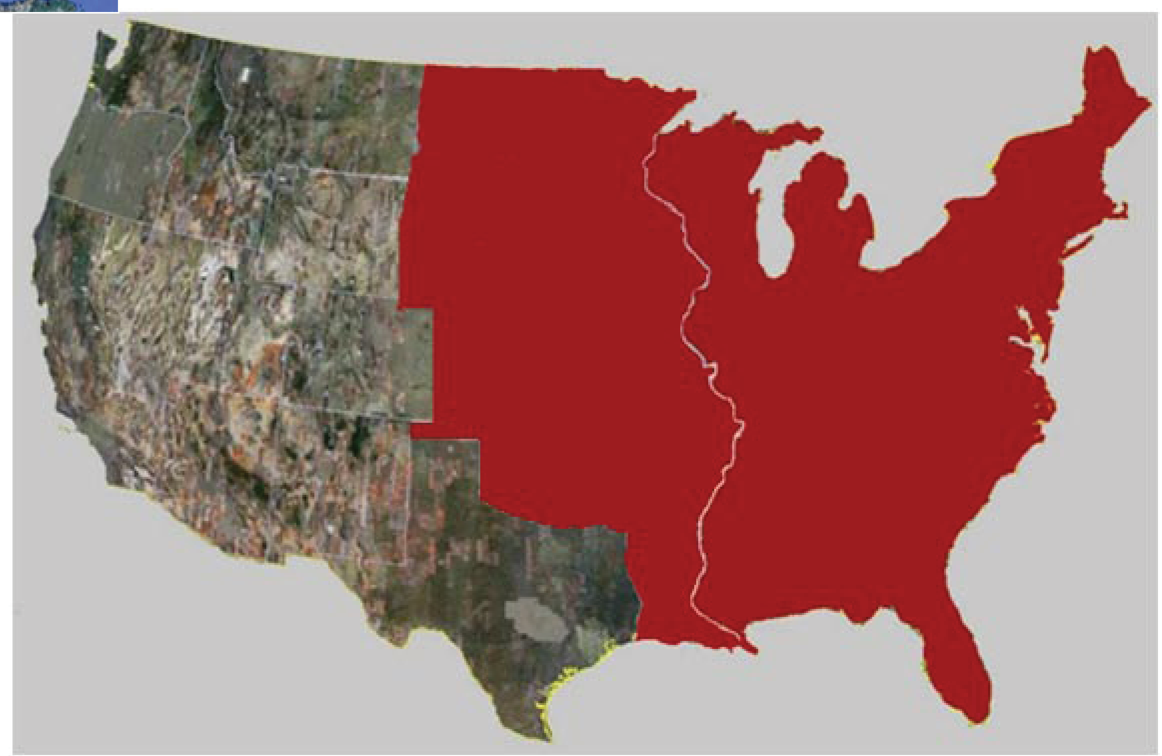
Change in Arctic Sea Ice Extent

September 1980 -- 7.8 million square kilometers
September 2012 -- 3.4 million square kilometers



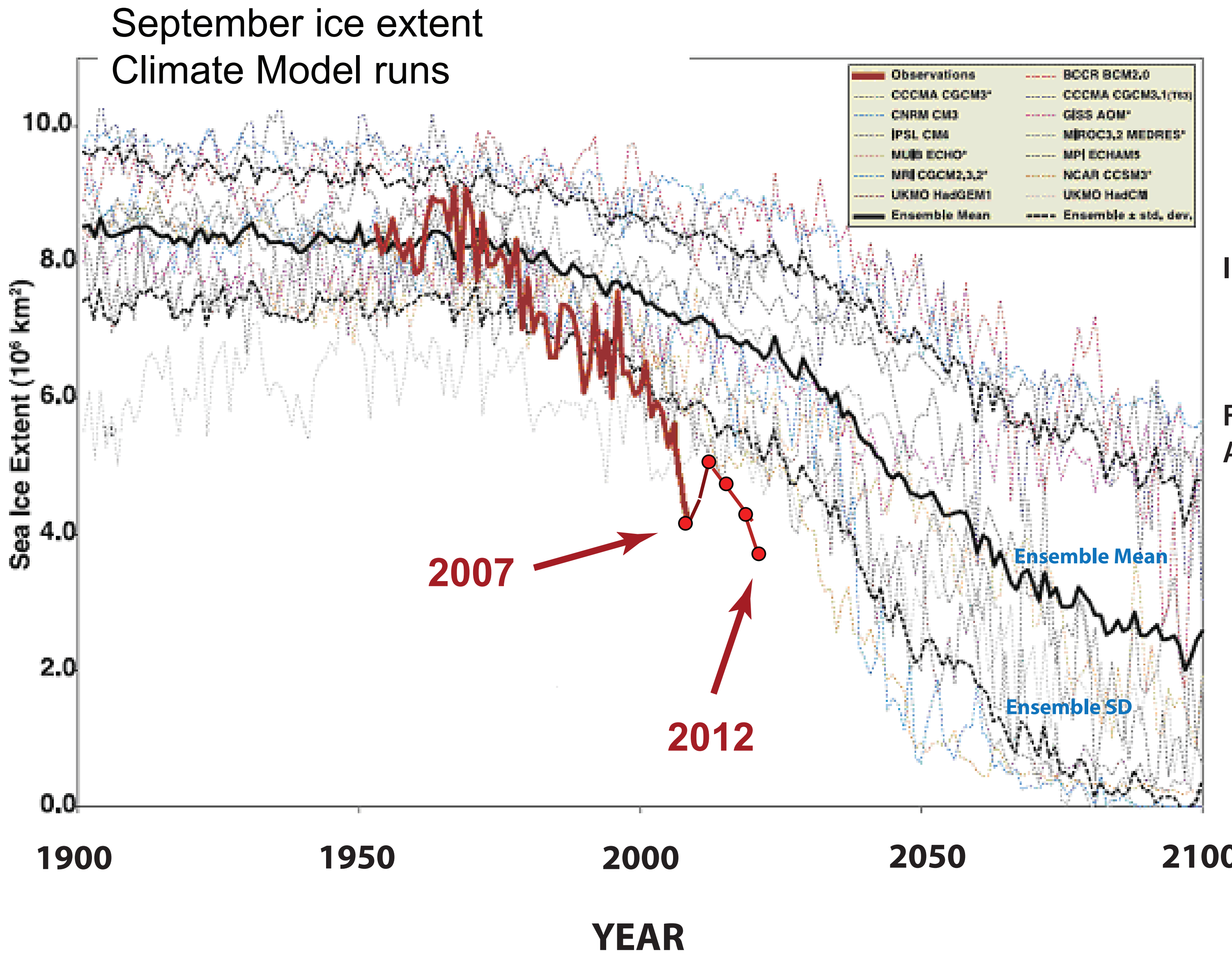
Perovich

recent losses in comparison to the United States



Arctic sea ice decline - faster than predicted by climate models

Stroeve et al., GRL, 2007



IPCC AR4 Models

Intergovernmental Panel on Climate Change (IPCC)

Fourth Assessment AR4, 2007

Perovich

challenge

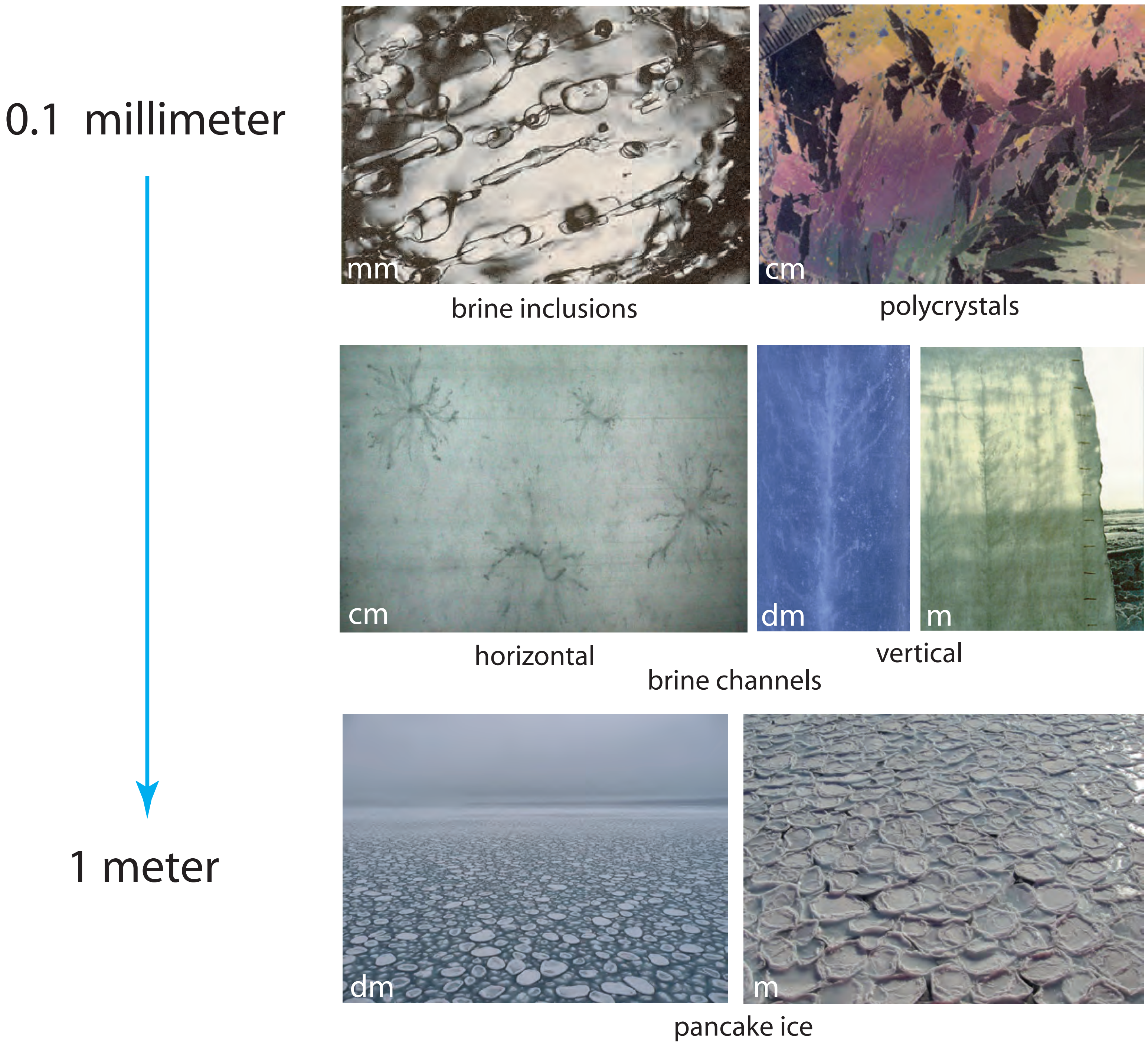
represent sea ice more rigorously in climate models

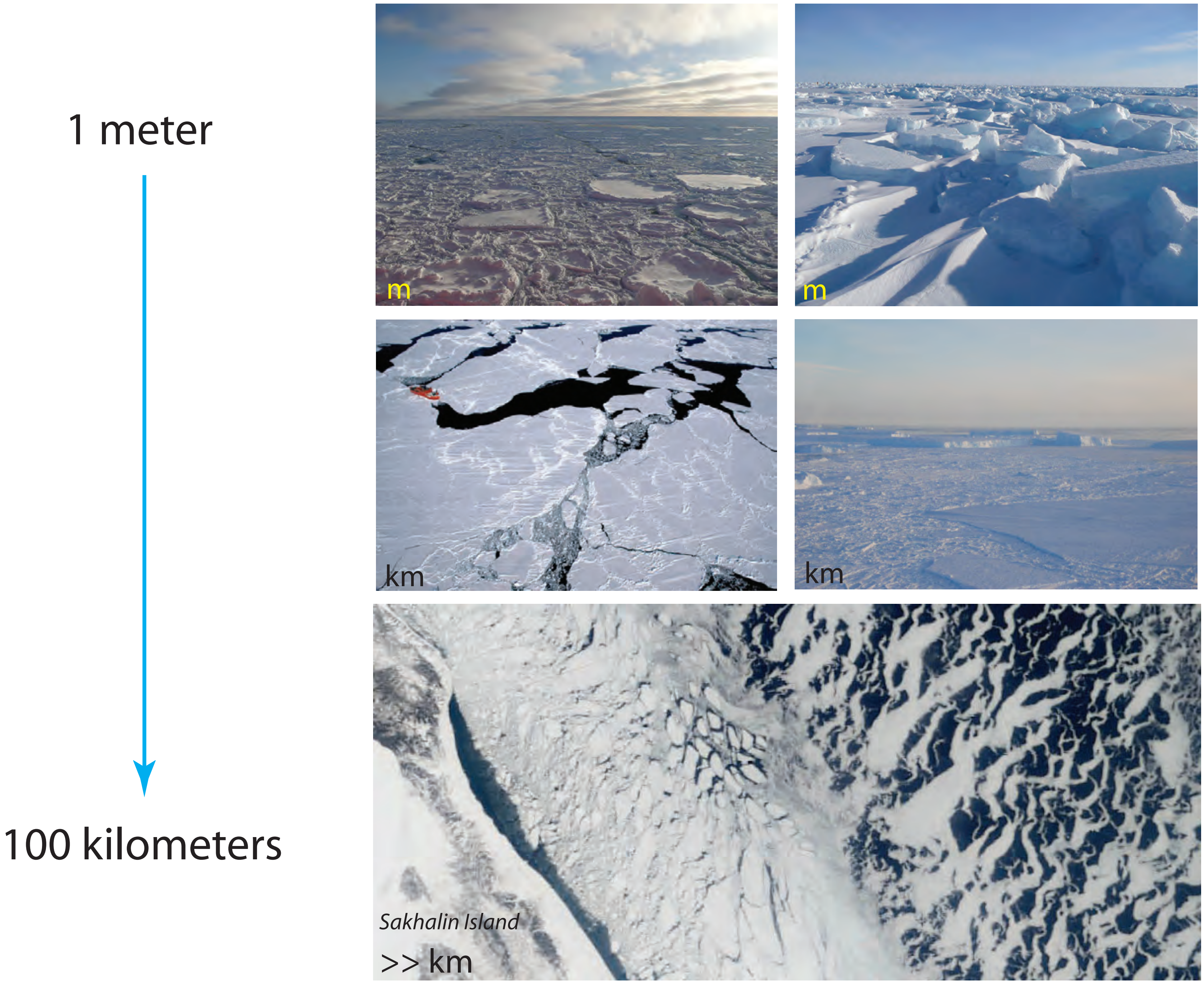
incorporate key processes

fundamental problem -- linkage of scales

sub-grid scale processes

sea ice displays ***multiscale*** structure over 10 orders of magnitude




1 meter
100 kilometers
m
m
km
km
Sakhalin Island
>> km

What is this talk about?

Using the mathematics of composite materials and statistical physics to study sea ice structures and processes ... to improve projections of climate change.

1. ***Fluid flow through sea ice - percolation***

   homogenzation for composite materials

2. ***Electromagnetic monitoring of sea ice***

   homogenzation for larger scale structures

3. ***Arctic and Antarctic experiments***

4. ***Fractal geometry of Arctic melt ponds***

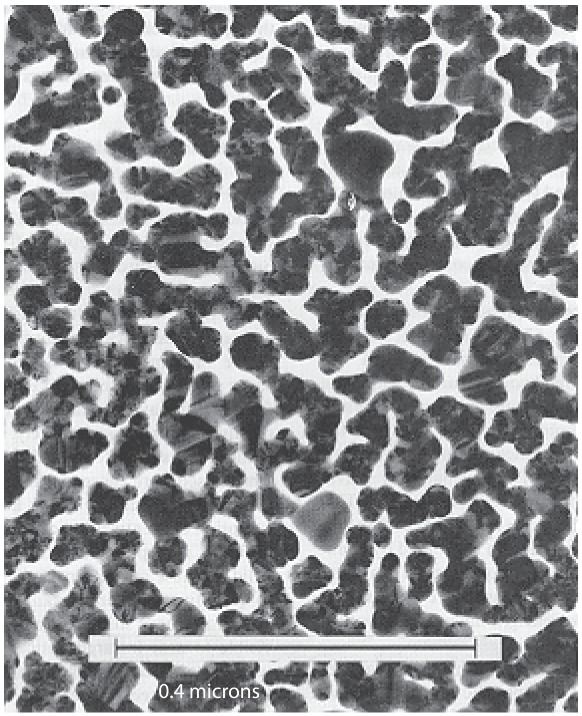
critical behavior ***linkage of scales***

cross-pollination

Develop rigorous representations of sea ice in climate models.

thin silver film

microns



(Davis, McKenzie, McPhedran, 1991)

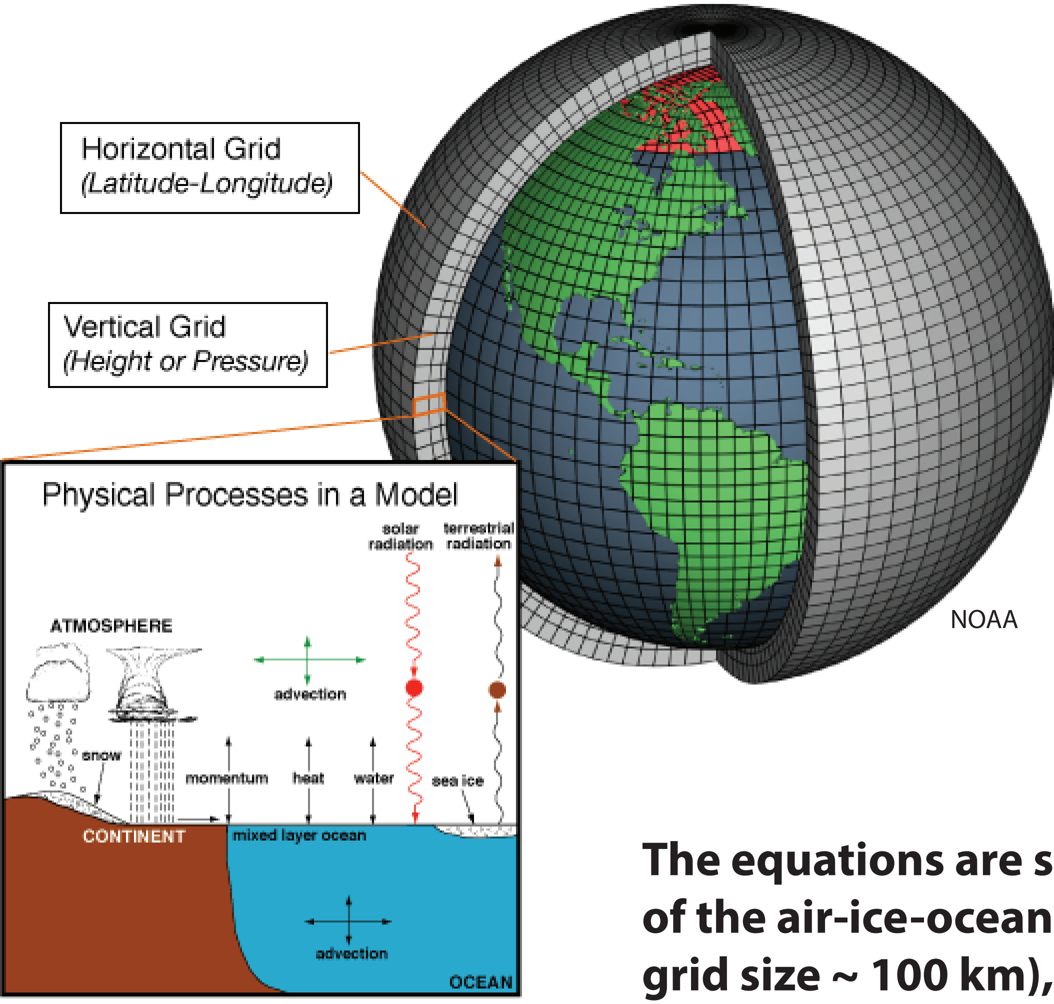
Arctic melt ponds

kilometers

(Perovich, 2005)

optical properties

composite geometry -- area fraction of phases, connectedness, necks



Global Climate Models

Climate models are systems of partial differential equations (PDE) derived from the basic laws of physics, chemistry, and fluid motion.

