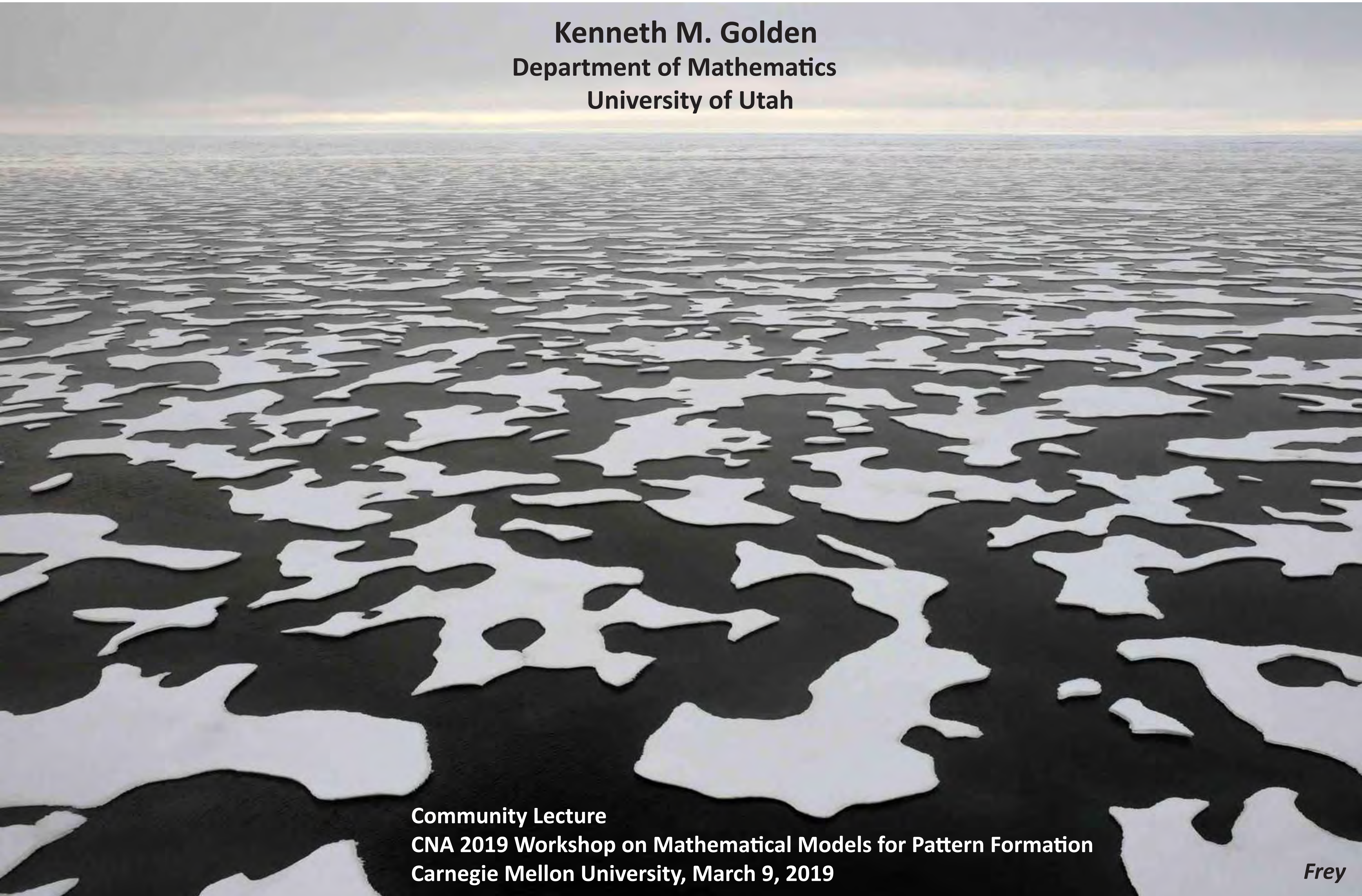
Pattern Formation in Melting Arctic Sea Ice



Kenneth M. Golden
Department of Mathematics
University of Utah

Community Lecture
CNA 2019 Workshop on Mathematical Models for Pattern Formation
Carnegie Mellon University, March 9, 2019

Frey

SEA ICE covers ~12% of Earth's ocean surface

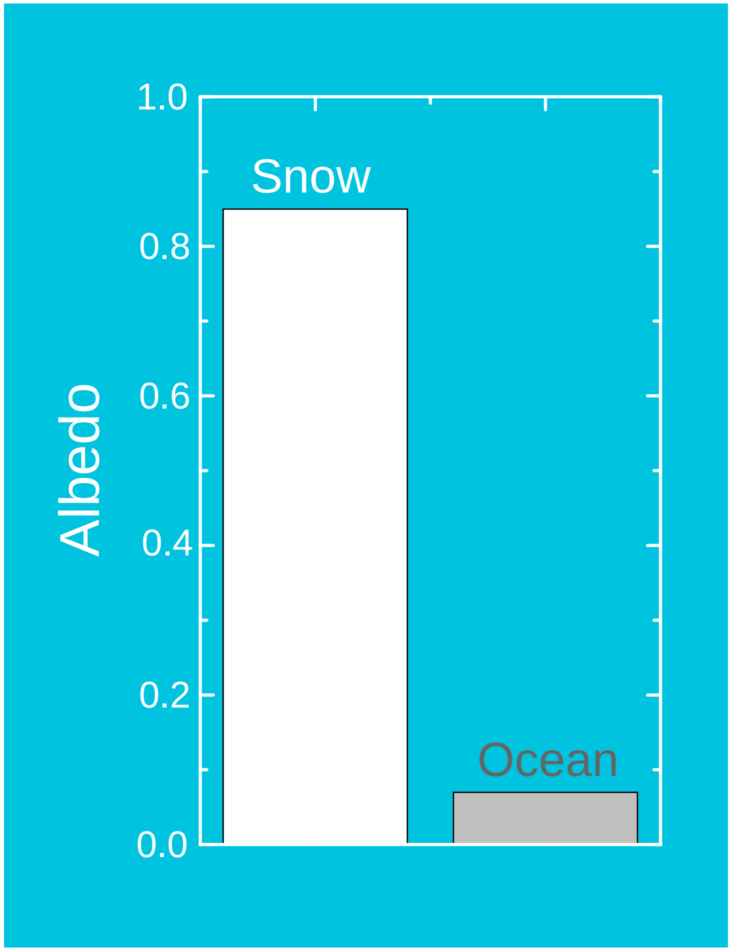
- boundary between ocean and atmosphere
- mediates exchange of heat, gases, momentum
- global ocean circulation
- indicator and agent of climate change

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

NASA

NASA

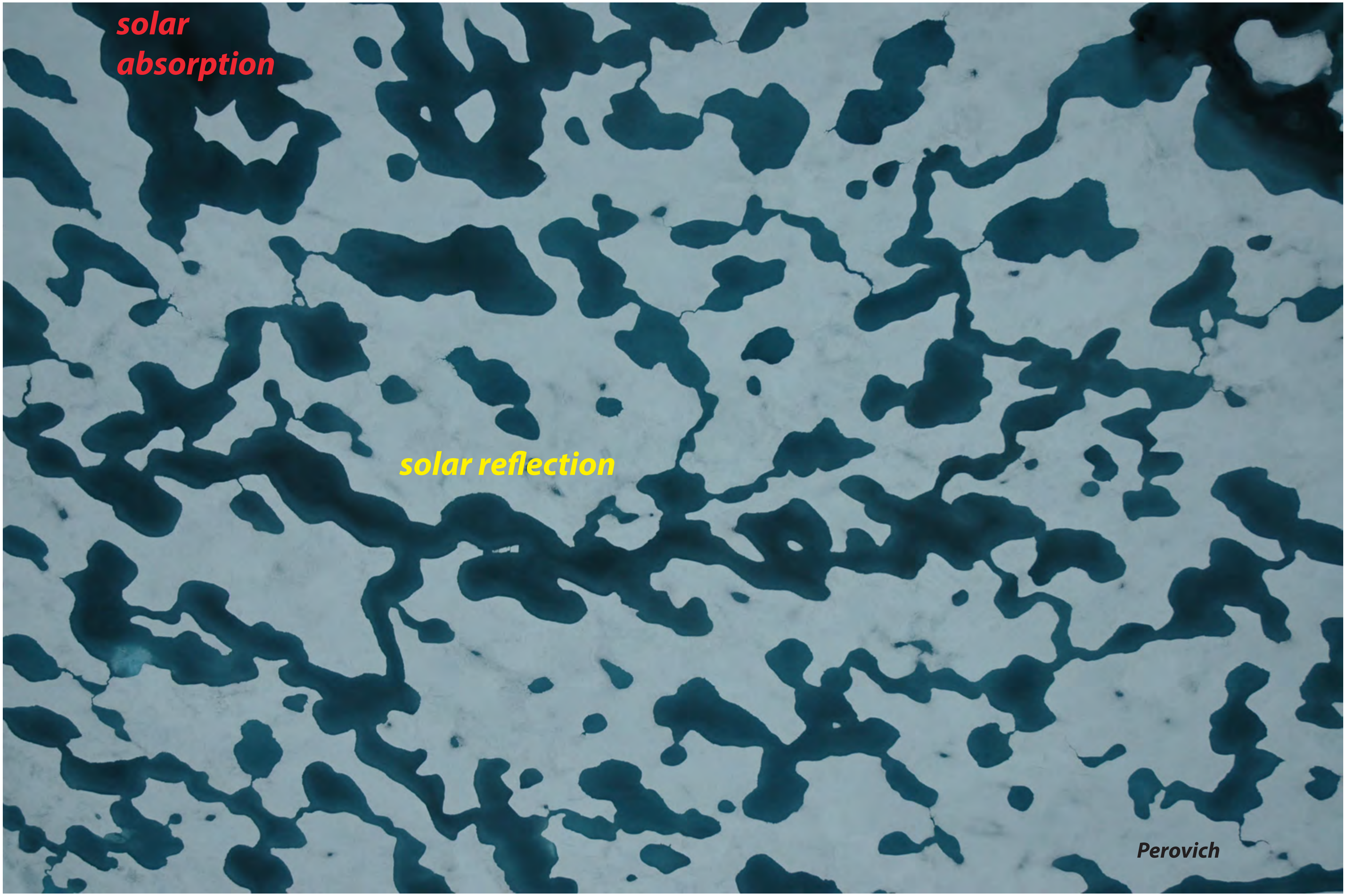
white snow and ice reflect



dark water and land absorb

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

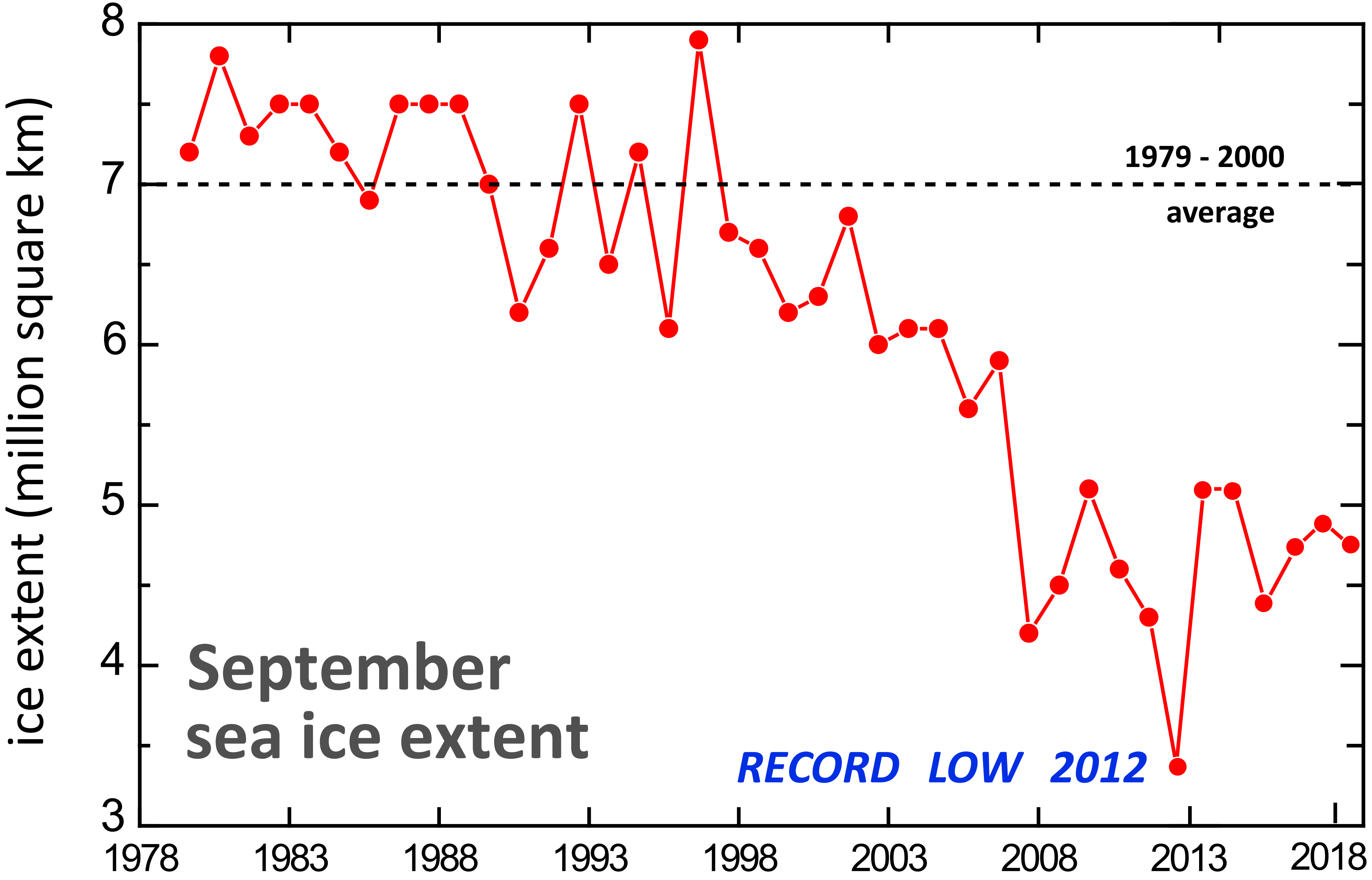
Arctic melt ponds



melt pond pattern formation and albedo evolution -- major drivers in polar climate