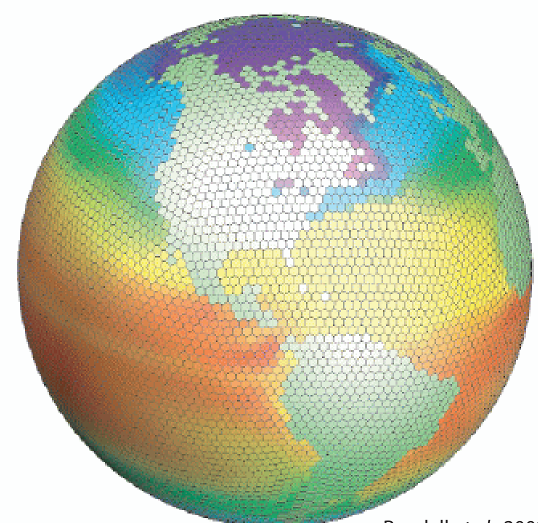
They describe the state of the ocean, ice, atmosphere, land, and their interactions.

The equations are solved on 3-dimensional grids of the air-ice-ocean-land system (with horizontal grid size ~ 100 km), using very powerful computers.

key challenge :

incorporating sub - grid scale processes

linkage of scales



Randall *et al*., 2002

sea ice component of a Global Climate Model

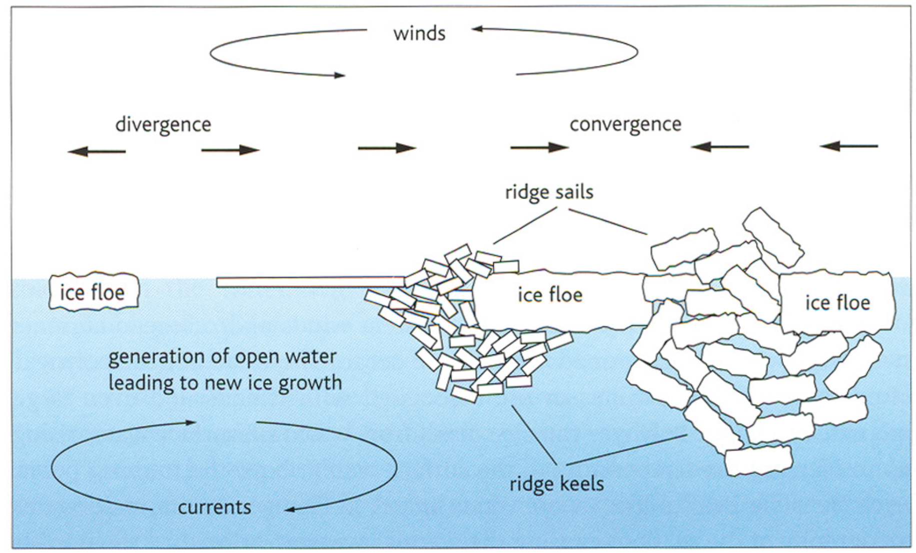
What are the key ingredients -- or ***governing equations***
that need to be solved on grids using powerful computers?

1. **Ice thickness distribution evolution equation**

(Thorndike *et al.* 1975)

dynamics + ***thermodynamics***

PDE incorporating ice velocity field
ice growth and melting
mechanical redistribution
ridging and opening



2. **Conservation of momentum, stress *vs*. strain relation** (Hibler 1979)

F* = *ma **for sea ice**

dynamics

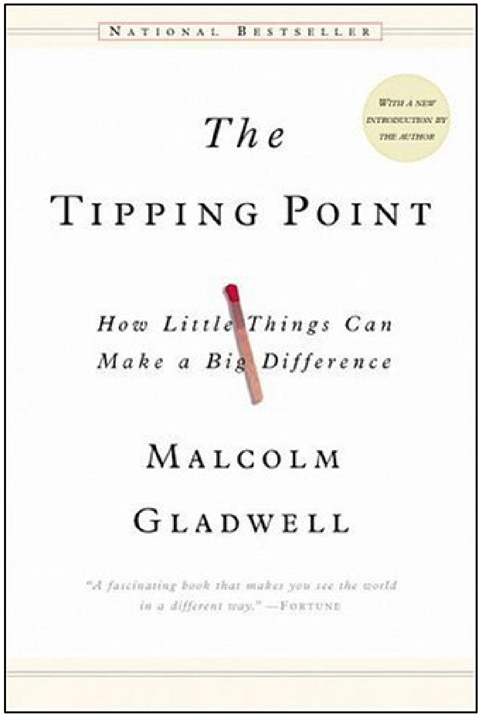
3. **Heat equation of sea ice and snow**

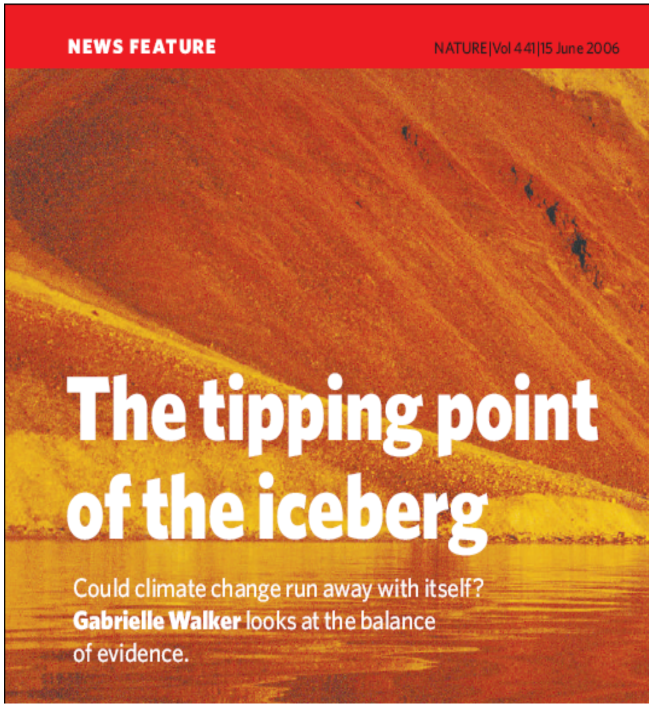
coupling ocean and atmosphere

thermodynamics

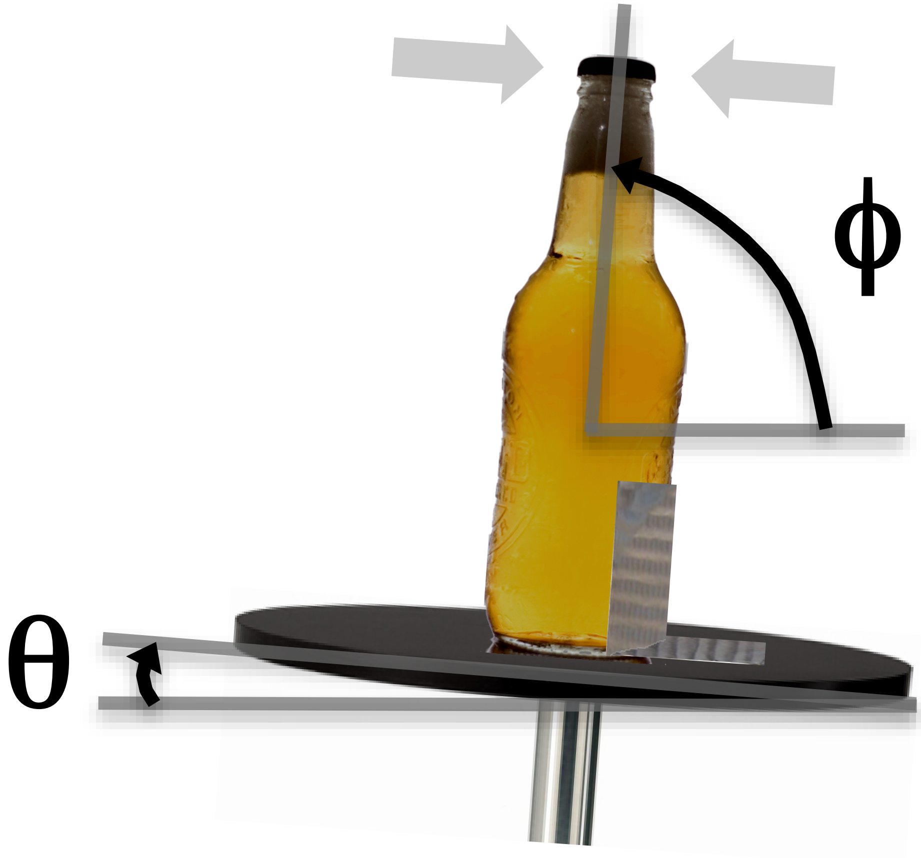
(Maykut and Untersteiner 1971)

tipping points in the mainstream





Increasing emphasis in recent years on idea of climate tipping points, with September Arctic sea ice cover receiving much of the attention.



“tipping point”

Tape a bottle to a tilted table, vary θ and observe φ.

Tilt the table until bottle tips -- irreversible process since bottle doesn’t tip back until table tilted back very far.

hysteresis

Ian Eisenman

active area of mathematical research on sea ice:

Has Arctic sea ice loss passed through a "tipping point"?

an irreversible downward slide to ice-free Arctic summers, driven by ice-albedo feedback

***Eisenman, Wettlaufer, PNAS 2009*:**

analyze a single nonlinear ODE
for the energy in the upper ocean

look for "bifurcations" in solutions

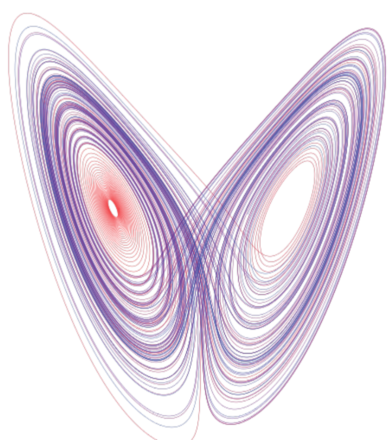
- unlikely in current loss of summer ice
- more likely in further loss of winter ice

***Abbot, Silber, Pierrehumbert, JGR 2011*:**

more robust bifurcation structure when include effects of clouds and ice loss

Serreze, Nature 2011; Tietsche et al. GRL 2011:

sea ice could recover quickly



Lorenz butterfly

dynamical systems

low order models of Arctic climate change

opposite "pole" from GCM's

Who cares if Arctic sea ice disappears?

Ralph (Malik) Ahkivgak, c. 20 Oct 1988

seaice.alaska.edu/gi

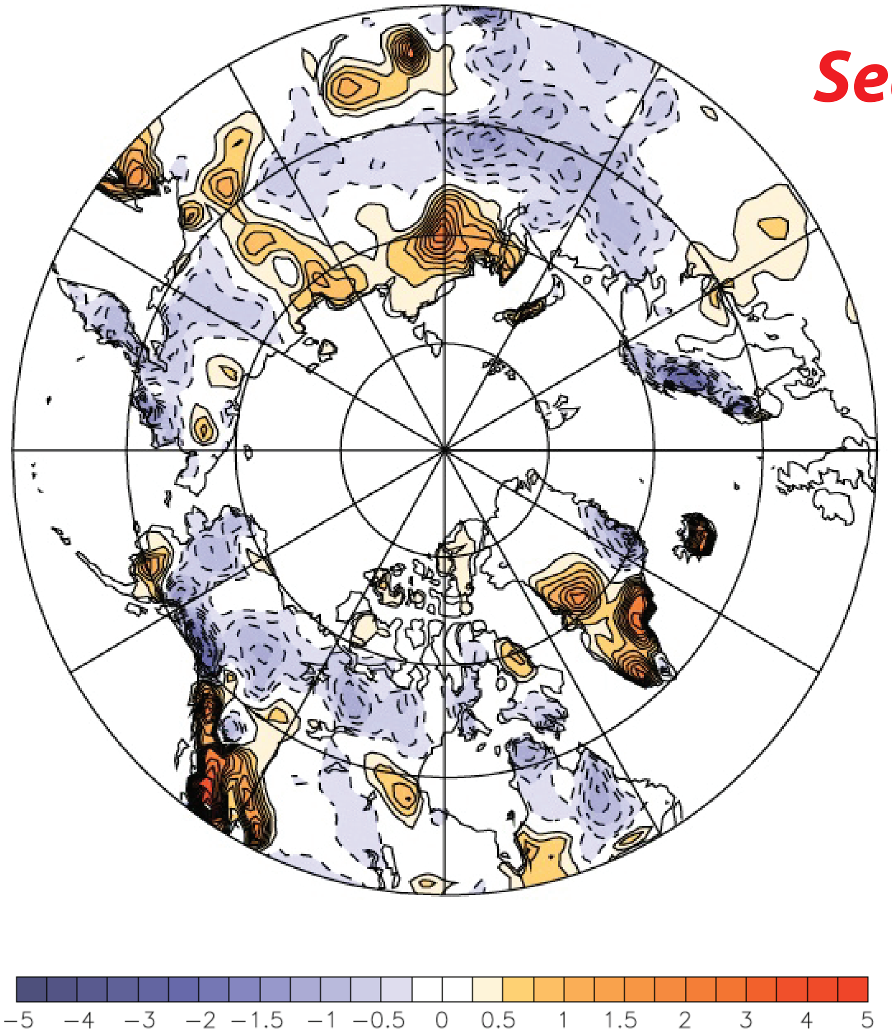
• The Arctic holds 25% of the world's undiscovered oil & gas reserves

• Sea ice is both a hazard and a supporting feature for hydrocarbon exploration & production

oil companies care about Arctic sea ice loss

Source: UNEP/GRID-Arendal

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)

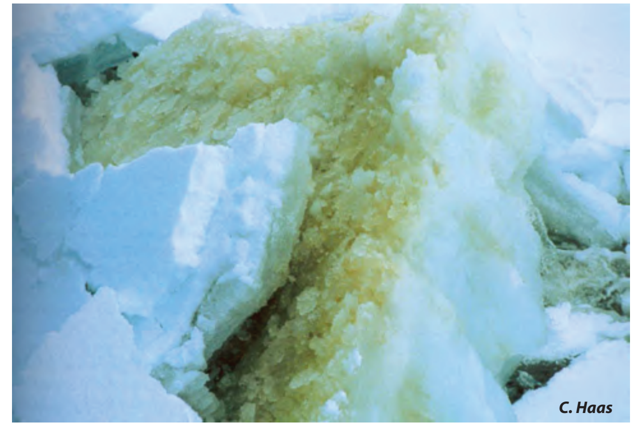
sea ice microphysics

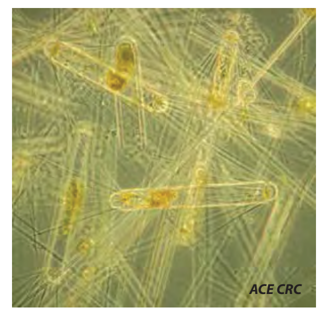
fluid transport

fluid flow through the porous microstructure of sea ice governs key processes in polar climate and ecosystems

evolution of Arctic melt ponds and sea ice albedo

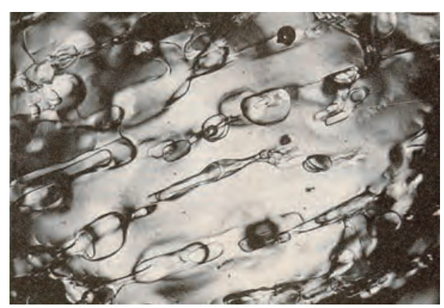
nutrient flux for algal communities





- *drainage of brine and melt water*
- *ocean-ice-air exchanges of heat, CO_2*
- *Antarctic surface flooding and snow-ice formation*
- *evolution of salinity profiles*

↕ linkage of scales



Darcy's Law for slow viscous flow in a porous medium

averaged fluid velocity

pressure gradient

$$\mathbf{v} = -\frac{\mathbf{k}}{\eta} \nabla p$$

viscosity

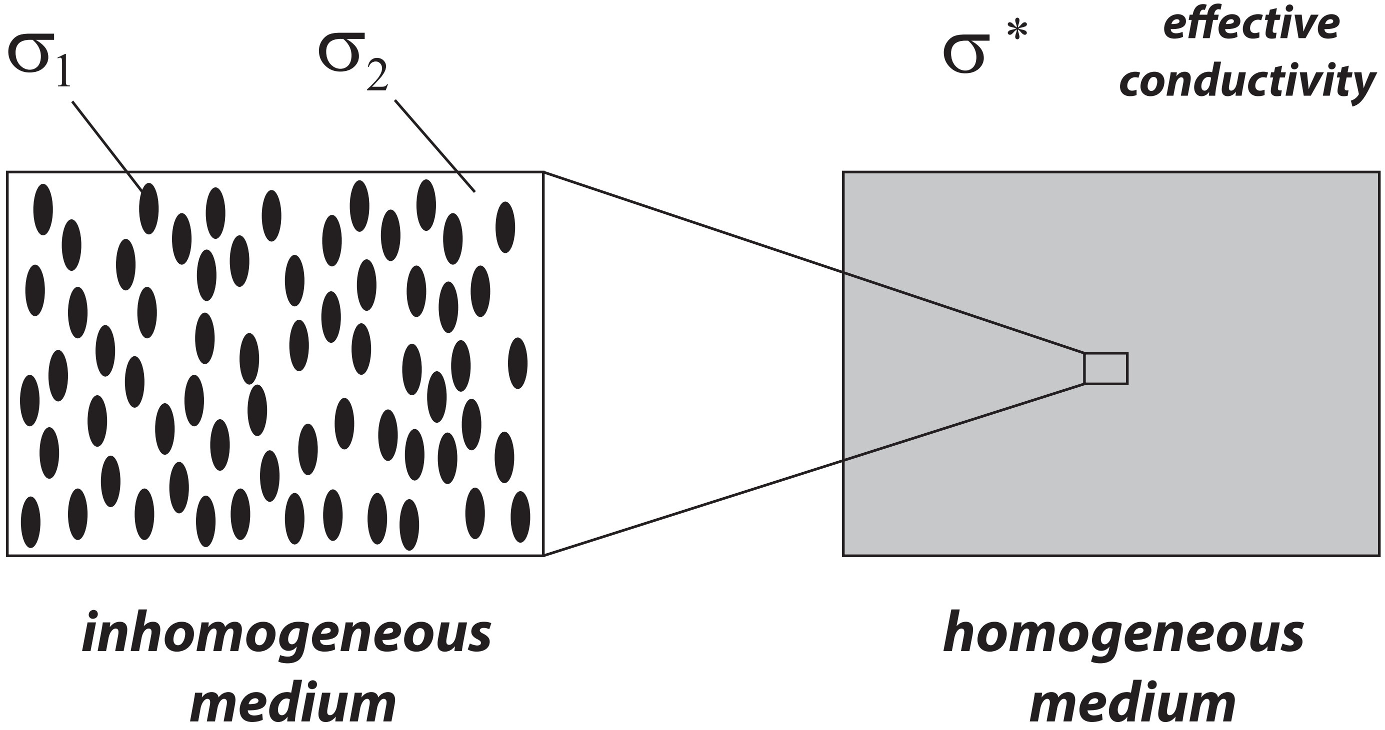
$\mathbf{k}$ = fluid permeability tensor

example of *homogenization*

mathematics for analyzing effective behavior of heterogeneous systems

e.g. transport properties of composites - electrical conductivity, thermal conductivity, etc.