key challenge for global climate models

the summer Arctic sea ice pack is melting

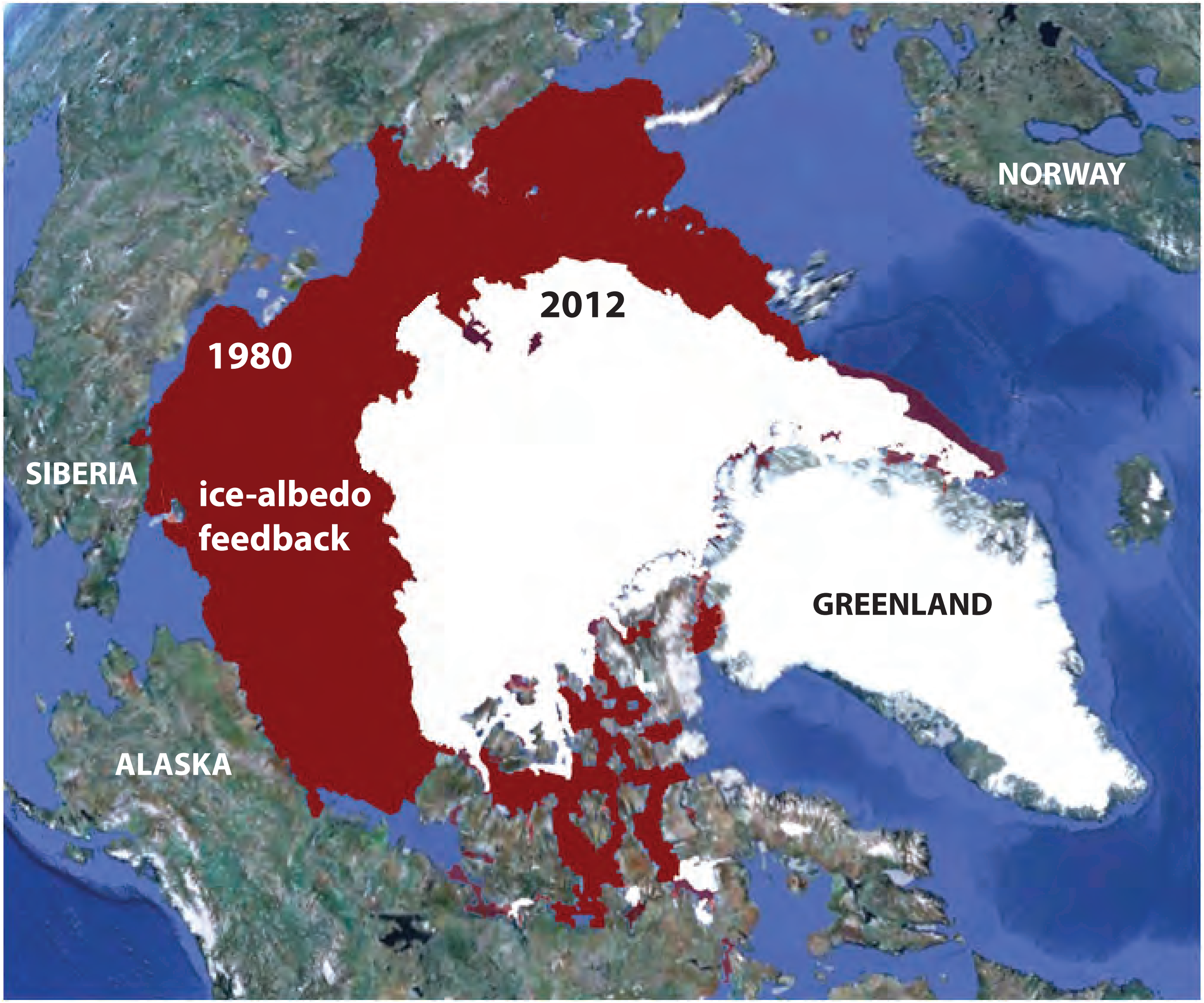


National Snow and Ice Data Center

Change in Arctic Sea Ice Extent

September 1980 -- 7.8 million square kilometers

September 2012 -- 3.4 million square kilometers



Perovich

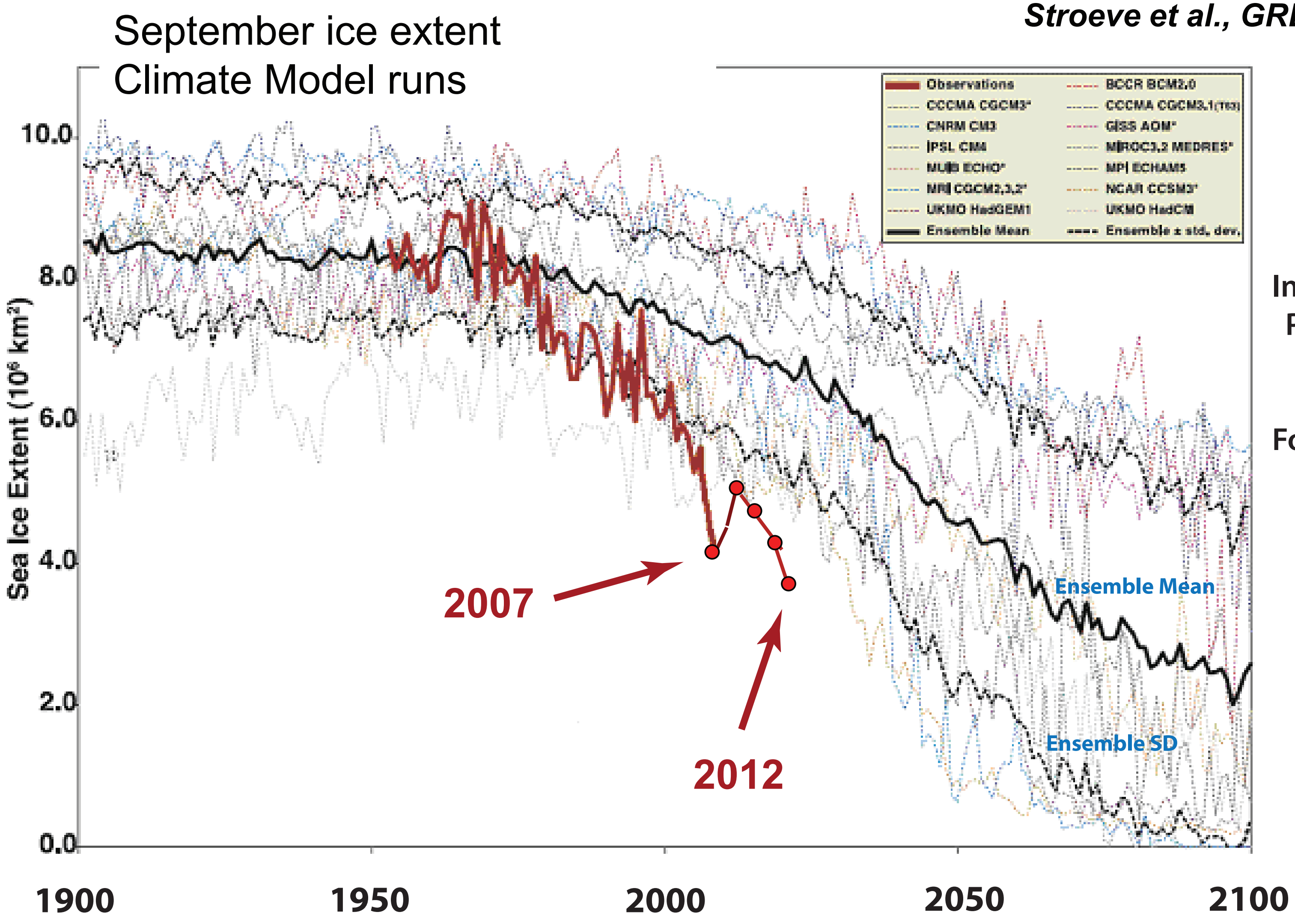
recent losses in comparison to the United States

Perovich

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

IPCC AR4
Models

Intergovernmental
Panel on Climate
Change (IPCC)

Fourth Assessment
AR4, 2007

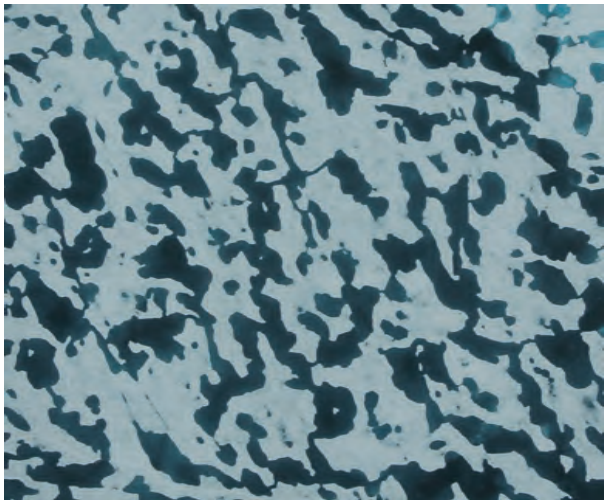
challenge

represent sea ice more realistically in climate models

account for key processes

such as melt pond evolution

How do patterns of dark and light evolve?



Impact of melt ponds on Arctic sea ice simulations from 1990 to 2007

Flocco, Schroeder, Feltham, Hunke, JGR Oceans 2012

For simulations with ponds September ice volume is nearly 40% lower.

... and other sub-grid scale structures and processes

linkage of scales

What is this talk about?

Tour the fascinating patterns in sea ice structure and how they form on scales from millimeters to tens of kilometers.

How do these patterns influence processes on larger scales?

[Use theories of multiscale composite materials and statistical physics to homogenize - compute effective behavior and improve climate models.]

1. Patterns in sea ice structure

mm	brine microstructure	} fluid flow and EM properties
cm	polycrystalline microstructure	
m/km	floe structure -- breakage patterns; wave propagation	
m/km	advective patterns -- enhanced diffusion	

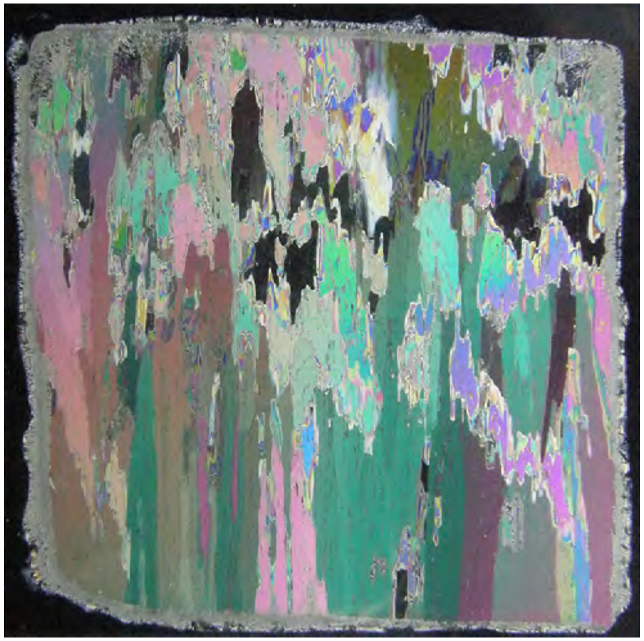
2. Fractal geometry of melt pond patterns

   observations, models, under-ice light field and algal blooms

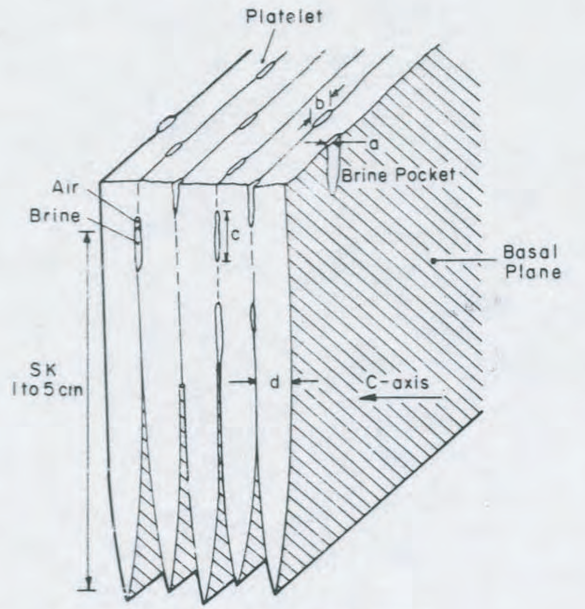
cross-sections of sea ice structure

$$T_{freeze} = -1.8^{\circ}\,\mathrm{C}$$

crystallographic texture



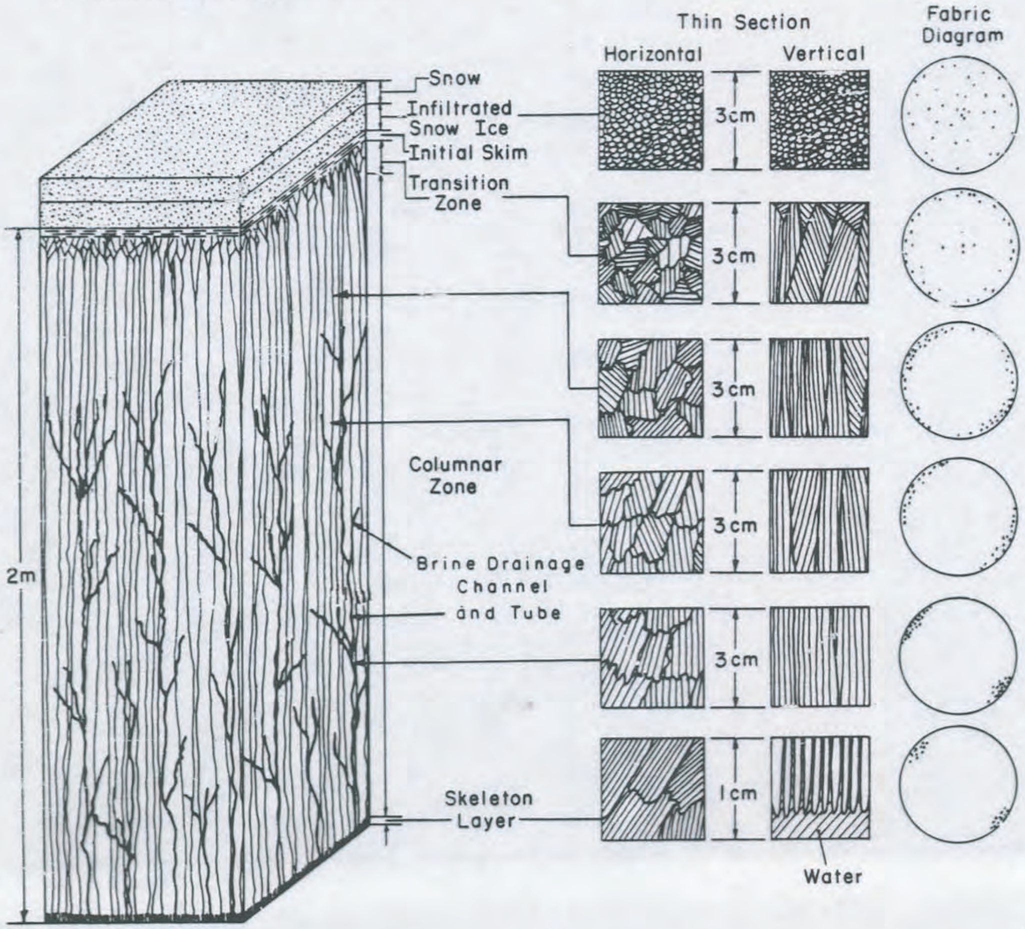
vertical thin section



$a \leq b$; $b \sim 1.5\,a \sim 0.1$ to 0.3 mm; $c > 5a$;
$d \sim 0.5$ to 1.5 mm. (avg. 0.8 to 1.0 mm)