HOMOGENIZATION



find the homogeneous medium which behaves macroscopically the same as the inhomogeneous medium

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

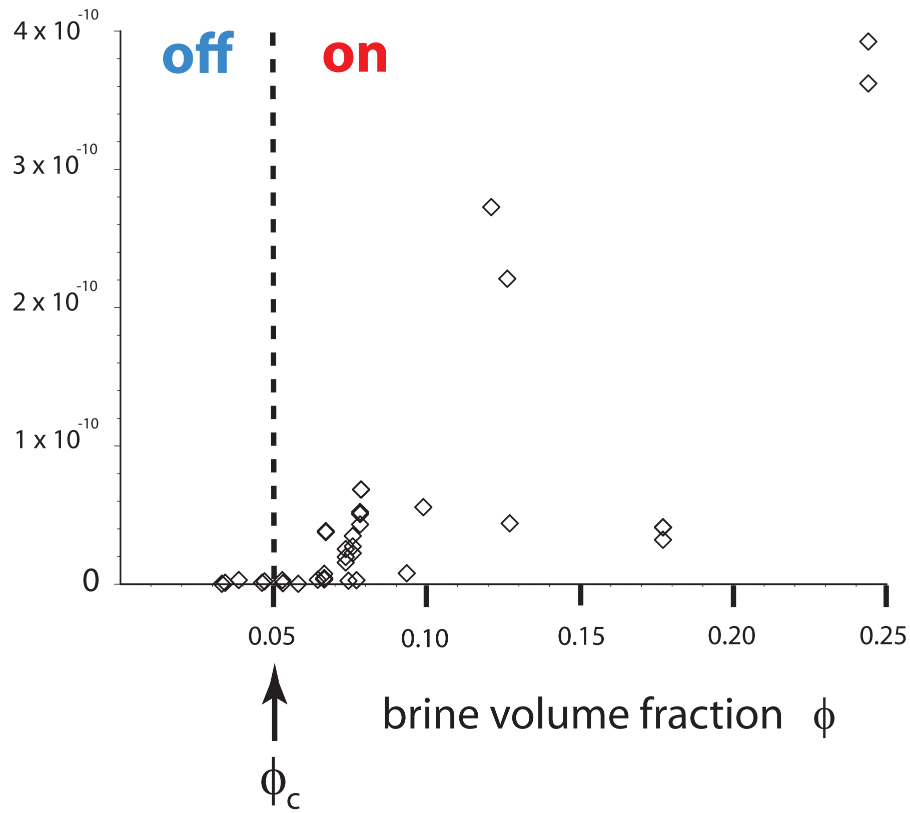
*Wiener 1912 : arithmetic and harmonic mean **bounds** on effective conductivity*
*Hashin and Shtrikman 1962 : variational **bounds** on effective conductivity*

Critical behavior of fluid transport in sea ice

impermeable permeable

Arctic field data

vertical fluid permeability k (m^2)



brine volume fraction ϕ

on - off switch for fluid flow

critical brine volume fraction $\phi_c \approx 5\%$ $\longleftrightarrow$ $T_c \approx -5^\circ$C, $S \approx 5$ ppt

RULE OF FIVES

Golden, Ackley, Lytle *Science* 1998

Golden, Eicken, Heaton, Miner, Pringle, Zhu, *Geophys. Res. Lett.* 2007

Pringle, Miner, Eicken, Golden *J. Geophys. Res.* 2009

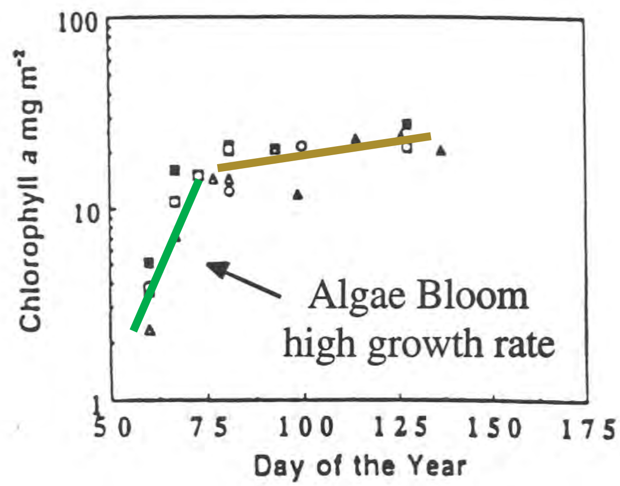
sea ice algal communities

D. Thomas 2004

nutrient replenishment
controlled by ice permeability

biological activity turns on
or off according to
rule of fives

critical behavior of microbial activity



Convection-fueled algae bloom
Ice Station Weddell

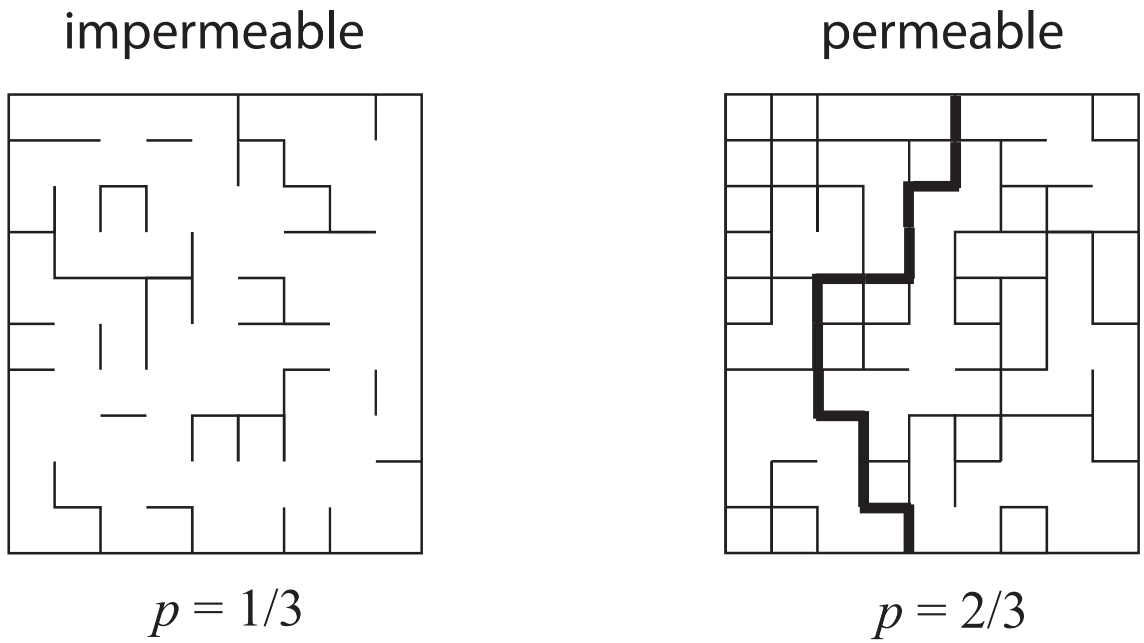
Golden, Ackley, Lytle ***Science 1998***

Fritsen, Lytle, Ackley, Sullivan ***Science 1994***

Why is the rule of fives true?

percolation theory

mathematical theory of connectedness



bond ⟶ *open* *with probability p*
closed with probability 1-p

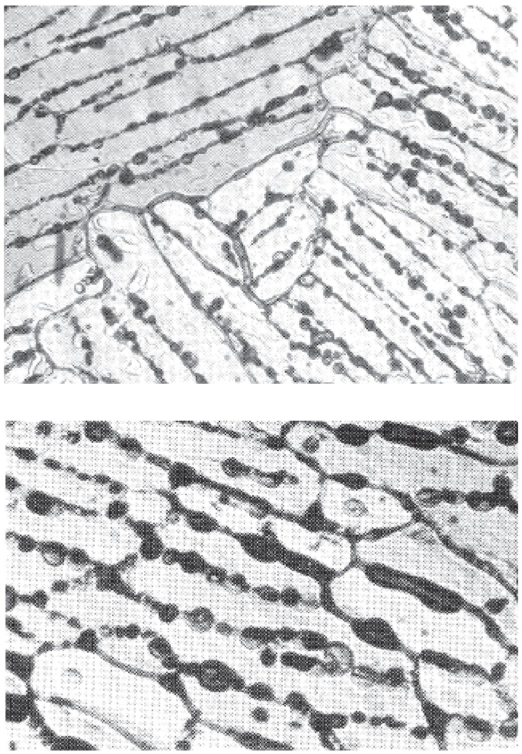
percolation threshold

$p_c = 1/2$ for $d = 2$

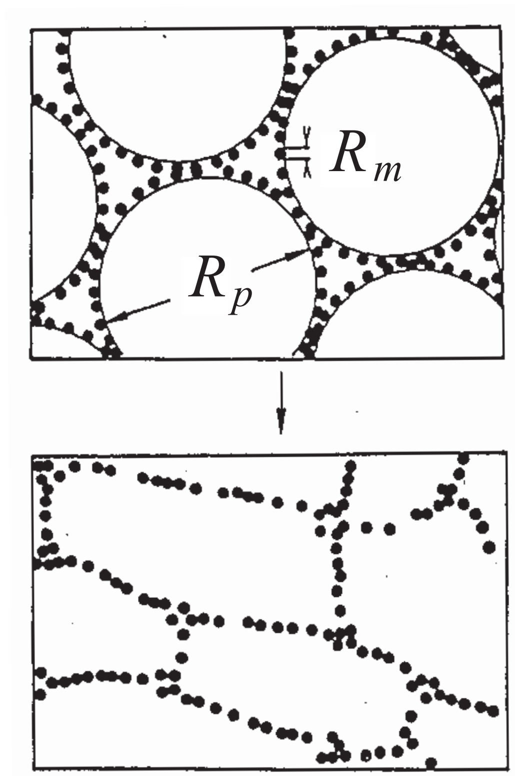
first appearance of infinite cluster ***"tipping point" for connectivity***

Continuum percolation model for ***stealthy*** materials applied to sea ice microstructure explains **Rule of Fives** and Antarctic data on ice production and algal growth

$\phi_c \approx 5\ \%$ Golden, Ackley, Lytle, *Science,* 1998



sea ice



compressed powder

radar absorbing composite

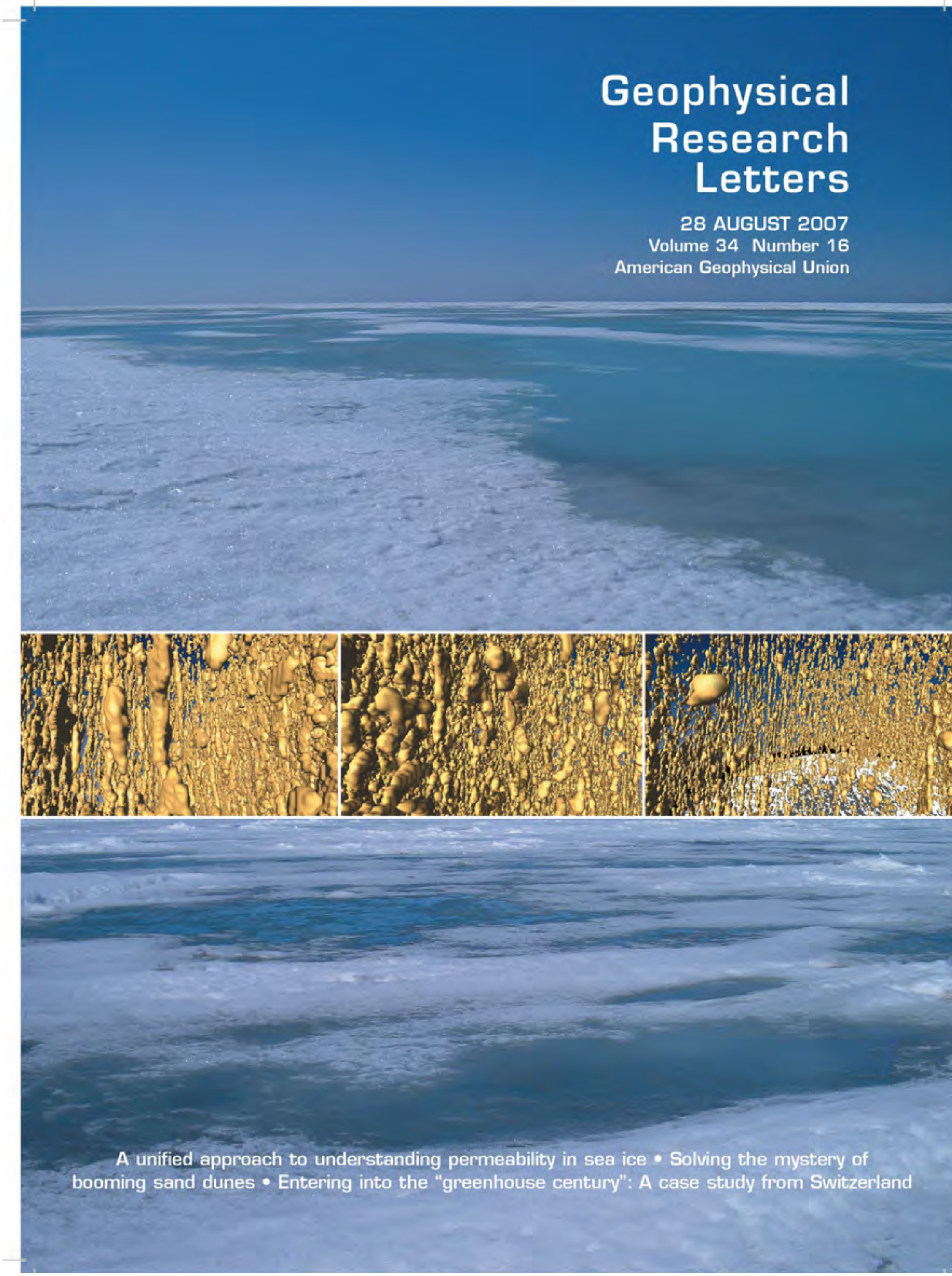
sea ice is radar absorbing

Thermal evolution of permeability and microstructure in sea ice **Golden, Eicken, Heaton, Miner, Pringle, Zhu**

micro-scale

controls

macro-scale processes



rigorous bounds
percolation theory
hierarchical model
network model

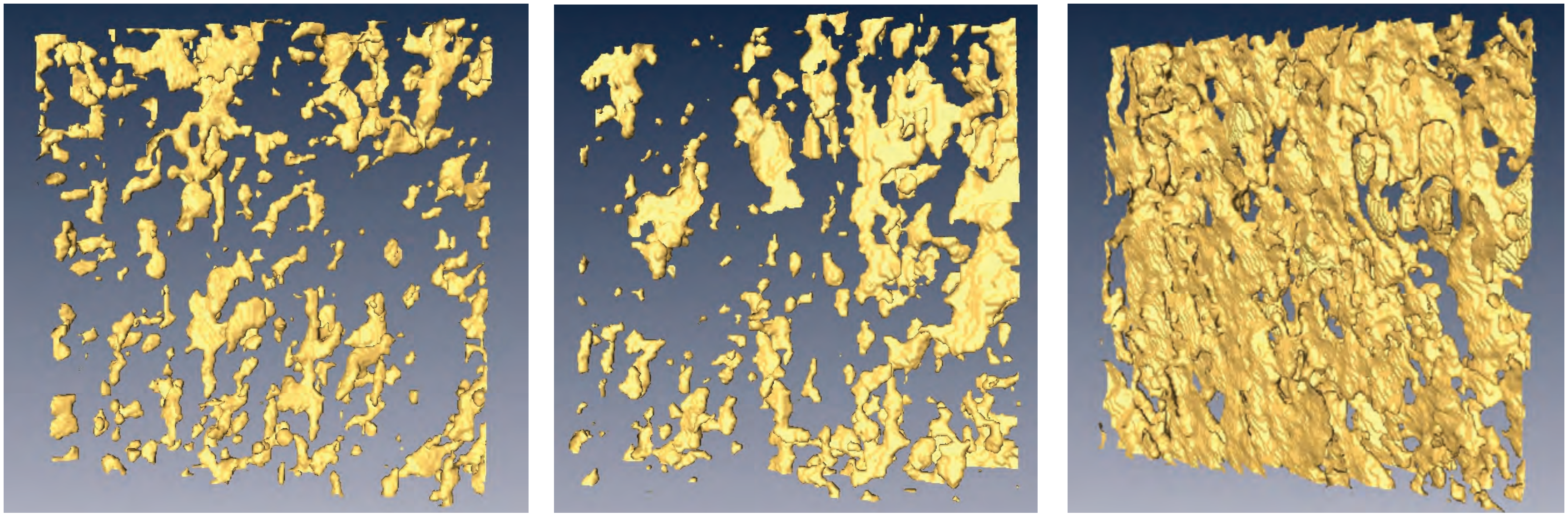
field data

X-ray tomography for brine inclusions

unprecedented look at thermal evolution of brine phase and its connectivity

brine connectivity (over cm scale)

8 x 8 x 2 mm



-15 °C, $\phi = 0.033$ -6 °C, $\phi = 0.075$ -3 °C, $\phi = 0.143$

X-ray tomography confirms percolation threshold

3-D images
pores and throats

→

3-D graph
nodes and edges

analyze graph connectivity as function of temperature and sample size

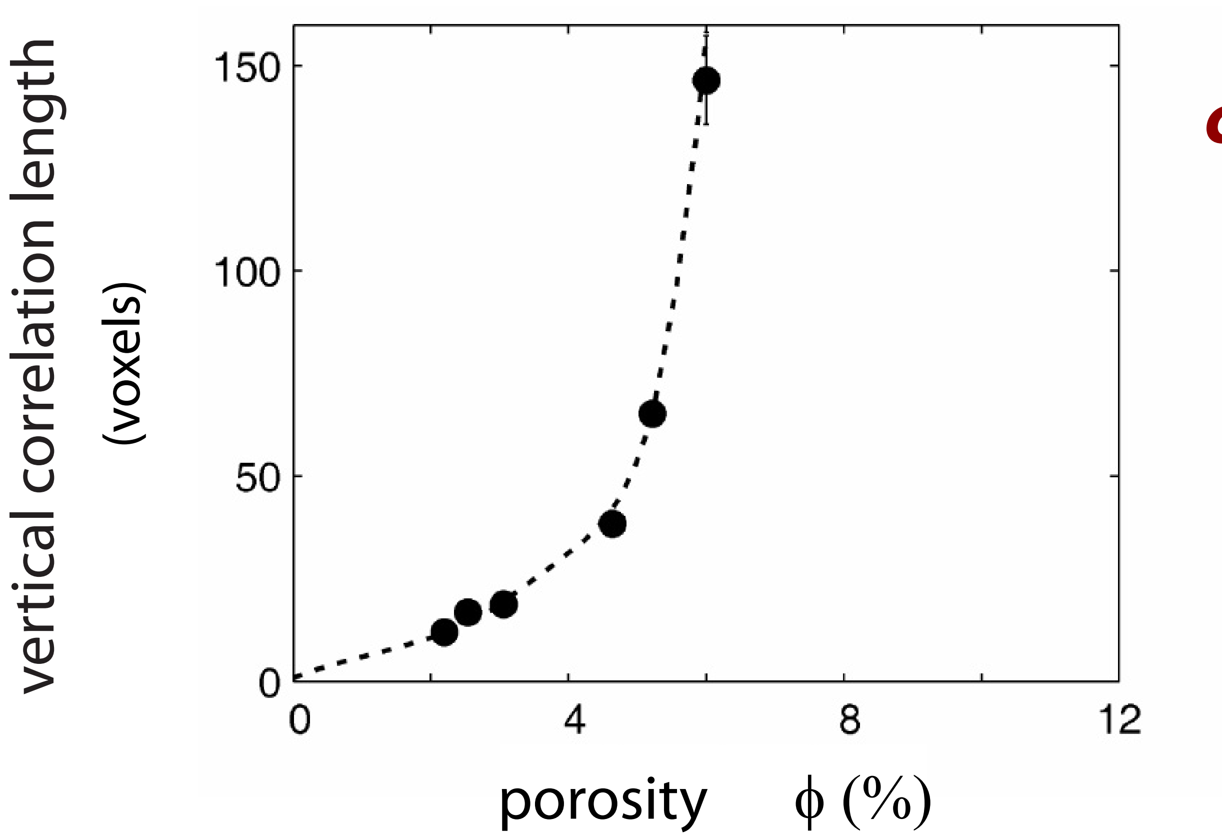
- ***use finite size scaling techniques to confirm rule of fives***
- ***order parameter data from a natural material***

Pringle, Miner, Eicken, Golden, J. Geophys. Res. 2009

The key connectivity functions of percolation theory have been computed extensively for many lattice models, but ***NOT*** for natural materials.