~ 1 cm

ice/water interface

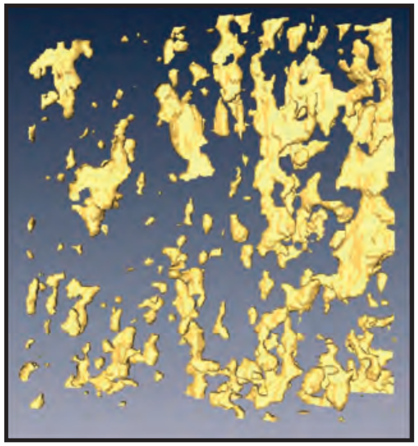


Multiscale Patterns of Sea Ice Structure

sea ice microstructure

brine inclusions

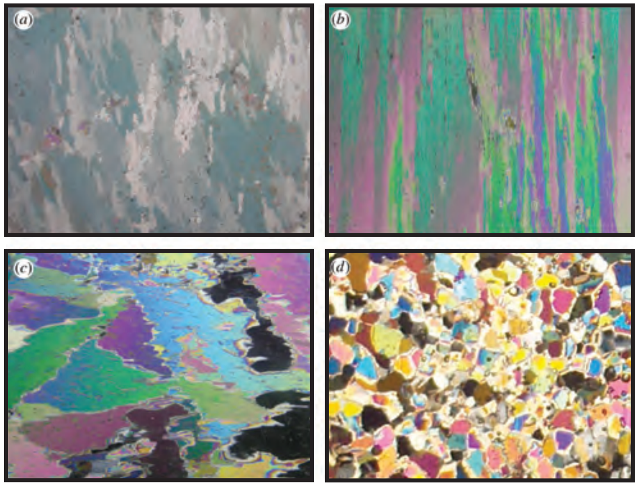
Weeks & Assur 1969



H. Eicken

Golden *et al. GRL* 2007

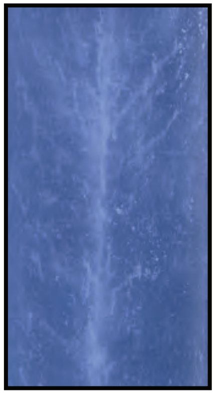
polycrystals



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

brine channels

D. Cole



K. Golden

millimeters

centimeters

---

sea ice mesostructure

sea ice macrostructure

Arctic melt ponds

K. Frey

Antarctic pressure ridges

K. Golden

sea ice floes

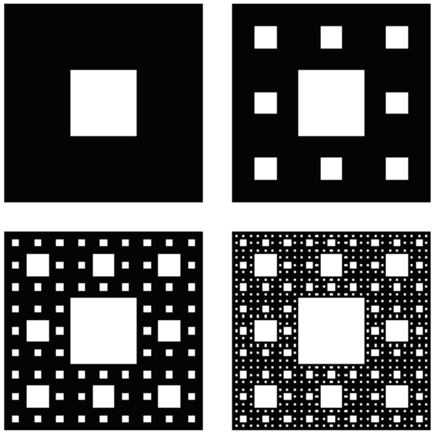
J. Weller

sea ice pack

NASA

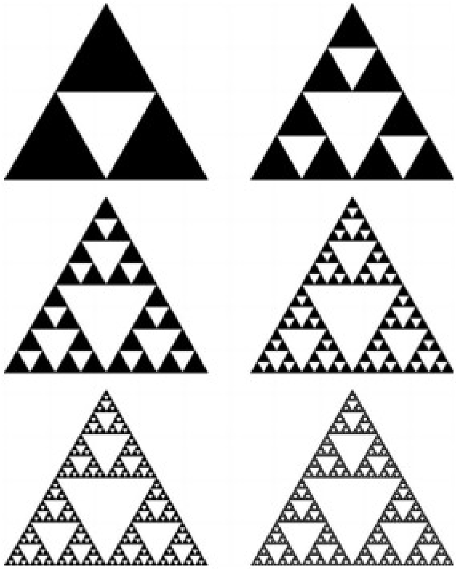
meters

kilometers



fractals

self-similar structure
non-integer dimension



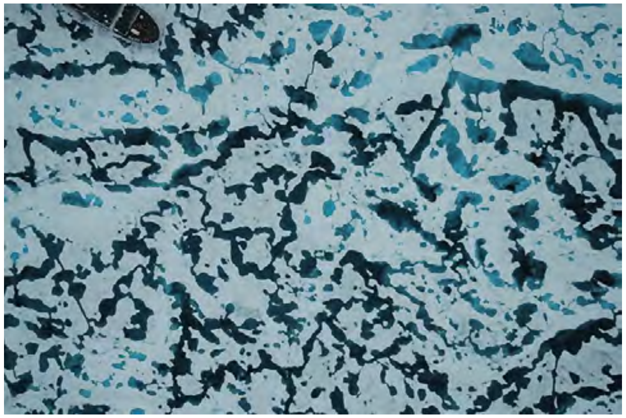
$$D = \frac{\log 3}{\log 2} = 1.585...$$

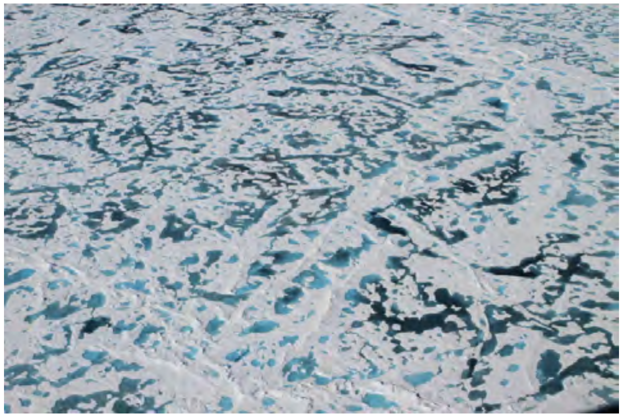
How do scales interact in the sea ice system?

basin scale -
grid scale
albedo

Linking Scales

km
scale
melt
ponds





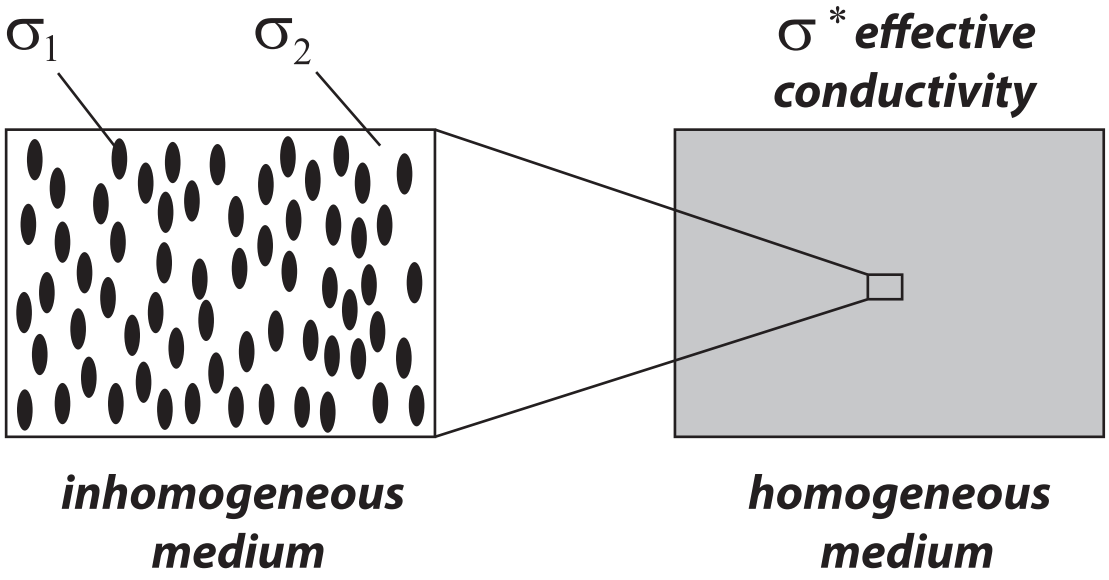
km
scale
melt
ponds

Linking **Scales**

mm
scale
brine
inclusions

meter
scale
snow
topography

HOMOGENIZATION - Linking Scales in Composites



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*

widespread use of composites in late 20th century due in large part to advances in mathematically predicting their effective properties

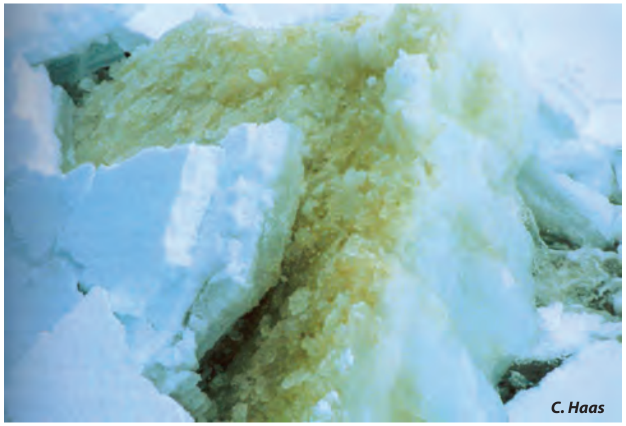
sea ice microphysics

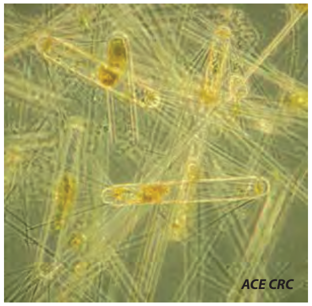
fluid transport

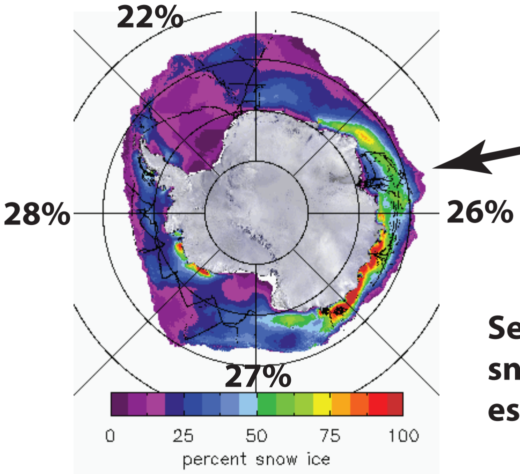
fluid flow through the porous microstructure of sea ice governs key processes in polar climate and ecosystems

evolution of Arctic melt ponds and sea ice albedo

nutrient flux for algal communities







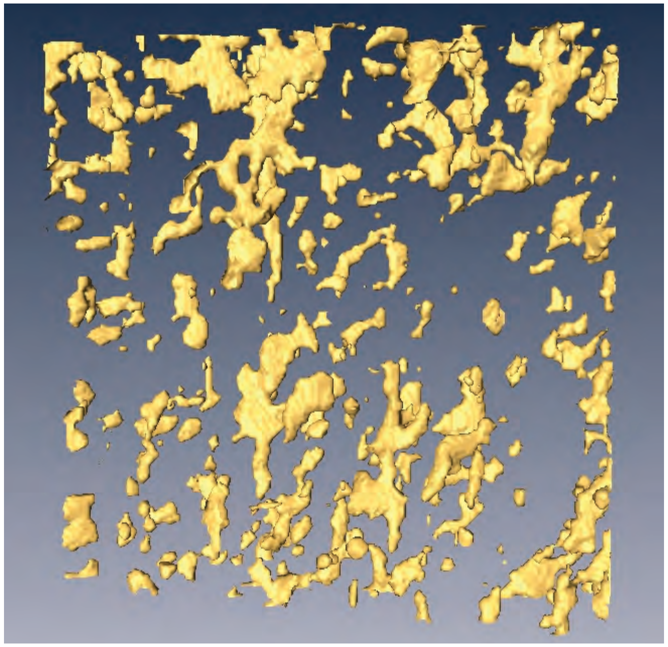
T. Maksym and T. Markus, 2008

September snow-ice estimates

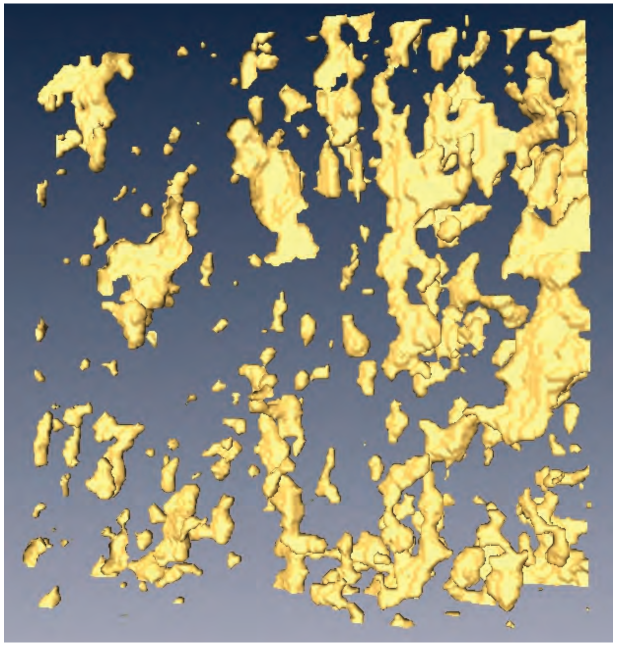
Antarctic surface flooding and snow-ice formation

- *evolution of salinity profiles*
- *ocean-ice-air exchanges of heat, CO_2*

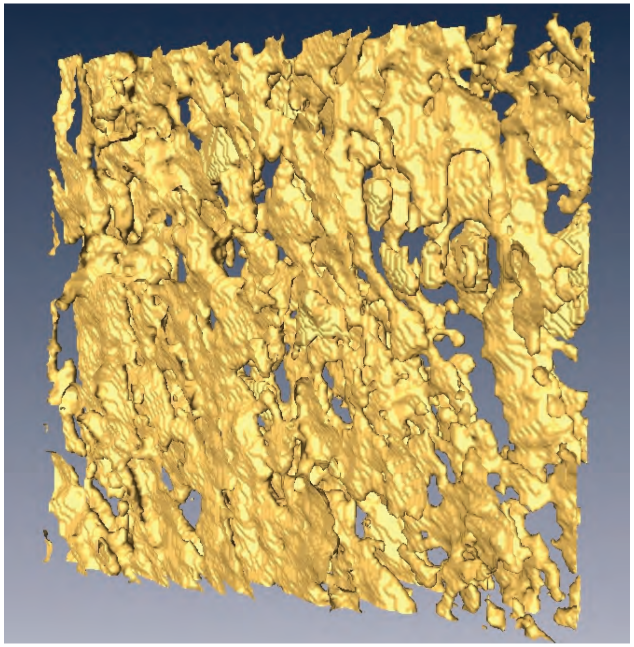
brine volume fraction and ***connectivity*** increase with temperature



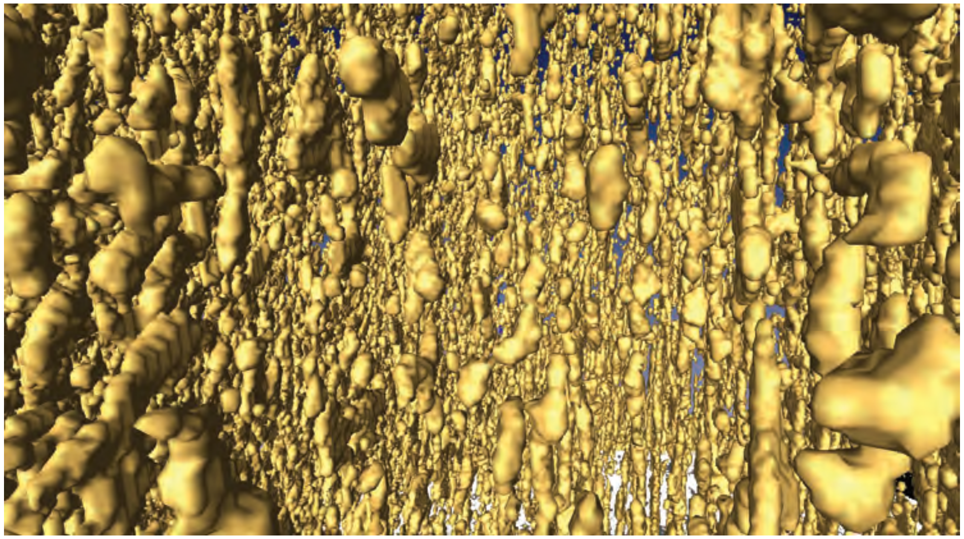
$T = -15\,^\circ\mathrm{C},\ \ \phi = 0.033$



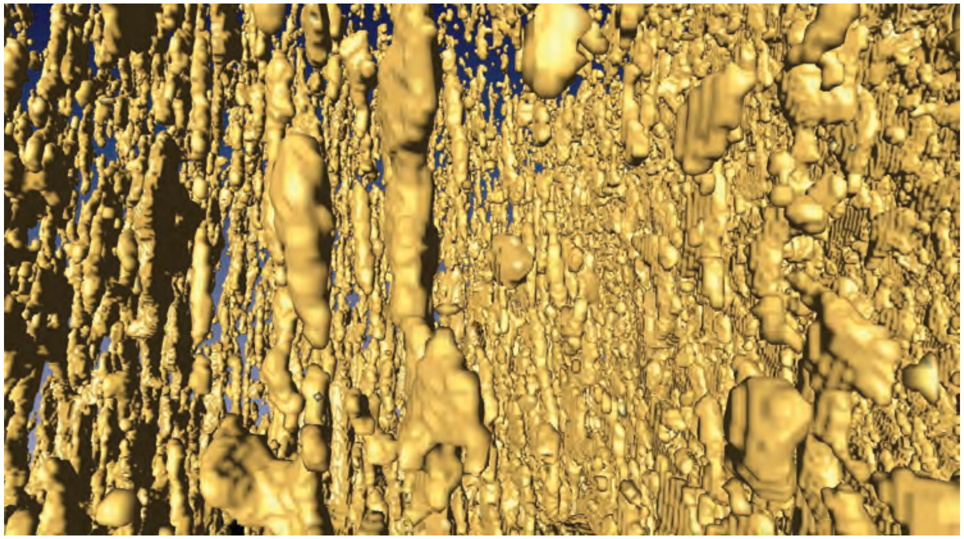
$T = -6\,^\circ\mathrm{C},\ \ \phi = 0.075$