We have calculated them for sea ice single crystals and estimated anisotropic percolation thresholds.

Pringle, Miner, Eicken, Golden, JGR (Oceans) 2009



correlation length

characteristic scale of connectedness

divergence of vertical ***correlation length*** for single crystal data

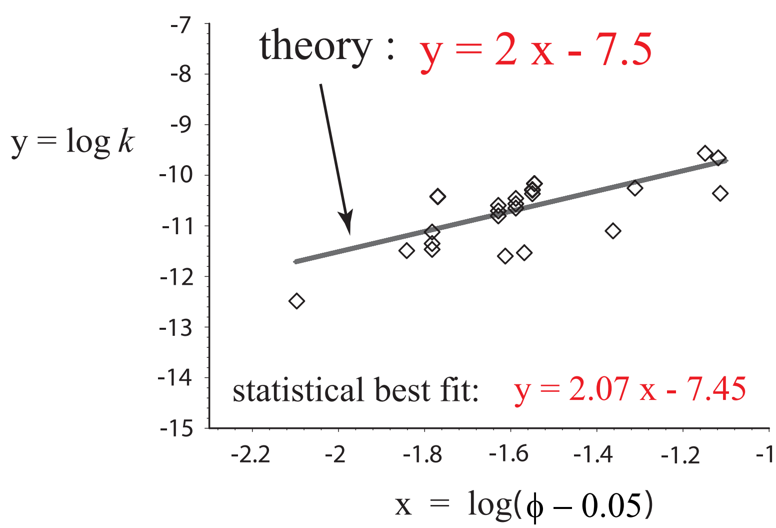
lattice and continuum percolation theories yield:

$$k(\phi) = k_0 (\phi - 0.05)^2$$

critical exponent t

$$k_0 = 3 \times 10^{-8} \text{ m}^2$$

- exponent is UNIVERSAL lattice value $t \approx 2.0$
- sedimentary rocks like sandstones also exhibit universality
- critical path analysis -- developed for electronic hopping conduction -- yields scaling factor k_0



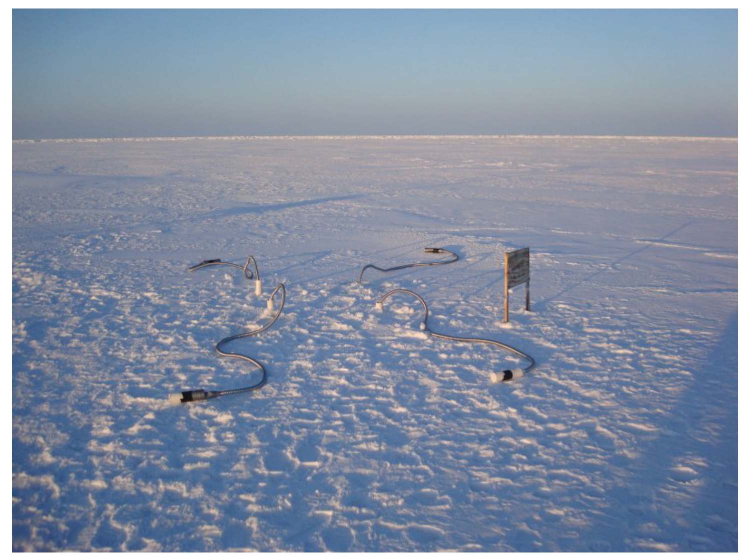
Remote sensing of sea ice

INVERSE PROBLEM

Recover sea ice properties from electromagnetic (EM) data

ε^*

effective complex permittivity
(dielectric constant, conductivity)



sea ice thickness
ice concentration

brine volume fraction
brine inclusion connectivity

ocean swells propagating through a vast field of pancake ice

HOMOGENIZATION: long wave sees an effective medium, not individual floes

Theory of Effective Electromagnetic Behavior of Composites

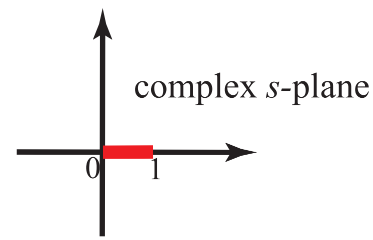
analytic continuation method

Forward Homogenization Bergman (1978), Milton (1979), Golden and Papanicolaou (1983)

composite geometry
(spectral measure μ) ⟶ ε^*

integral representations, rigorous bounds, approximations, etc.

$$F(s) = 1 - \frac{\epsilon^*}{\epsilon_2} = \int_0^1 \frac{d\mu(z)}{s-z} \qquad s = \frac{1}{1 - \epsilon_1 / \epsilon_2}$$



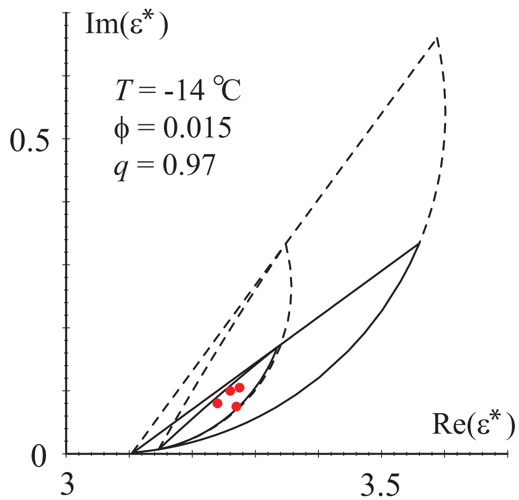
Inverse Homogenization Cherkaev and Golden (1998), Day and Thorpe (1999), Cherkaev (2001)
(McPhedran, McKenzie, and Milton, 1982)

ε^* ⟶ **composite geometry**
(spectral measure μ)

recover brine volume fraction, connectivity, etc.

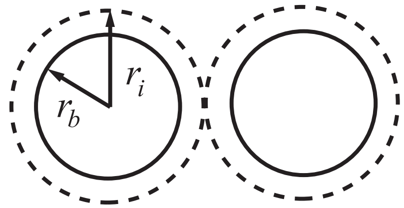
forward and inverse bounds for sea ice

forward bounds



4.75 GHz data

matrix particle

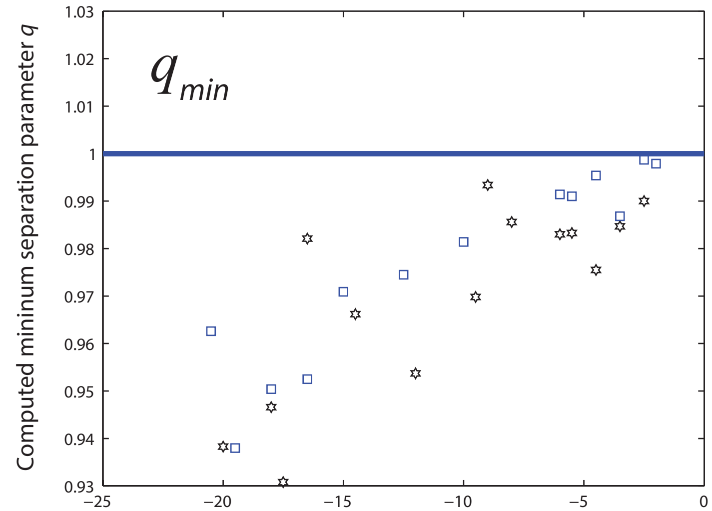


$$q = r_b / r_i$$

$$0 < q < 1$$

Golden 1995, 1997

inverse bounds



Slab temperature °C

inversion for brine inclusion separations in sea ice from measurements of effective complex permittivity ε^*

rigorous inverse bound on spectral gap

construct algebraic curves which bound admissible region in (p,q)-space

Orum, Cherkaev, Golden
Proc. Roy. Soc. A, 2012

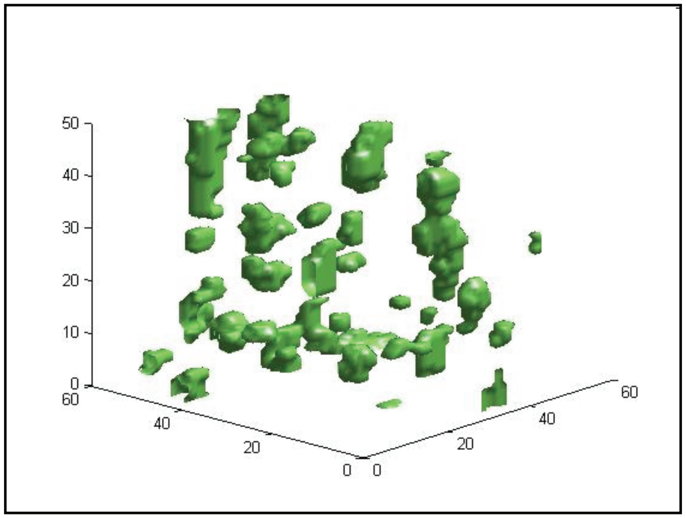
inverse bounds and recovery of brine porosity

Gully, Backstrom, Eicken, Golden
Physica B, 2007

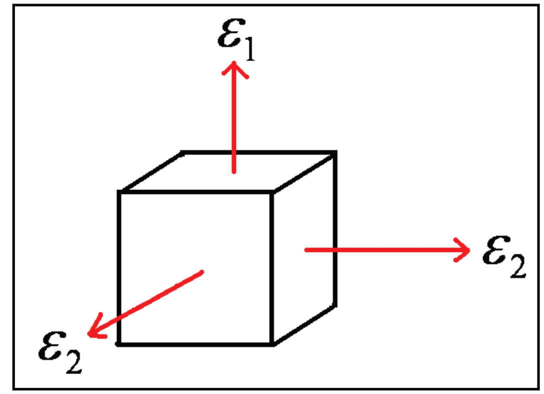
polycrystalline bounds two-scale homogenization

Gully, Lin, Cherkaev, Golden, 2014

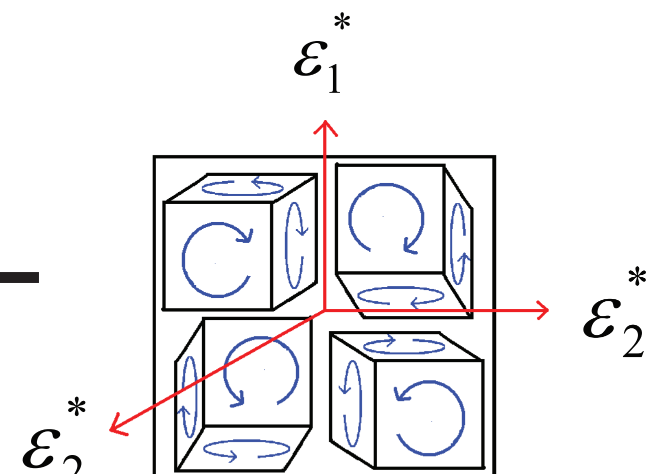
two scale homogenization for polycrystalline sea ice



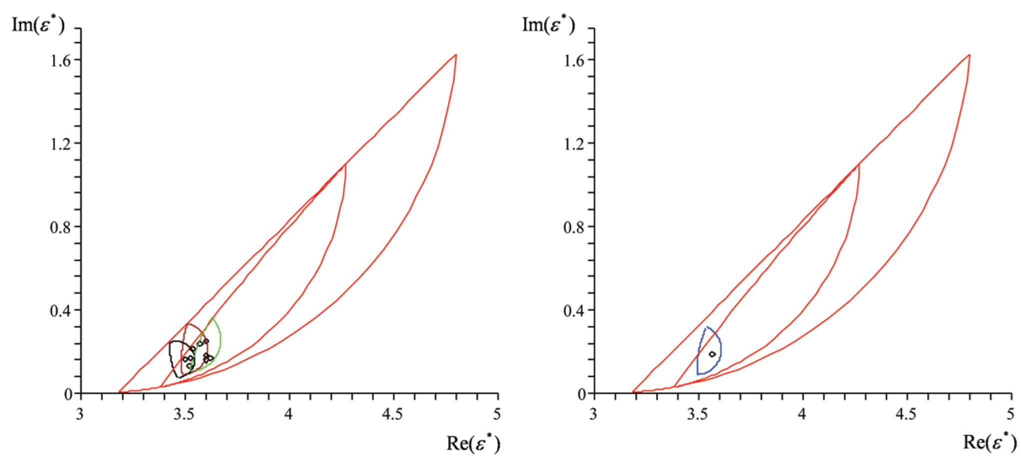
numerical homogenization for single crystal



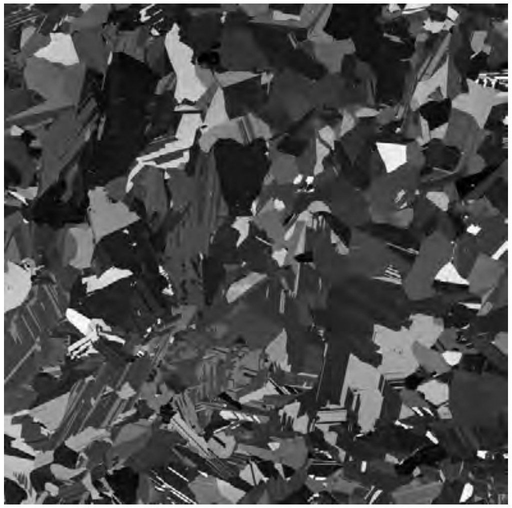
analytic continuation for polycrystals



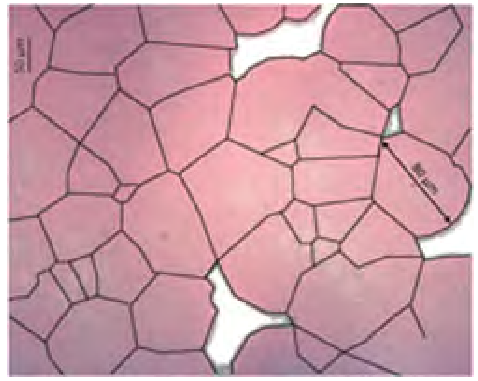
bounds



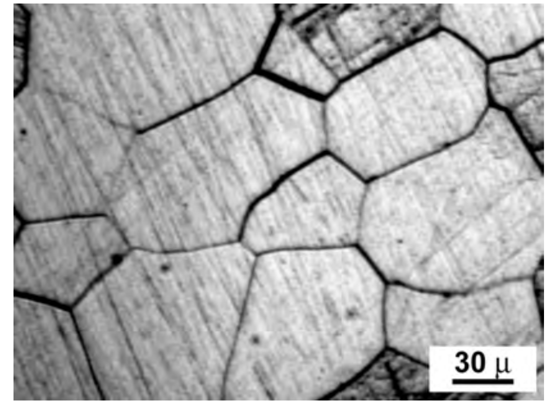
Gully, Lin, Cherkaev, Golden 2014



non-sedimentary rocks

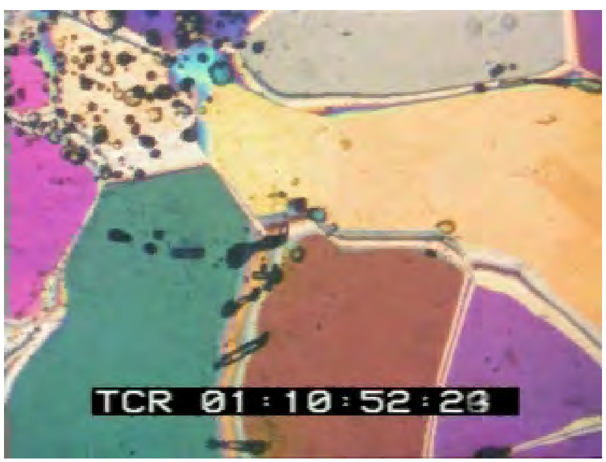


poly-silicon, crystal grains up to 150 microns photovoltaic -- solar industry

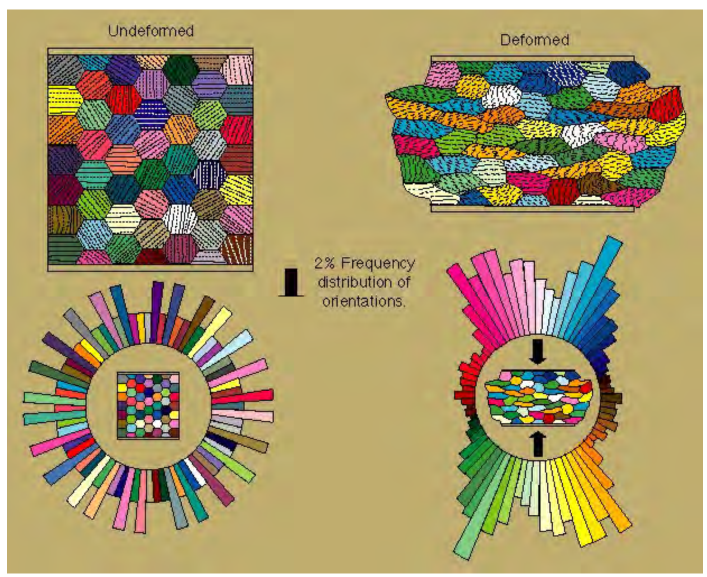


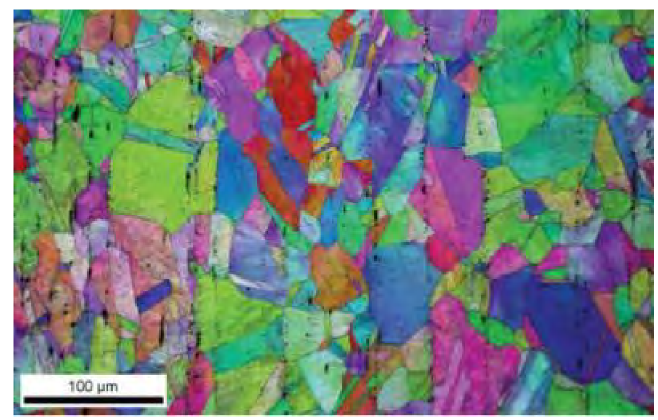
micrograph of polycrystalline metal

polycrystalline materials



polycrystalline ice aggregate deformed in pure shear





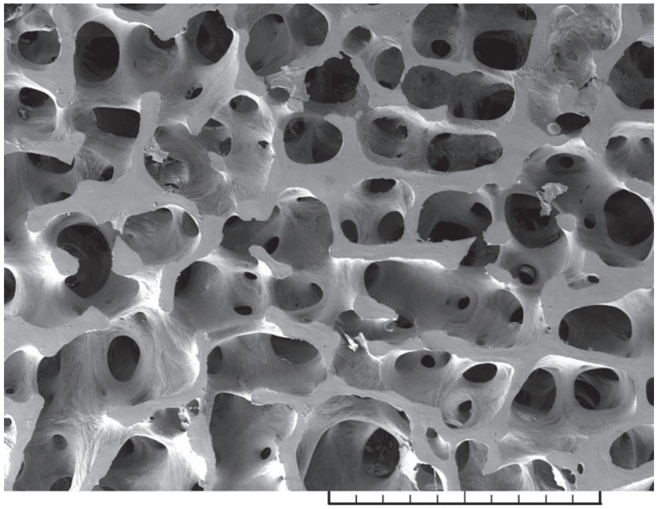
EBSD grain orientation map for copper

Electron backscattered diffraction using SEM

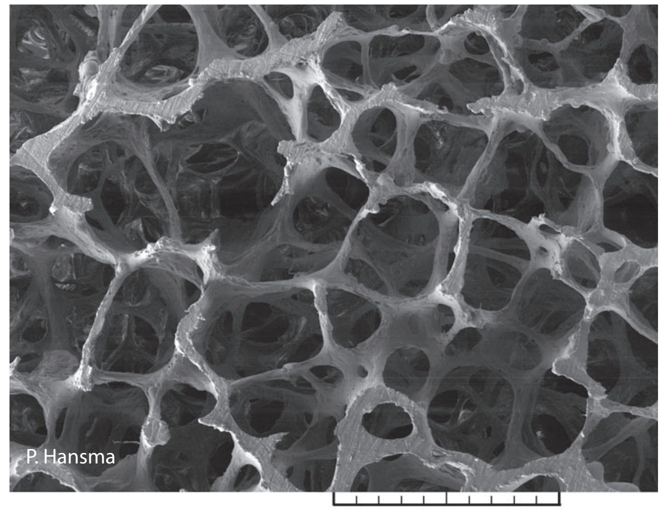
spectral characterization of porous microstructures in bone

Golden, Murphy, Cherkaev, J. Biomechanics 2011

(a) young healthy trabecular bone



(b) old osteoporotic trabecular bone

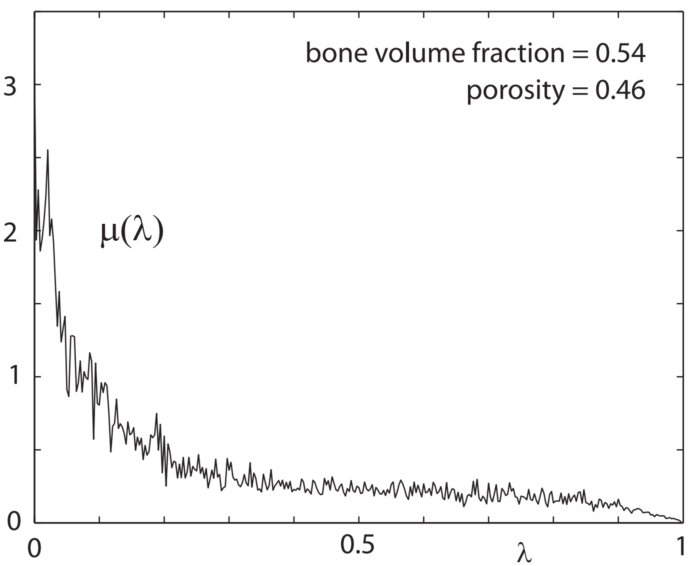


+

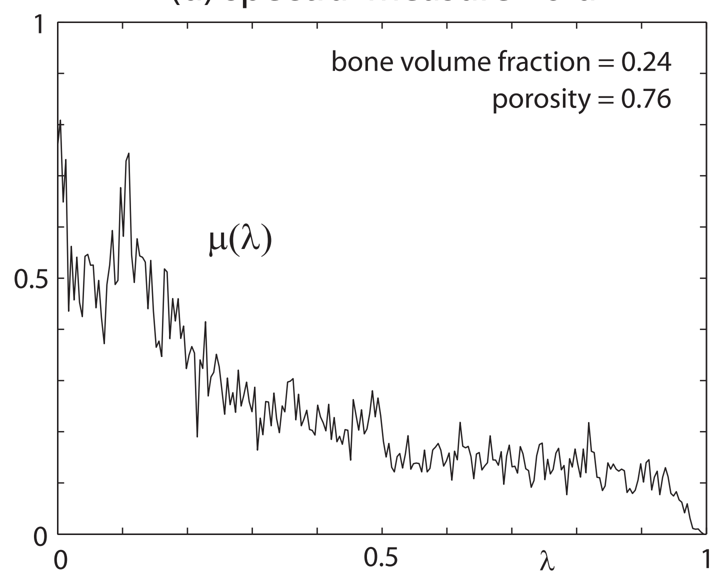
reconstruction of spectral measures from complex permittivity data

using regularized inversion scheme

(c) spectral measure - young



(d) spectral measure - old



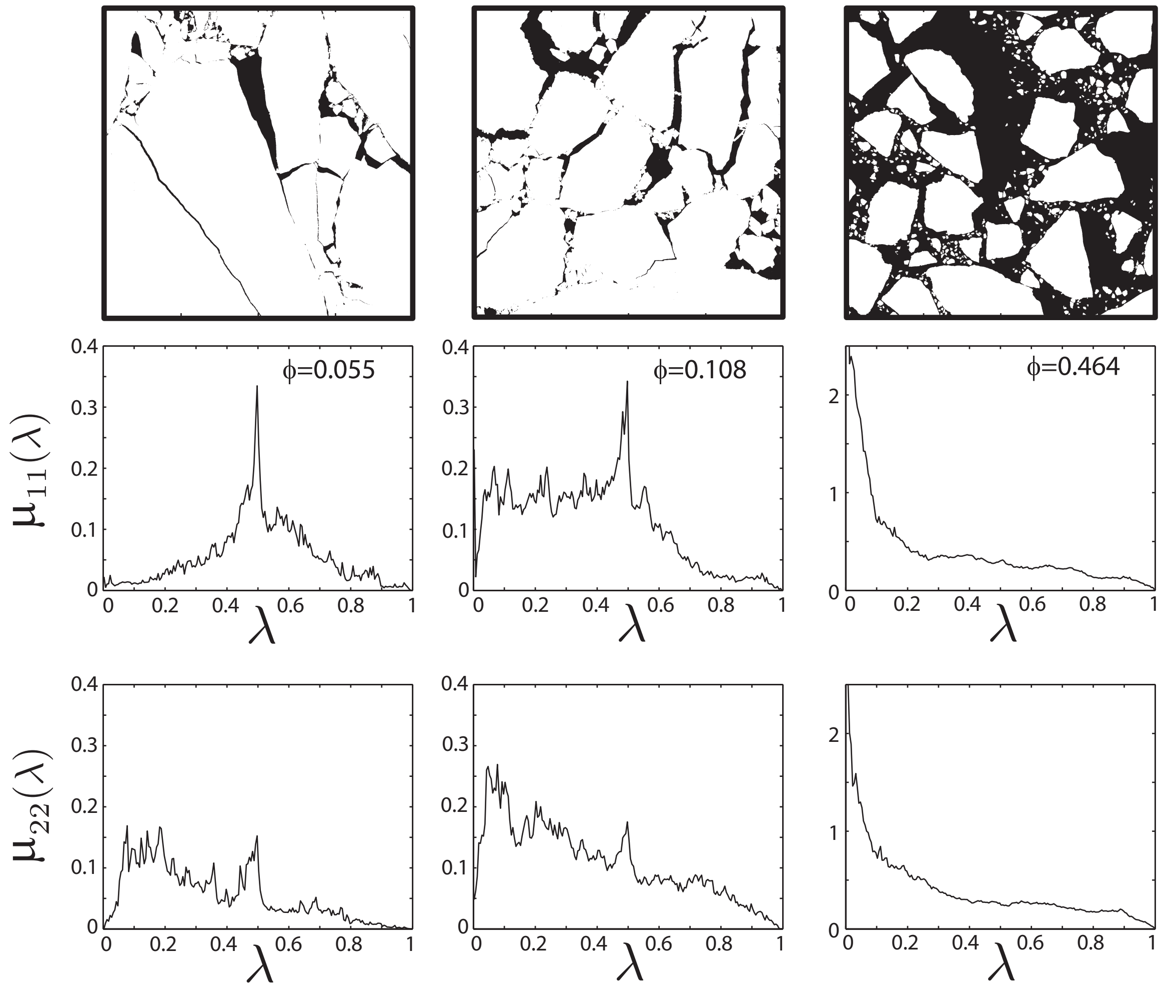
EM monitoring of osteoporosis

loss of bone connectivity

the math doesn't care if it's sea ice or bone!

spectral measures provide a path toward rigorously incorporating "composite microstructure" into calculations of effective behavior on larger scales

spectral measures for the Arctic sea ice pack



area under curve = φ = open water fraction

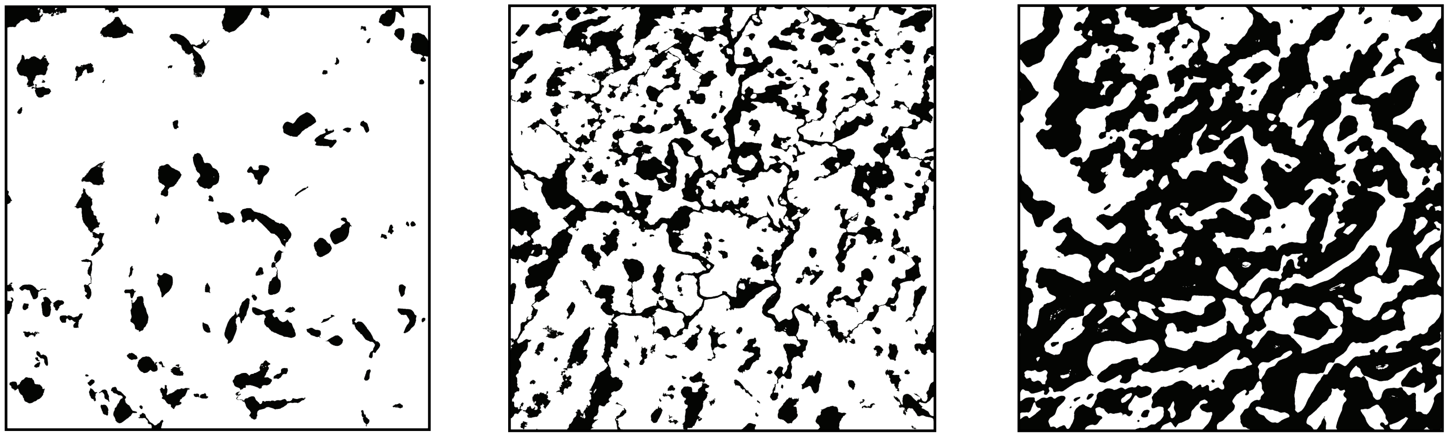
spectral gap closes as ocean phase becomes connected

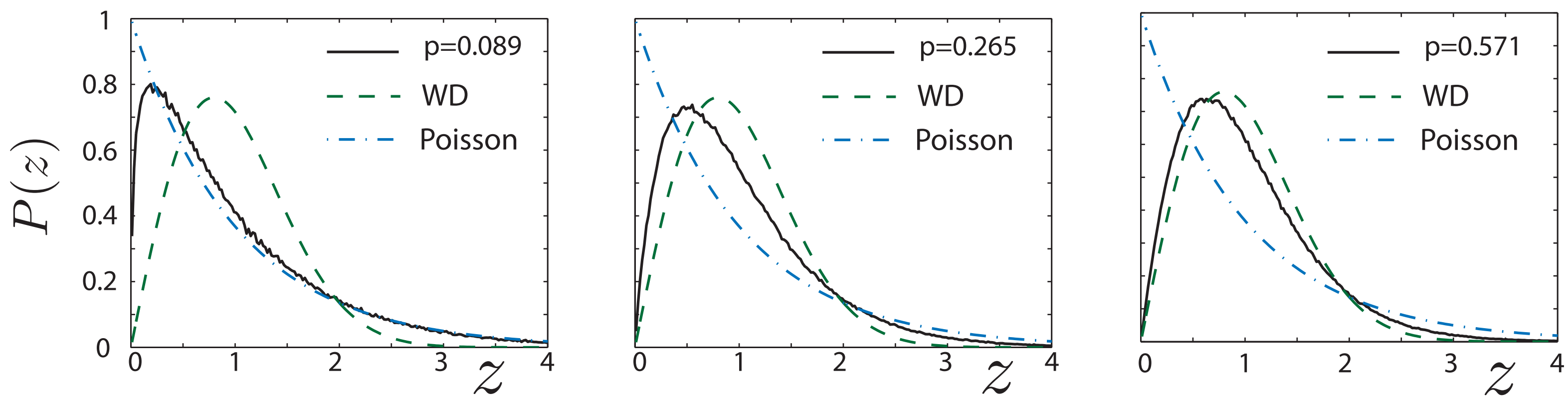
N. B. Murphy, C. Hohenegger, C. S. Sampson, D. K. Perovich, H. Eicken, E. Cherkaev, B. Alali, and K. M. Golden, 2014

random matrix characterization of connectedness transition -- discretization of $\chi\Gamma\chi$

Unfolded Eigenvalue Spacing Distribution

ARCTIC MELT PONDS





eigenvalue statistics for transport tend toward the UNIVERSAL Wigner-Dyson distribution as the "conducting" phase becomes connected over large scales

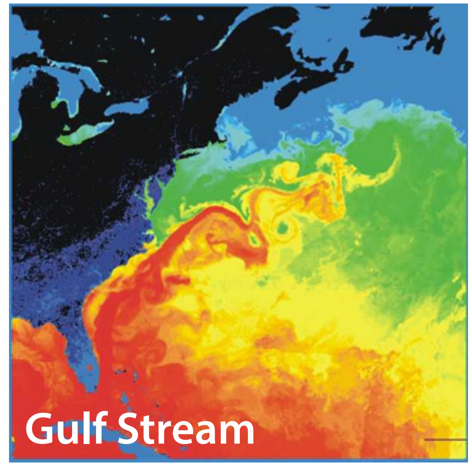
uncorrelated → *"level repulsion"*

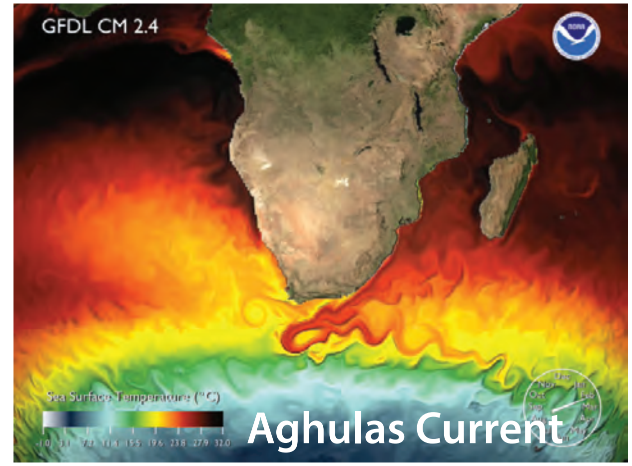
N. B. Murphy, K. M. Golden 2014

advection enhanced diffusion

effective diffusivity

tracers, buoys diffusing in ocean eddies
diffusion of pollutants in atmosphere
salt and heat transport in ocean





advection diffusion equation with a velocity field $\vec{u}$

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \vec{\nabla} T = \kappa_0 \Delta T$$