$T = -3\,^\circ\mathrm{C},\ \ \phi = 0.143$



$T = -8\,^\circ\mathrm{C},\ \ \phi = 0.057$



$T = -4\,^\circ\mathrm{C},\ \ \phi = 0.113$

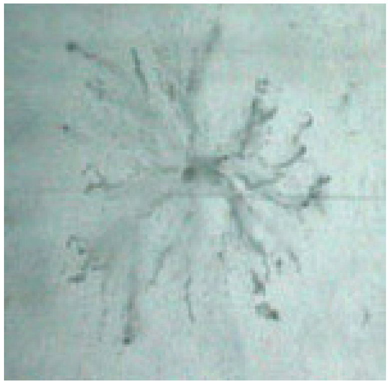
X-ray tomography for brine in sea ice

Golden *et al.*, *Geophysical Research Letters*, 2007

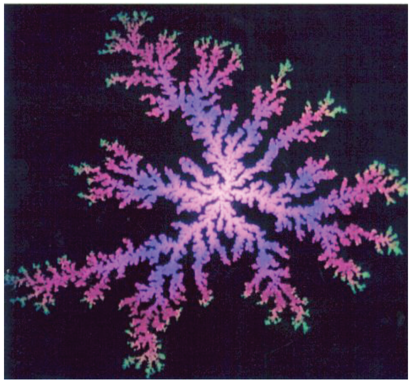
brine movie

fractal microstructures

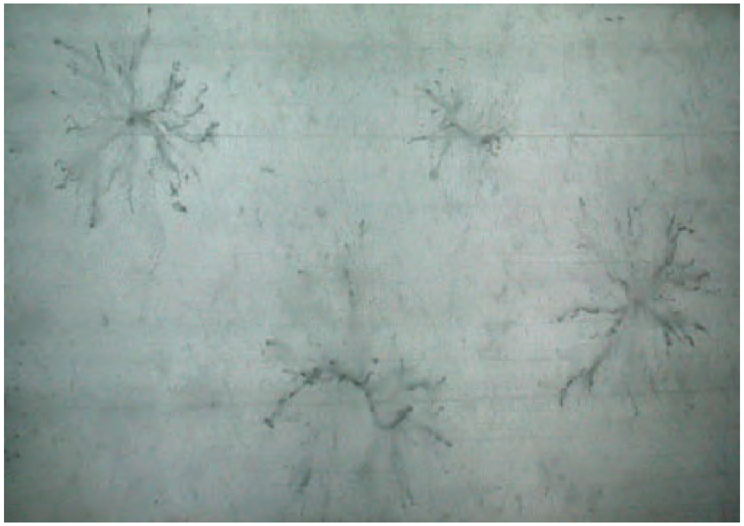
electrorheological fluid
with metal spheres



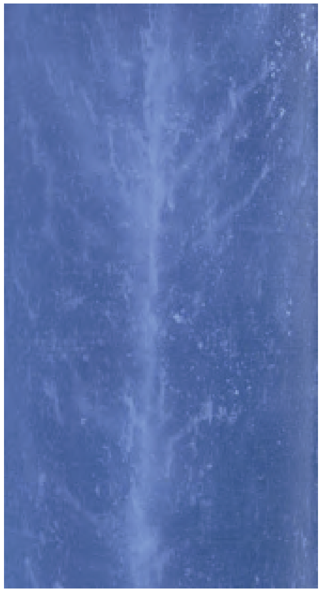
brine channel
in sea ice



diffusion limited
aggregation



brine channels



fluid permeability *k* of a porous medium

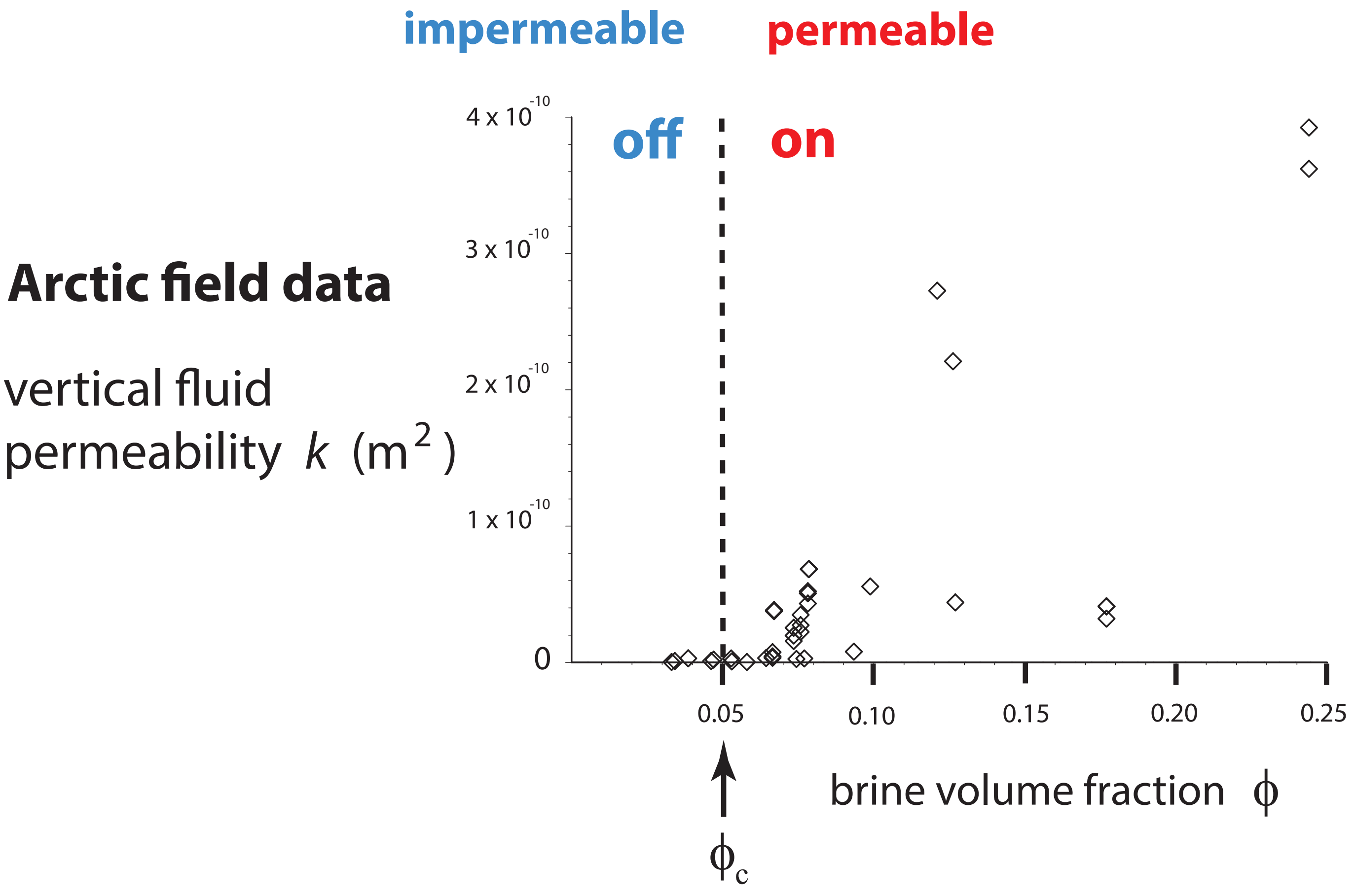
porous
concrete

how much water
gets through the
sample per unit
time?

HOMOGENIZATION

mathematics for analyzing effective behavior of heterogeneous systems

Critical behavior of fluid transport in sea ice



"on - off" switch for fluid flow

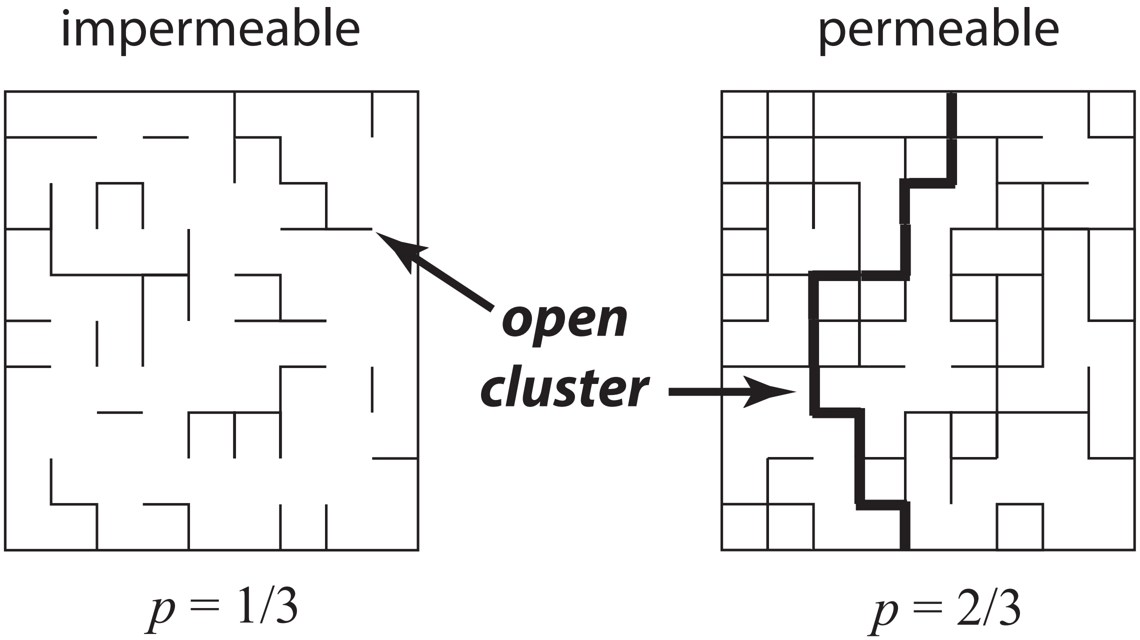
critical brine volume fraction $\phi_c \approx 5\%$ ⟷ $T_c \approx -5^\circ$C, $S \approx 5$ ppt