$$\vec{\nabla} \cdot \vec{u} = 0$$

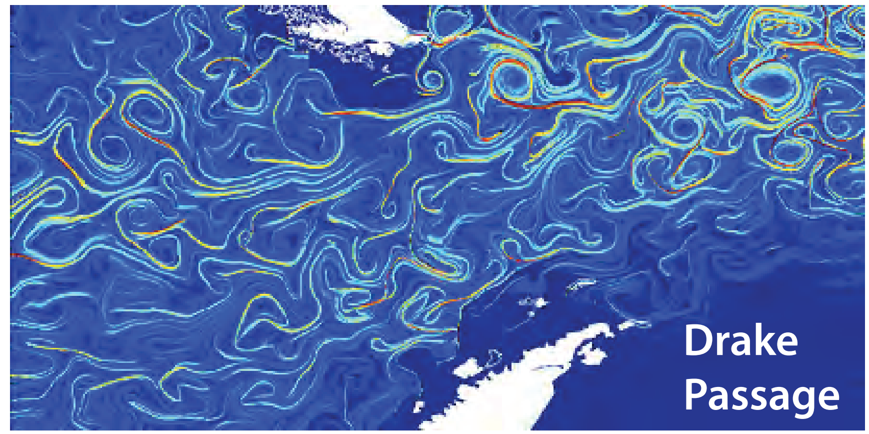
homogenize

$$\frac{\partial \overline{T}}{\partial t} = \kappa^* \Delta \overline{T}$$

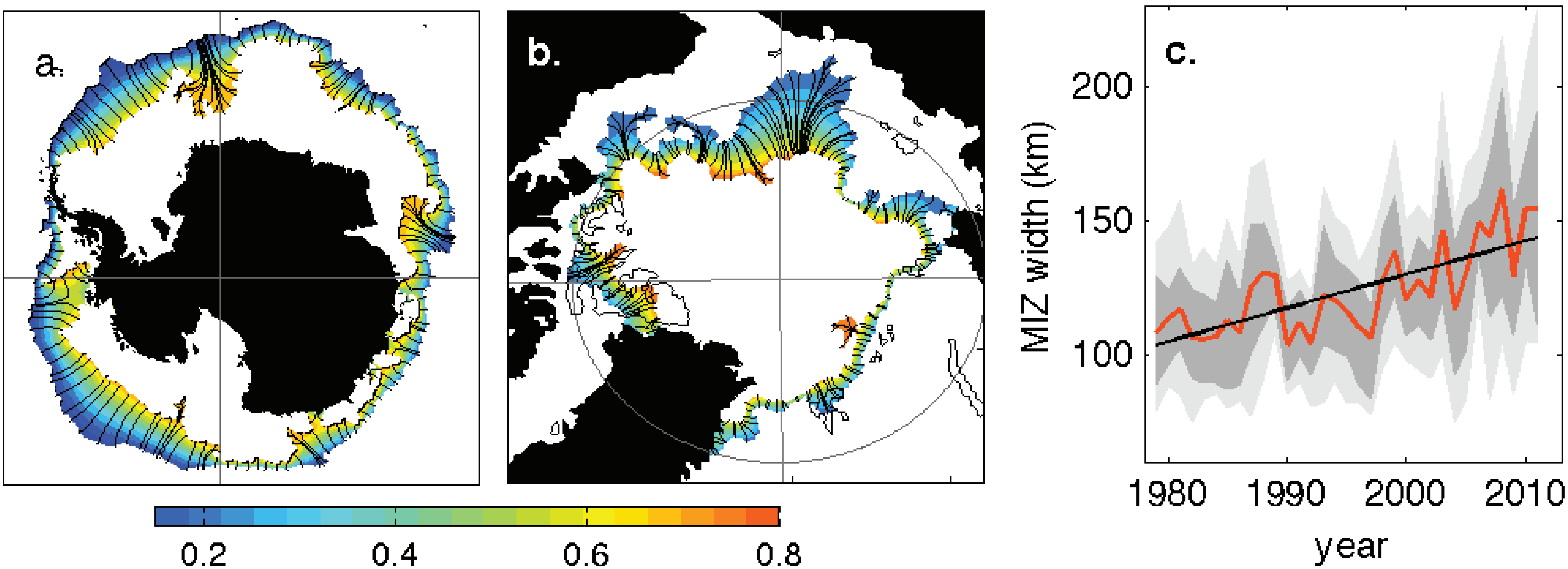
κ^* ***effective diffusivity***

Stieltjes integral for κ^* ***with spectral measure***

Avellaneda and Majda, PRL 89, CMP 91 ***Murphy, Zhu, Golden 2014***



Objective measure of MIZ width



idealized sea ice concentration field satsifies Laplace's equation with BC

-- ***electric potential*** --

MIZ width based on length of ***electric field lines***

Strong, *Climate Dynamics* 2012 Strong and Rigor, *Geophys. Res. Lett.* 2013

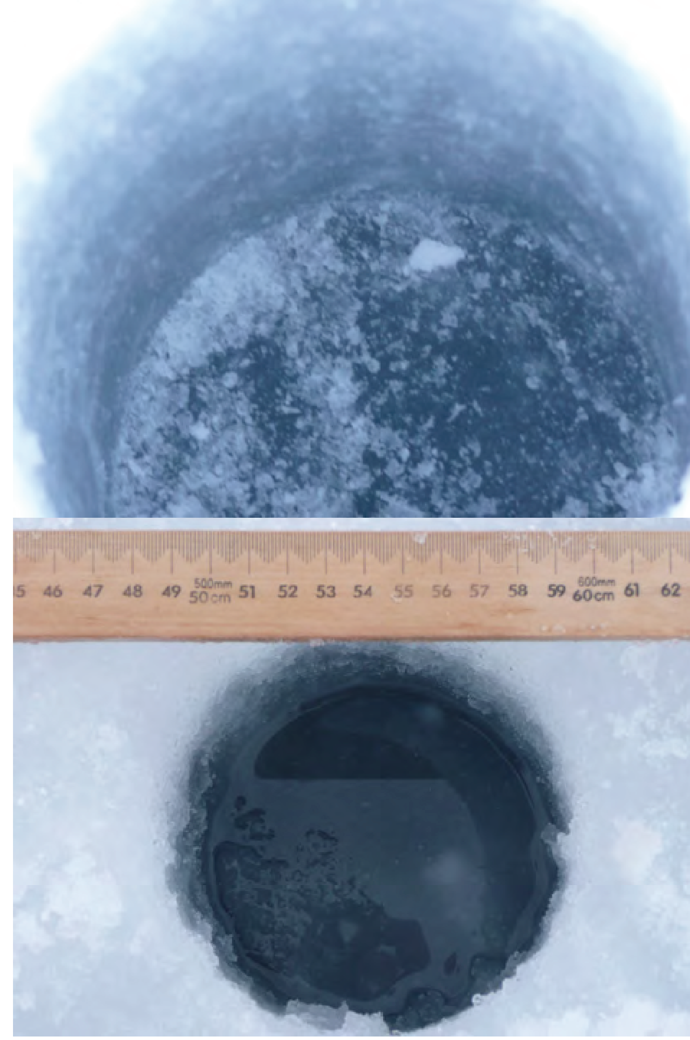
Arctic and Antarctic field experiments

develop electromagnetic methods of monitoring fluid transport and microstructural transitions

extensive measurements of fluid and electrical transport properties of sea ice:

2007	*Antarctic*	*SIPEX*
2010	*Antarctic*	*McMurdo Sound*
2011	*Arctic*	*Barrow AK*
2012	*Arctic*	*Barrow AK*
2012	*Antarctic*	*SIPEX II*
2013	*Arctic*	*Barrow AK*

photo by Jan Lieser

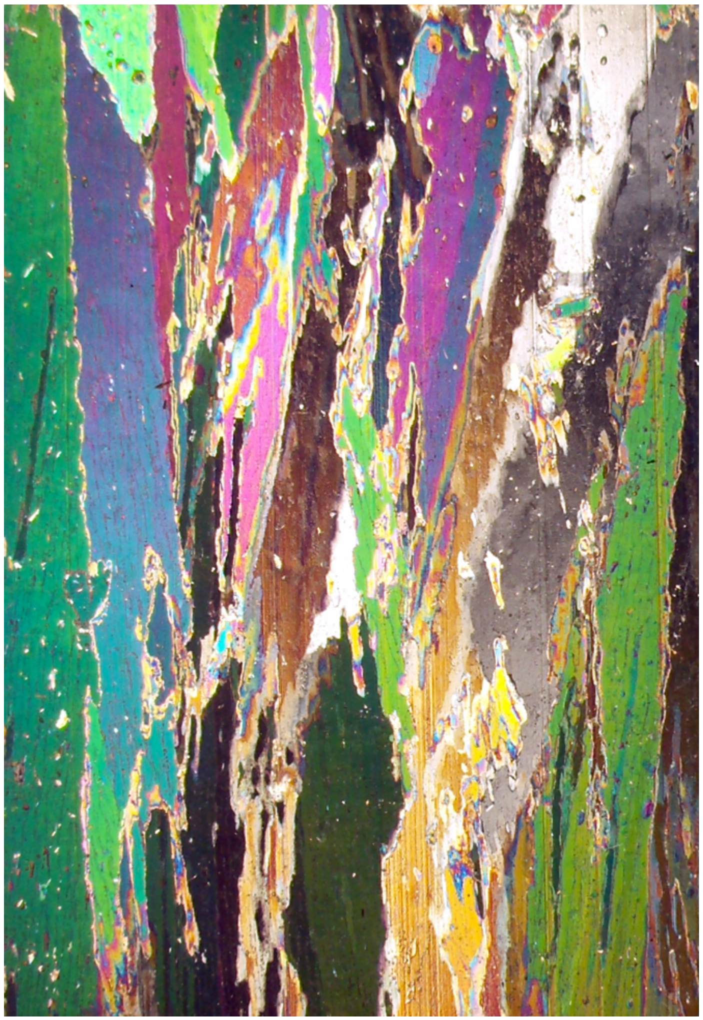


measuring fluid permeability of Antarctic sea ice

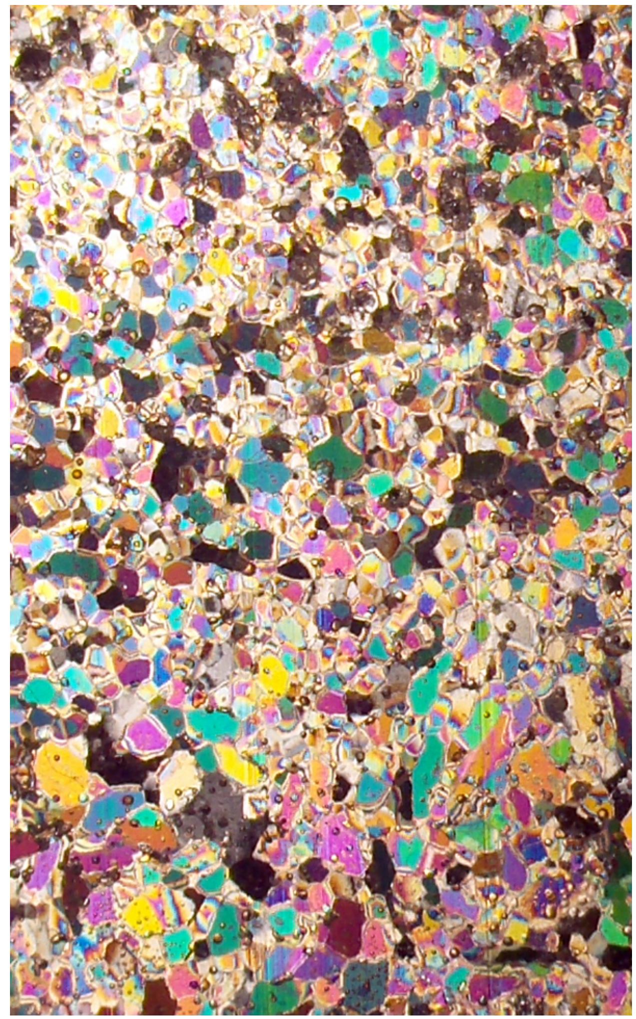
SIPEX 2007

higher threshold for fluid flow in Antarctic granular sea ice

columnar



granular



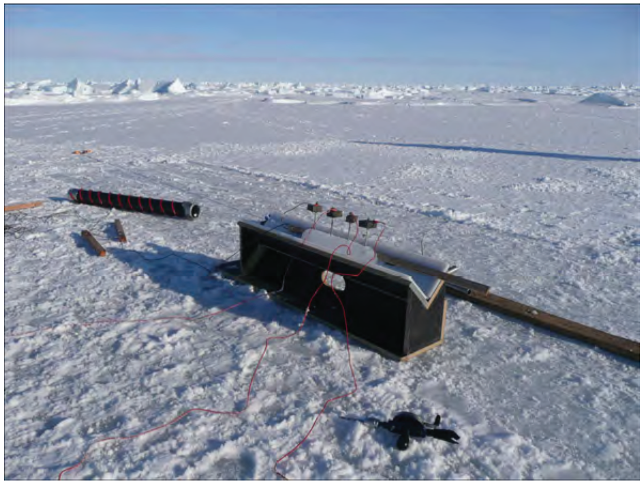
5%

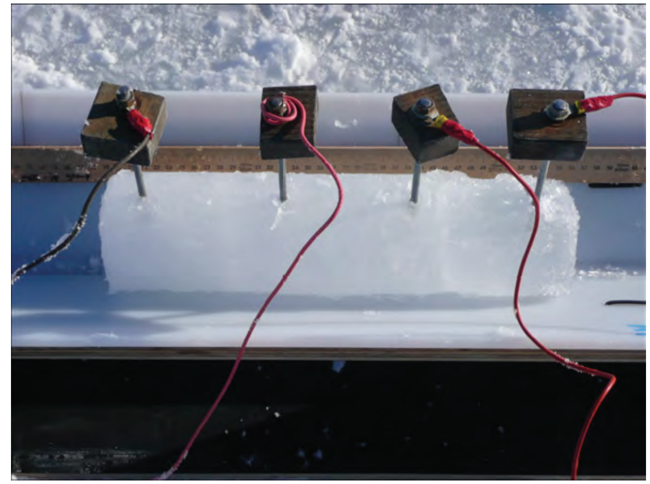
10%

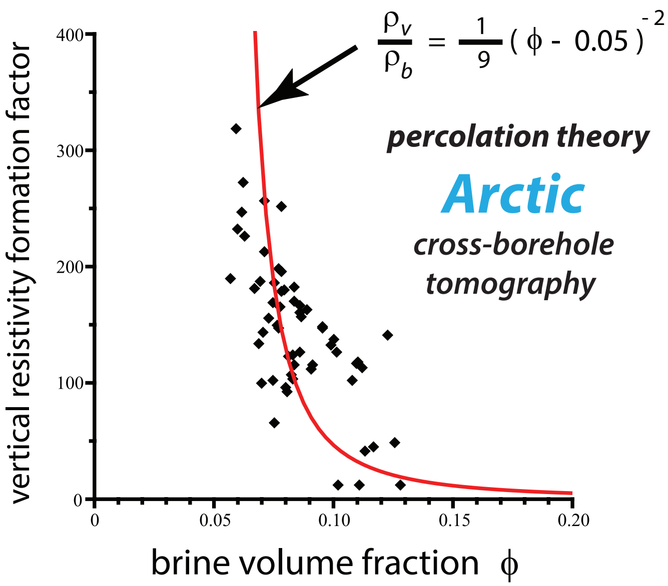
Golden, Gully, Lubbers, Sampson, Tison 2014

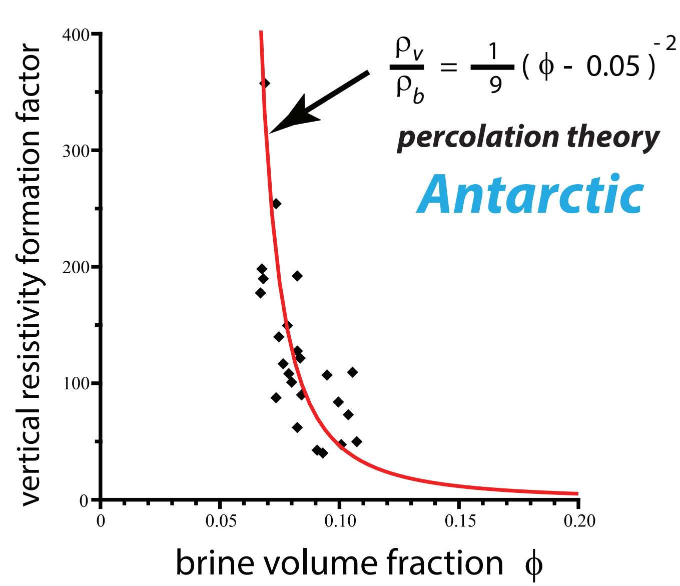
critical behavior of electrical transport in sea ice

electrical signature of the on-off switch for fluid flow







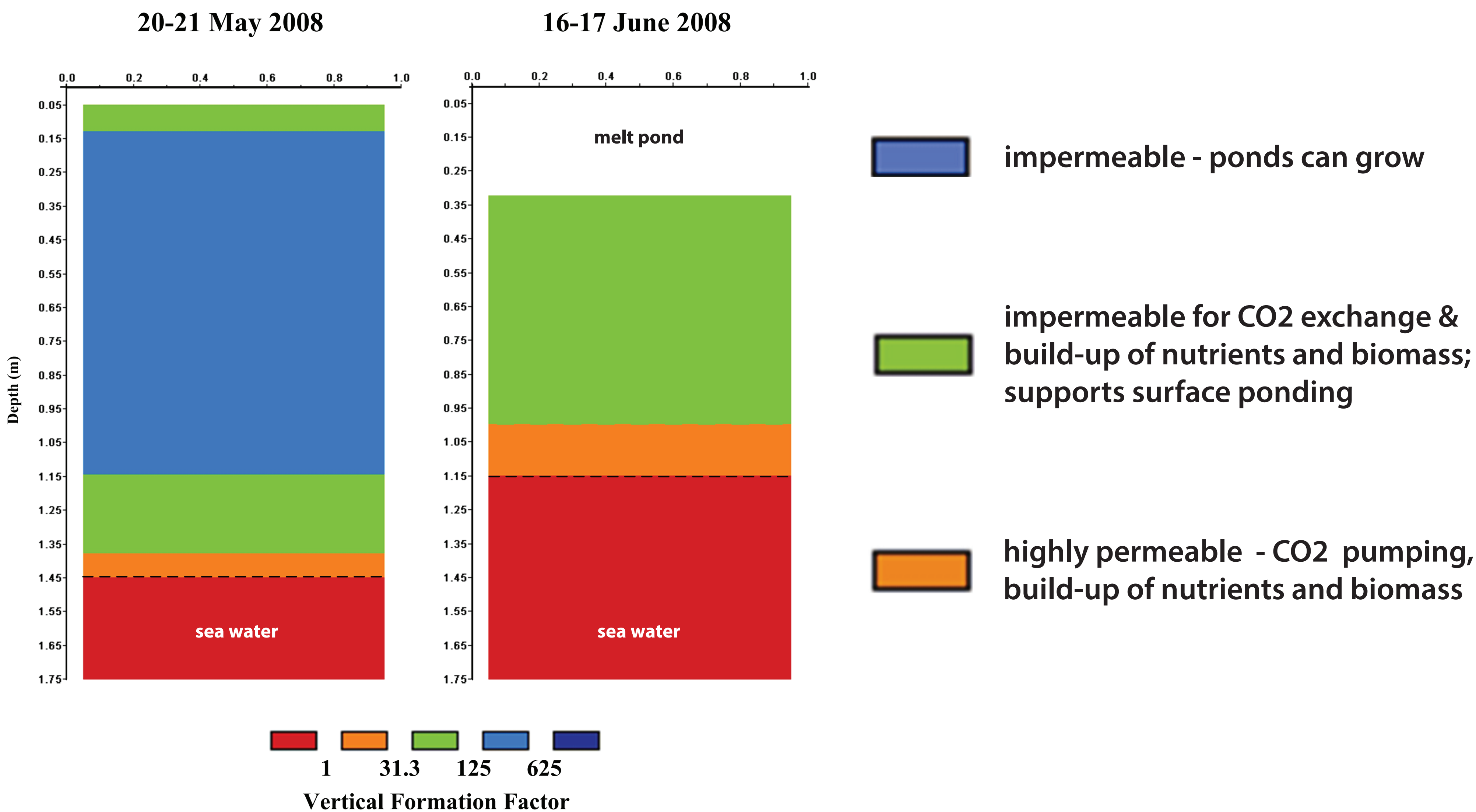


cross-borehole tomography - electrical classification of sea ice layers

Golden, Eicken, Gully, Ingham, Jones, Lin, Reid, Sampson, Worby 2014

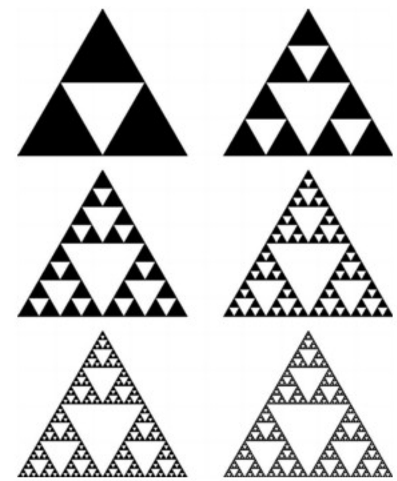
Cross-borehole tomographic reconstructions of sea ice resistivity

before and after melt pond formation



Golden, Eicken, Gully, Ingham, Jones, Lin, Reid, Sampson, and Worby 2014

fractals and multiscale structure



melt ponds on the surface of Arctic sea ice


Frey

melt pond formation and albedo evolution:

- ***major drivers in polar climate***
- ***key challenge for global climate models***

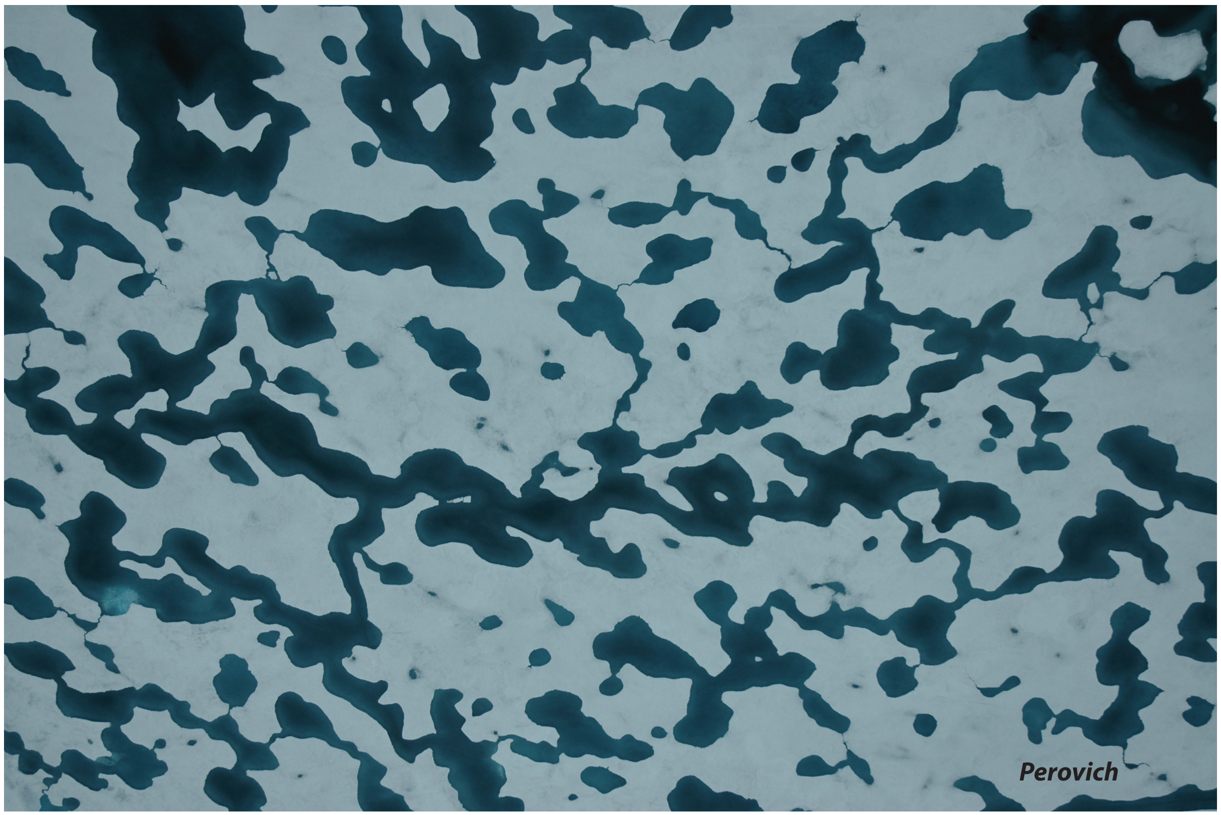
numerical models of melt pond evolution, including topography, drainage (permeability), etc.

Lüthje, Feltham, Taylor, Worster 2006

Flocco, Feltham 2007

Skyllingstad, Paulson, Perovich 2009

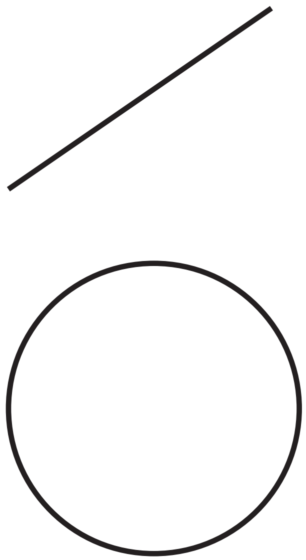
Flocco, Feltham, Hunke 2012

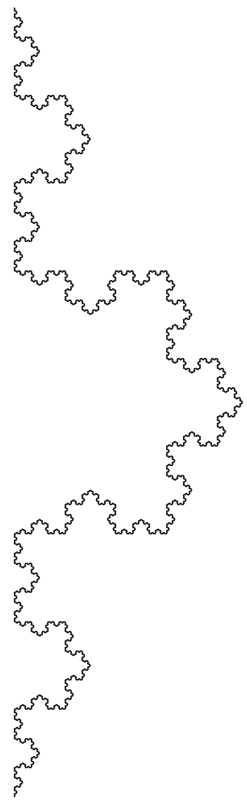


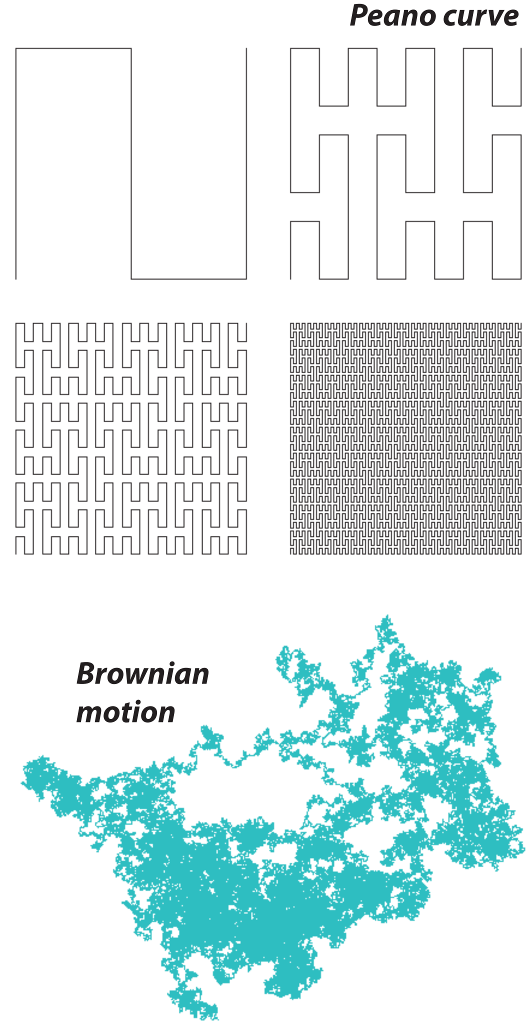
Are there universal features of the evolution similar to phase transitions in statistical physics?

fractal curves in the plane

they wiggle so much that their dimension is >1







simple curves

Koch snowflake

space filling curves

D = 1

D = 1.26

D = 2

clouds exhibit fractal behavior from 1 to 1000 km

use ***perimeter-area*** data to find that cloud and rain boundaries are fractals

$$D \approx 1.35$$

S. Lovejoy, Science, 1982

$$P \sim \sqrt{A}$$

simple shapes

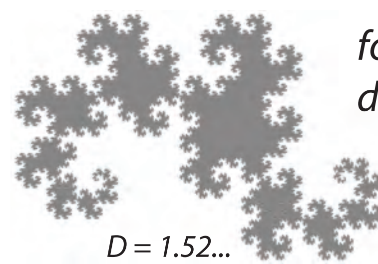
L

L

$A = L^2$

$P = 4L = 4\sqrt{A}$

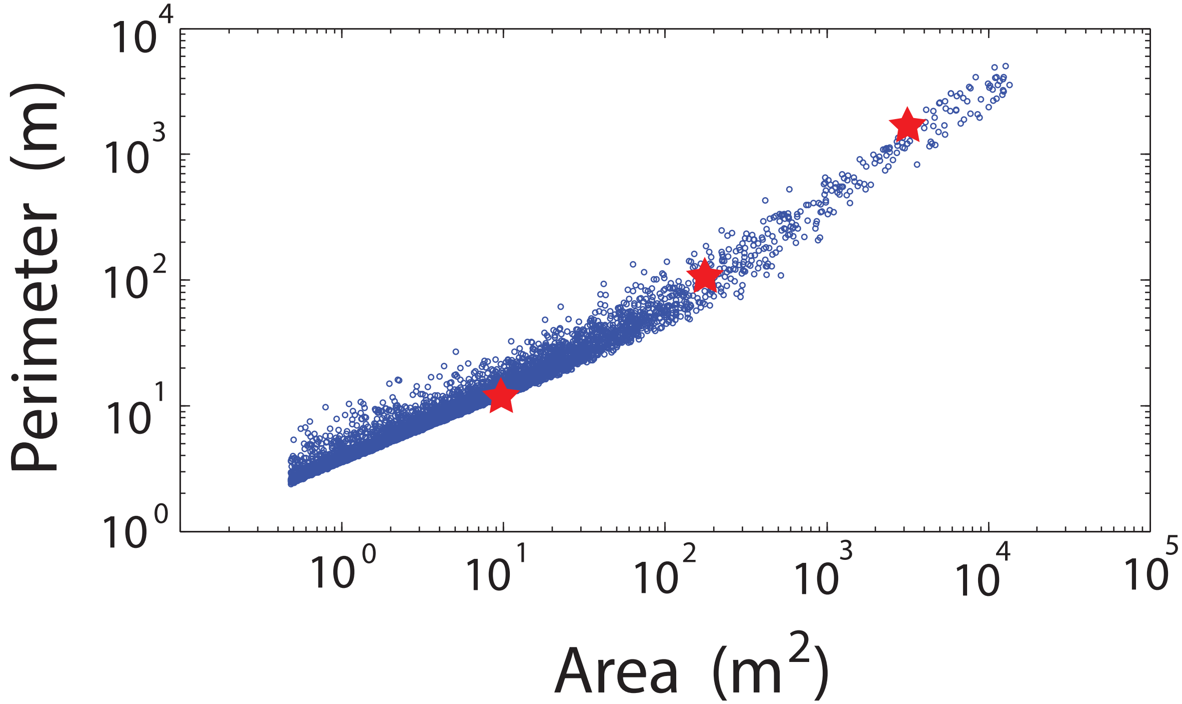
$$P \sim \sqrt{A}^{\,D}$$



for fractals with dimension D

Transition in the fractal geometry of Arctic melt ponds — *The Cryosphere, 2012*

Christel Hohenegger, Bacim Alali, Kyle Steffen, Don Perovich, Ken Golden

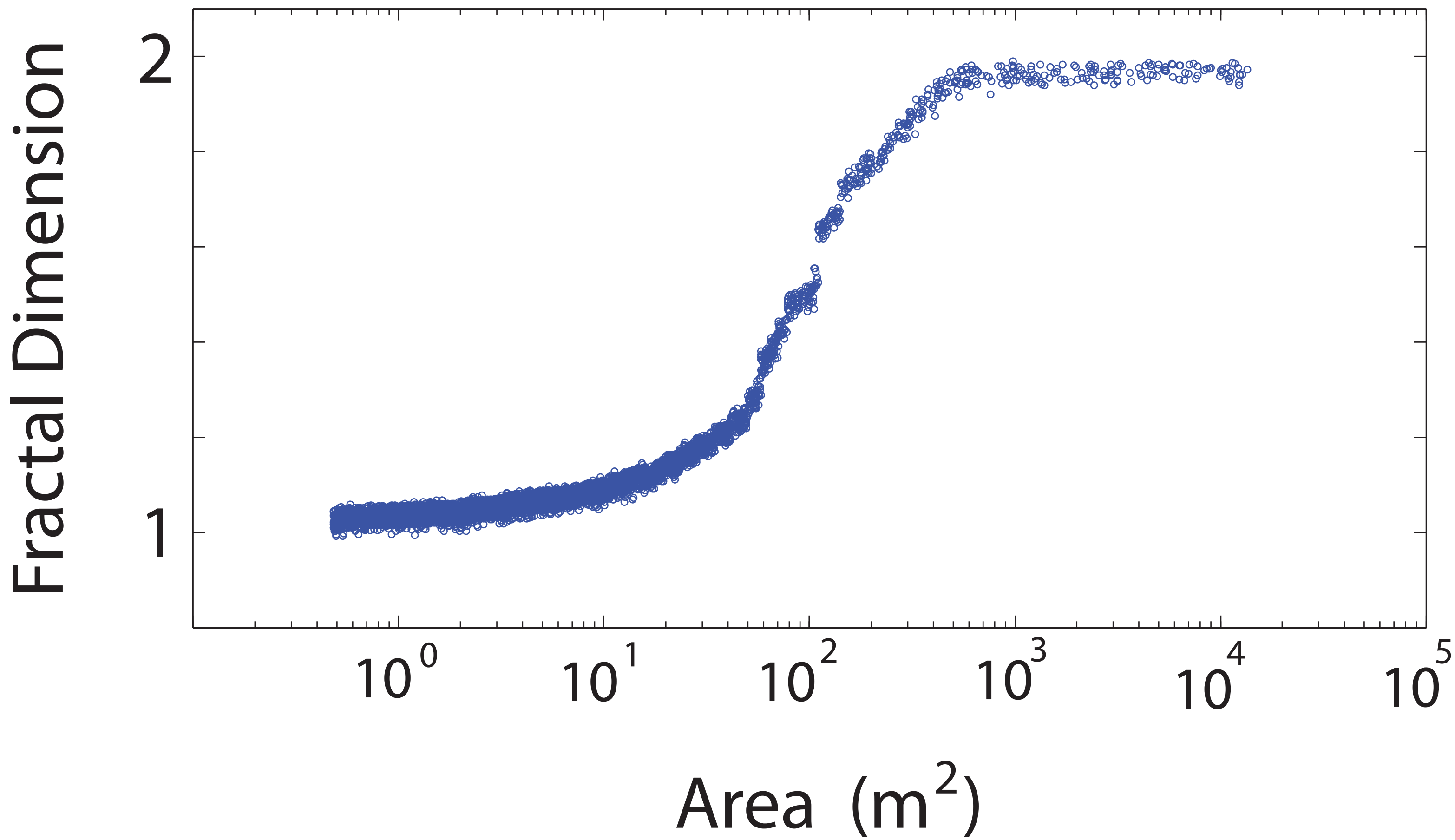


data from
5269 Arctic
melt ponds

simple pond ***transitional pond*** ***complex pond***

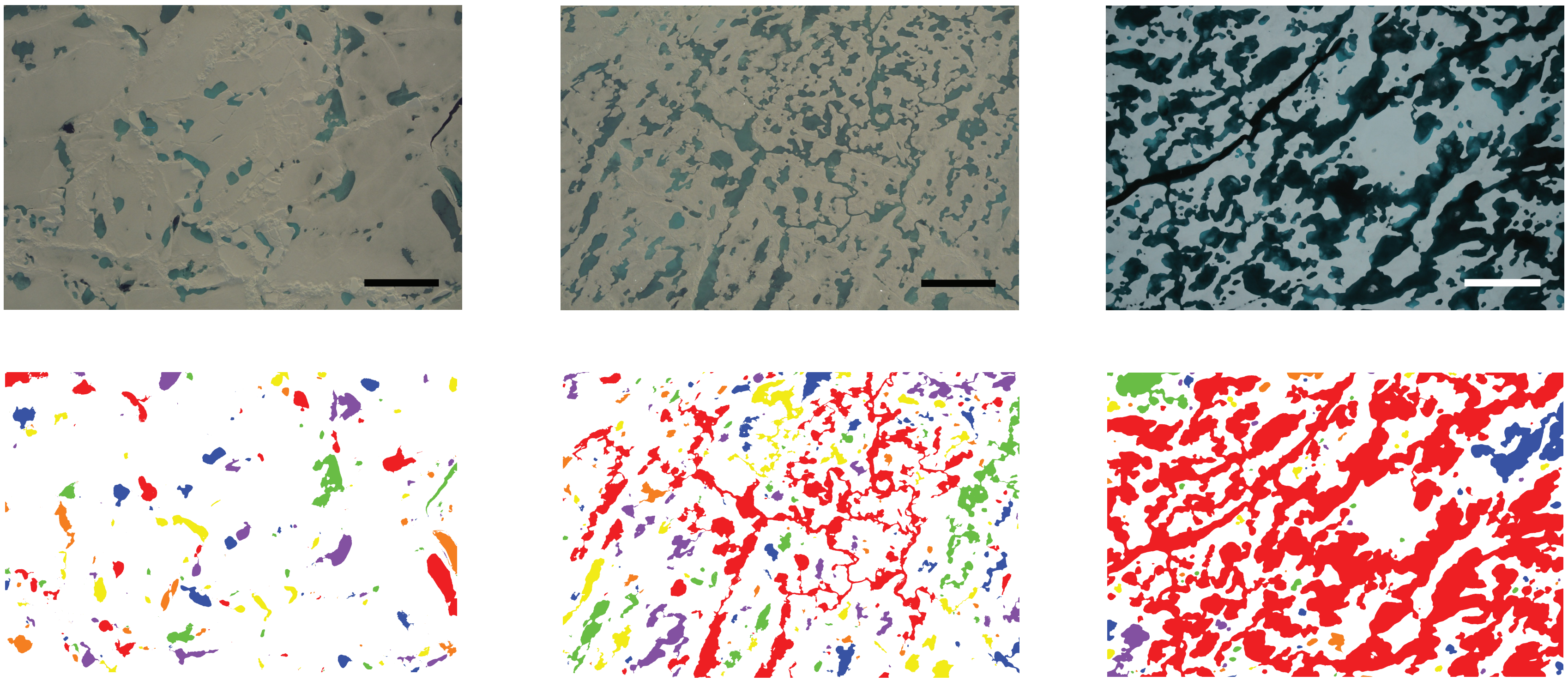
transition in the fractal dimension

complexity grows with length scale



compute "derivative" of area - perimeter data

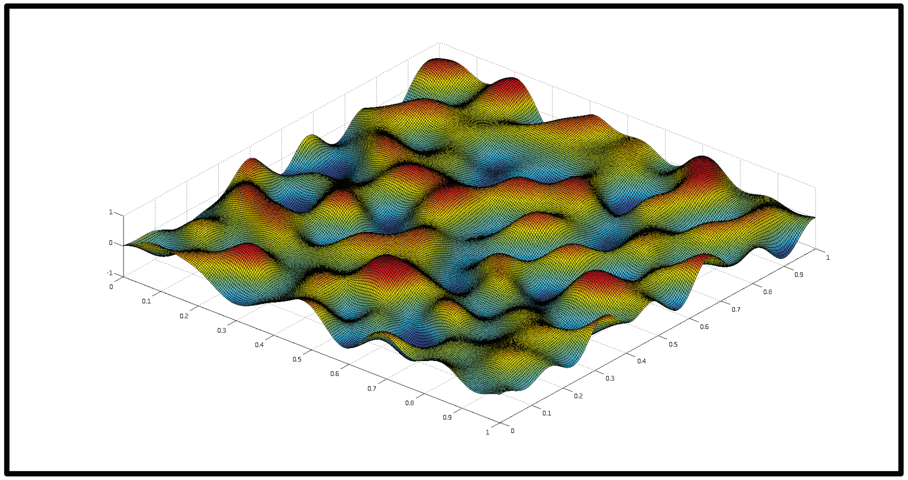
small simple ponds coalesce to form large connected structures with complex boundaries

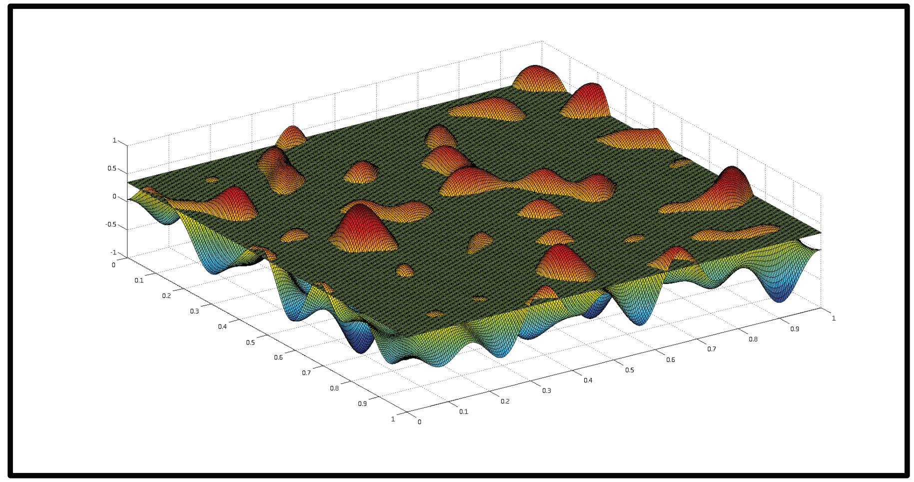


melt pond percolation

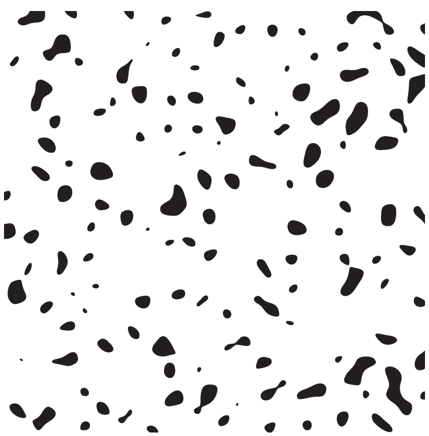
Continuum percolation model for melt pond evolution

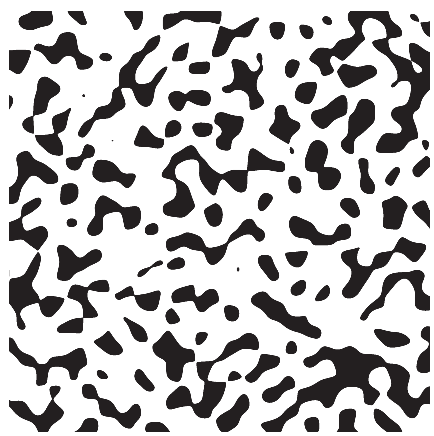
(Brady Bowen and Ken Golden, 2013)

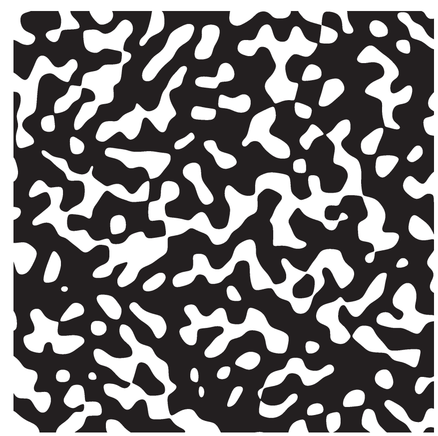




intersections of a plane with the surface define melt ponds





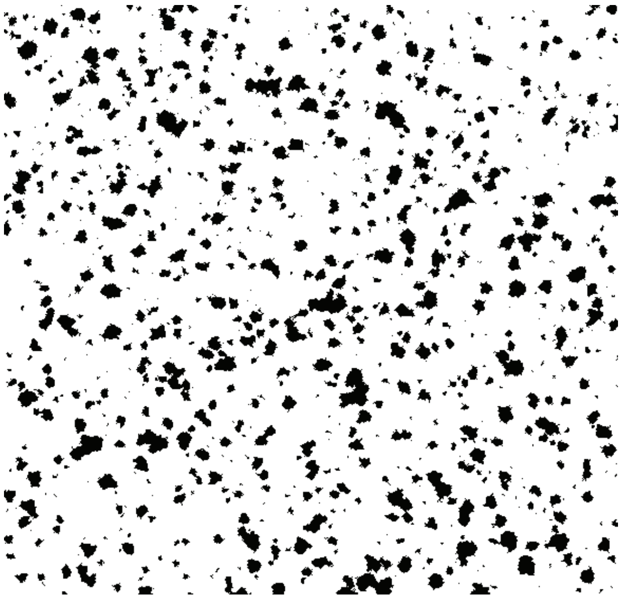


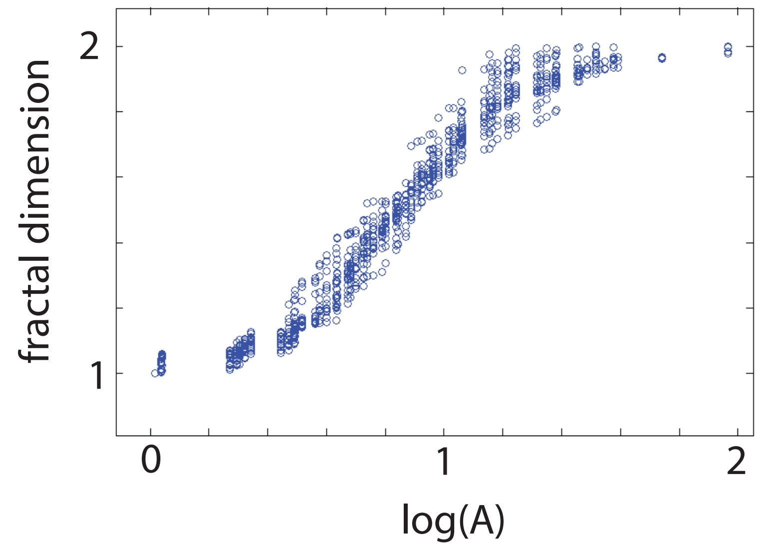
electronic transport in disordered media

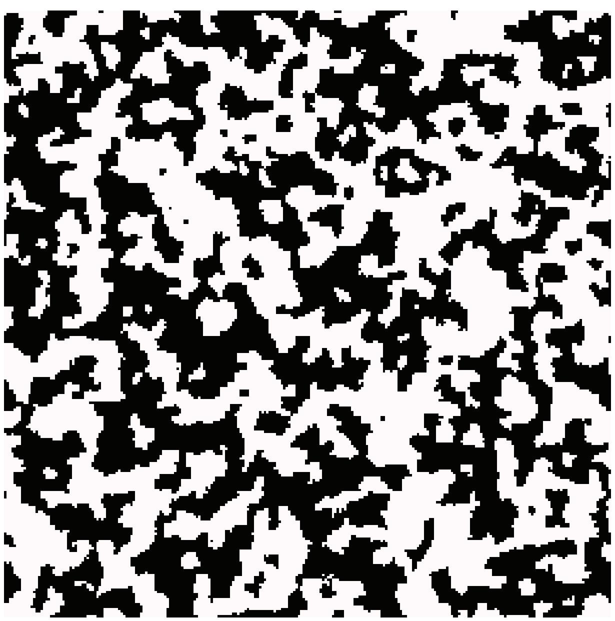
diffusion in turbulent plasmas

(Isichenko, Rev. Mod. Phys., 1992)

simple stochastic growth model of melt pond evolution







voter model

a square is more likely to melt if its neighbors have melted

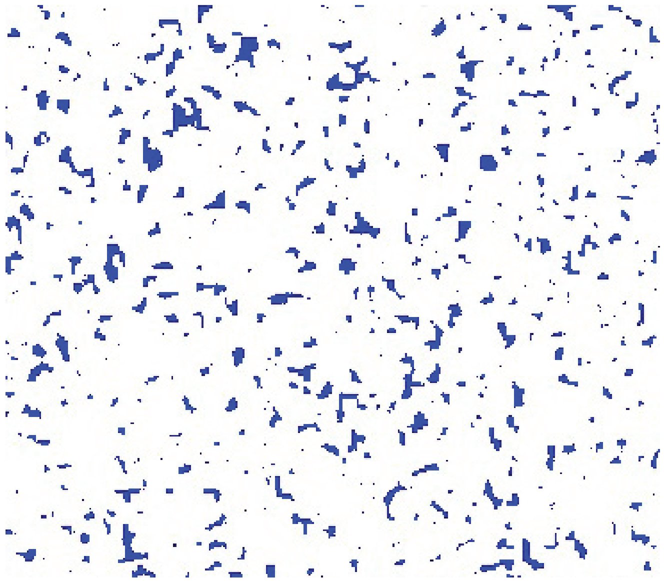
Rebecca Nickerson (West HS, Salt Lake City) and Ken Golden

Ising model for ferromagnets → Ising model for melt ponds

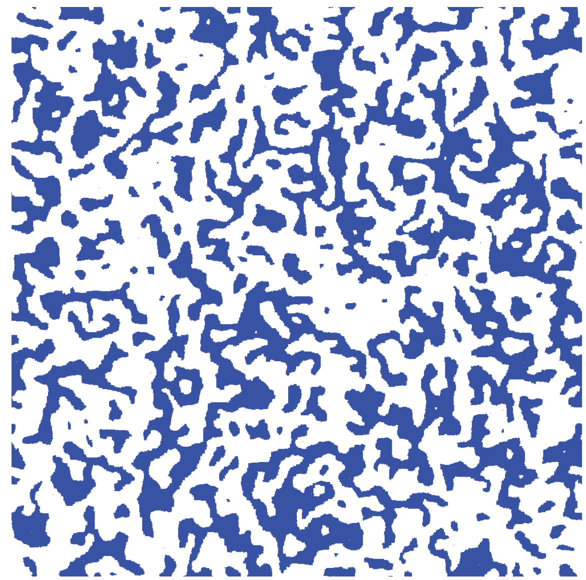
$$\mathcal{H}_\omega = -J \sum_{<i,j>}^{N} s_i s_j - H \sum_{i}^{N} s_i$$

$$s_i = \begin{cases} \uparrow & +1 \quad \text{ice} \\ \downarrow & -1 \quad \text{water} \end{cases}$$

$$M = \lim_{N\to\infty} \frac{1}{N} \left\langle \sum_j s_j \right\rangle$$



COLD



WARM

"melt ponds" are clusters of magnetic spins that align with the applied field

clusters exhibit transition in fractal dimension

Thekkedath, Alali, Strong, Golden
Sudakov, Ma, Golden

Conclusions

1. Summer Arctic sea ice is melting rapidly.

2. Fluid flow through sea ice mediates many processes of importance to understanding climate change and the response of polar ecosystems.

3. Mathematical models of composite materials and statistical physics help unravel the complexities of sea ice structure and processes, and provide a path toward rigorous representation of sea ice in climate models .

4. Field experiments are essential to developing relevant mathematics.

5. Our research will help to improve projections of climate change and the fate of the Earth sea ice packs.

THANK YOU

National Science Foundation

Division of Mathematical Sciences

Arctic Natural Sciences

Office of Polar Programs

CMG Program

(Collaboration in Mathematical Geosciences)

Office of Naval Research

Applied Computational Analysis Program

Arctic and Global Prediction Program

Department of the Navy ONR Science & Technology

MCRN Mathematics and Climate Research Network

Australian Government
Department of the Environment and Water Resources
Australian Antarctic Division

ace CRC Antarctic Climate & Ecosystems Cooperative Research Centre

NSF

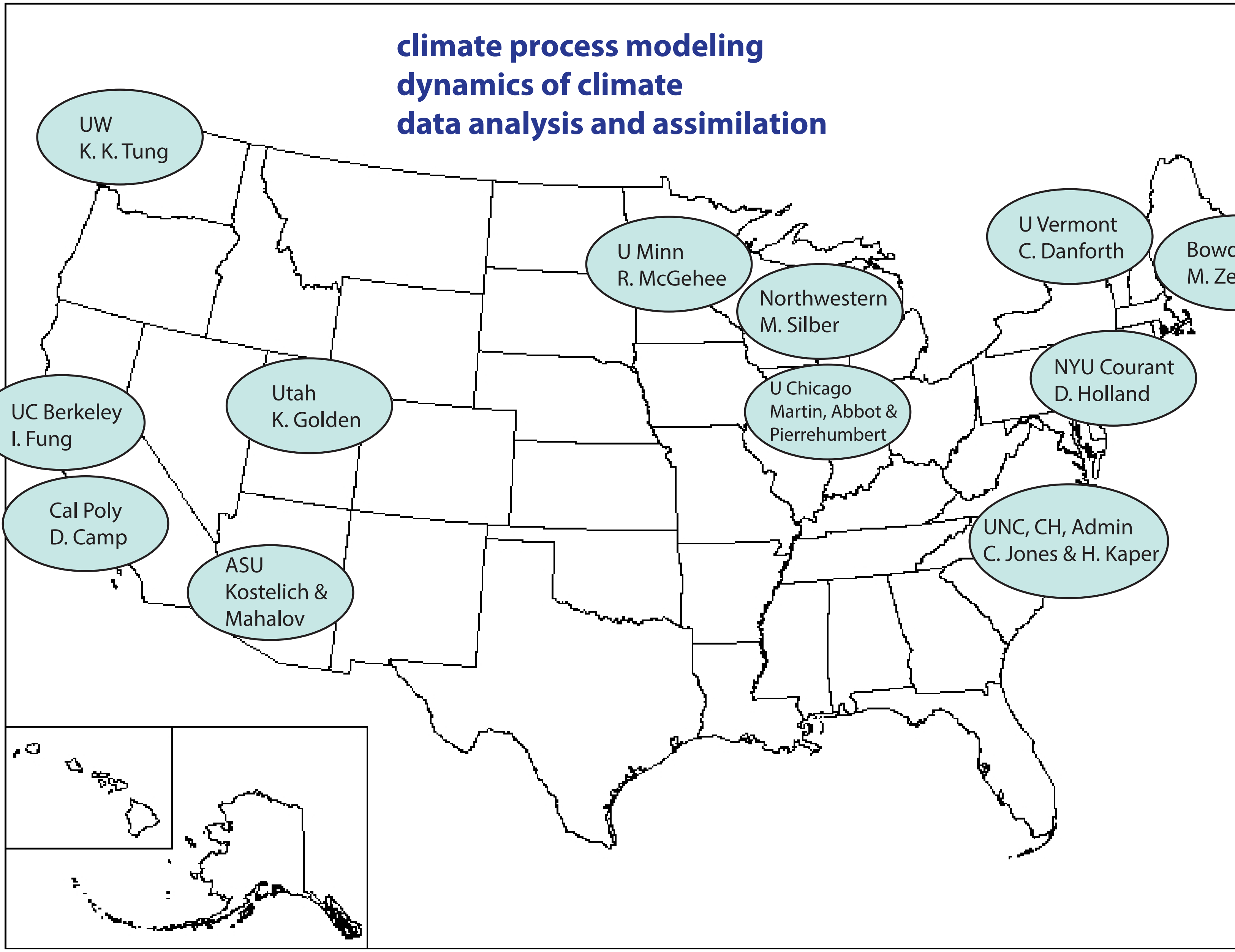
Antarctica New Zealand

UAF University of Alaska Fairbanks

The University of Utah

Buchanan Bay, Antarctica   Mertz Glacier Polynya Experiment   July 1999

Mathematics and Climate Research Network (MCRN)



NSF DMS 2010-2015, Lorenz postdocs, grad, undergrad, polar expeditions

Jones, Golden, Kaper, Zeeman

2 — THE MERCURY Thursday, July 23, 1998

Fire endangers Hobart's ice ship

By DAVID CARRIGG

AN engine-room fire has left the Hobart-based Antarctic research ship Aurora Australis without power in dangerous sea ice off the Antarctic coast.

None of the 79 people on board was injured in the blaze, which broke out early yesterday morning while the ship was in deep water 185km off the coast.

The extent of the damage is not known.

Australian Antarctic Division director Rex Moncur said the fire was extinguished by flooding the engine room with an inert gas.

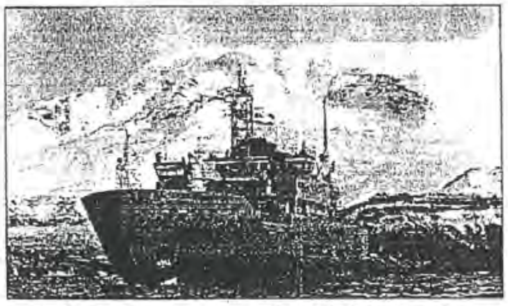
The gas had to be cleared before crew wearing breathing apparatus could enter and assess the situation.

He said it could be some time before the extent of damage was known.

The 25 crew and 54 expeditioners, mostly from Hobart, would wear thermal clothing and stay below decks to keep warm.

"There is always a risk of becoming ice-bound in these waters at this time of the year but at this stage we don't expect to launch a rescue mission from Hobart," Mr Moncur said.

The ship was in regular radio contact with the Antarctic Division's Hobart office.



A file photo of the Aurora Australis in Antarctica.

He expected the expeditioners and crew to abandon the pioneering winter voyage and return the ship to Hobart for repairs in about a week.

The Antarctic Division, which hires the ship from P&O Australia, would not be hiring another vessel for the expedition.

"It's a pretty specialist vessel so you couldn't get the sort of research capability that this ship has got readily available," Mr Moncur said.

"We hope the next voyage can still proceed on schedule, which is early September."

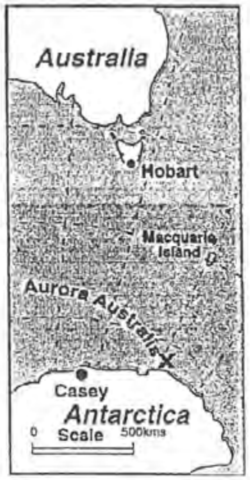
The Aurora Australis is owned by P&O Australia and charted by the Antarctic Division for about $11 million a year.

P&O Australia managing director Richard Hein said yesterday the company was assessing the situation and a number of rescue options were being considered.

It was too early to say whether P&O would be liable for the cost of the aborted mission.

The vessel left Hobart last Wednesday for a seven-week voyage mainly to study a polynya, an area where savage winds break up the sea ice and cause heavy, salt-laden water to sink to the bottom.

The ship was nearing the polynya when the fire broke out.



Oceanographers believe a closer study of the phenomenon will lead to a better understanding of climate change.

CSIRO Marine Research oceanographer Steve Rintoul said the dense bottom water, created only in a few places in Antarctica and to a lesser extent in the North Atlantic, was critical to the chemistry and biology of the world's oceans.

THE ADVERTISER (Adelaide)
Thurs 23 July 1998 Page 14

Fire strands Antarctic ship in sea ice

AN engine room fire has disabled the icebreaker Aurora Australis in sea ice, deep in Antarctic waters.

There were no injuries and the ship was not in danger after Tuesday night's fire, Australian Antarctic Division director Mr Rex Moncur said. But Mr Moncur said he expected it would have to abandon its pioneering mid-winter voyage to the edge of the Antarctic continent and return to Hobart for repairs.

The cause of the fire was not known but the engines have been turned off, with the ship 100 nautical miles from the Antarctic coast.

THE CANBERRA TIMES
Thursday 23 July 1998 Page 4

Antarctic voyage stopped by fire

HOBART: An engine room fire has disabled the Australian icebreaker Aurora Australis in sea ice, deep in Antarctic waters.

Australian Antarctic Division director Rex Moncur said there were no injuries and the ship was not in danger after Tuesday night's fire.

But Mr Moncur said he expected Aurora Australis would have to abandon its pioneering mid-winter voyage to the edge of the Antarctic continent to return to Hobart for repairs.

The fire had been extinguished and the engines were turned off, leaving the ship in sea ice about 100 nautical miles from the Antarctic coast, he said. The weather was good.

Crew had to wear breathing apparatus to enter the engine room and it was likely to be 24 hours before the damage could be fully assessed.

The Aurora, with 54 expeditioners and 25 crew, left Hobart last Wednesday for a seven-week voyage which was to have focused on a polynya, an area where savage winds break up the sea ice and cause heavy, salt-laden water to sink to the bottom.

Mr Moncur said, the cause of the fire was not yet known.

Sydney Morning Herald
23 July, 1998

ICEBREAKER BURNS

A pioneering $2 million Australian scientific voyage to the mid-winter Antarctic pack-ice is expected to be scrapped following an engine-room fire on the Aurora Australis yesterday.

The 54 people on board were forced on deck in the...

2:45 am July 22, 1998

``Please don't be alarmed but we have an uncontrolled fire in the engine room ...."

about 10 minutes later ...

``Please don't be alarmed but we're lowering the lifeboats ...."