RULE OF FIVES

Golden, Ackley, Lytle Science 1998
Golden, Eicken, Heaton, Miner, Pringle, Zhu GRL 2007
Pringle, Miner, Eicken, Golden J. Geophys. Res. 2009

percolation theory

probabilistic theory of connectedness



impermeable

permeable

open cluster

$p = 1/3$

$p = 2/3$

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

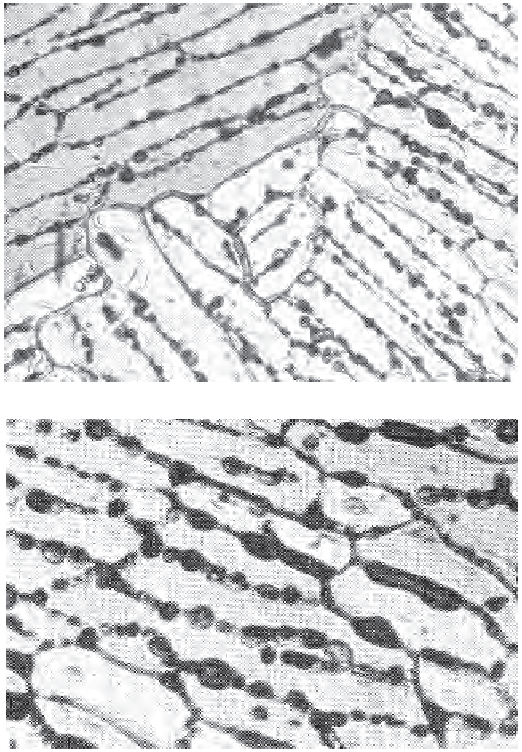
percolation threshold

$$p_c = 1/2 \quad \text{for} \quad d = 2$$

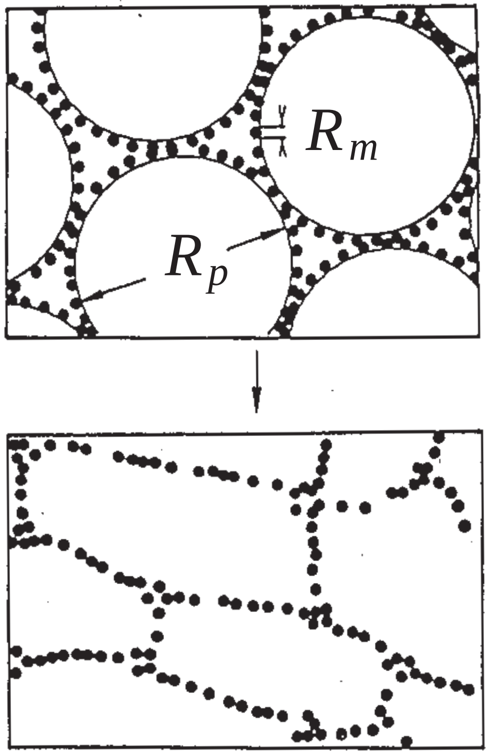
smallest *p* for which there is an infinite open cluster

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



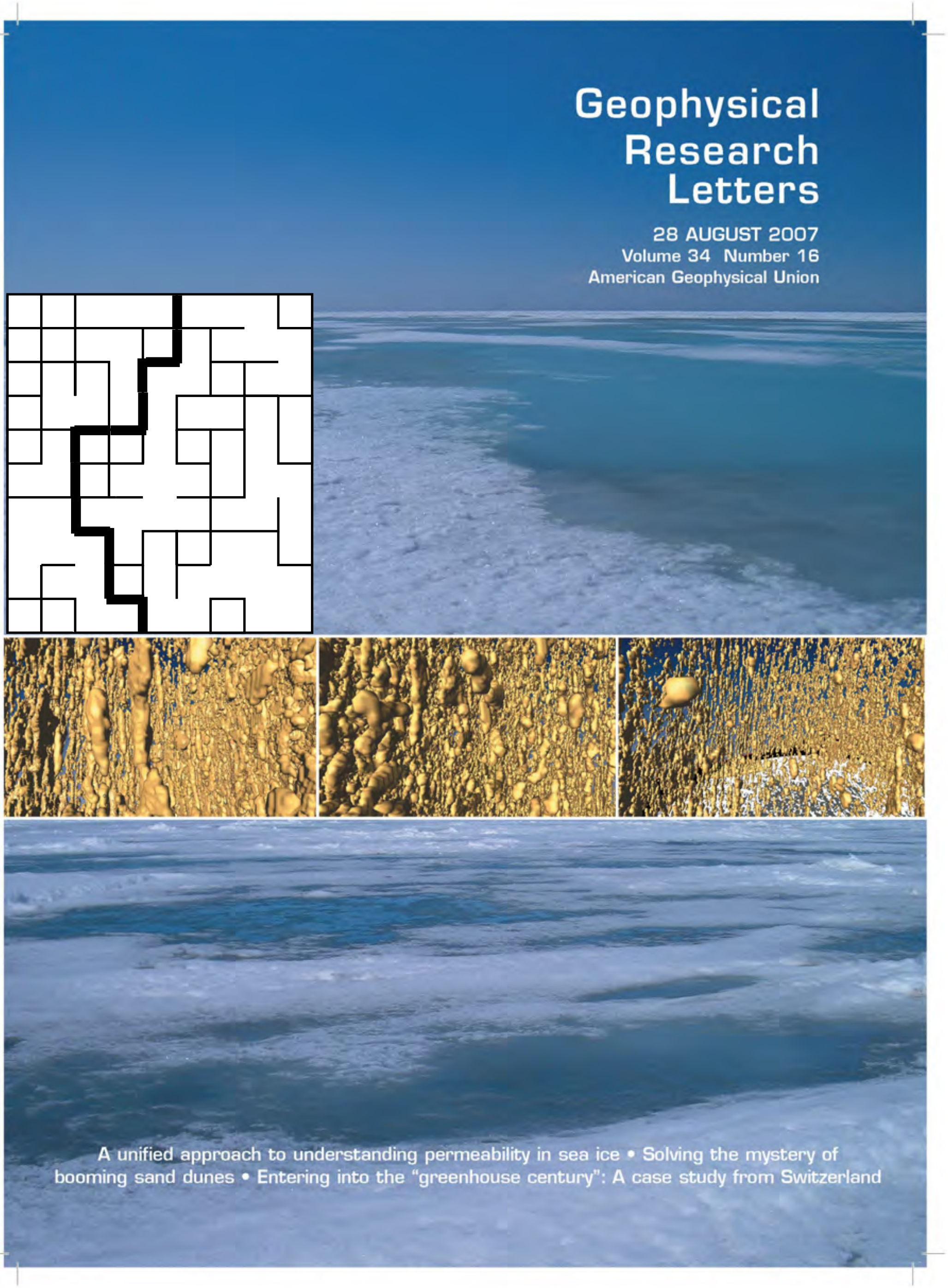
compressed powder

radar absorbing composite

sea ice is radar absorbing

Thermal evolution of permeability and microstructure in sea ice

Golden, Eicken, Heaton, Miner, Pringle, Zhu, Geophysical Research Letters 2007



Geophysical
Research
Letters

28 AUGUST 2007
Volume 34 Number 16
American Geophysical Union

A unified approach to understanding permeability in sea ice • Solving the mystery of booming sand dunes • Entering into the "greenhouse century": A case study from Switzerland

micro-scale

controls

macro-scale

processes

percolation theory

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

critical
exponent
t

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

hierarchical model
network model
rigorous bounds

agree closely
with field data

X-ray tomography for
brine inclusions

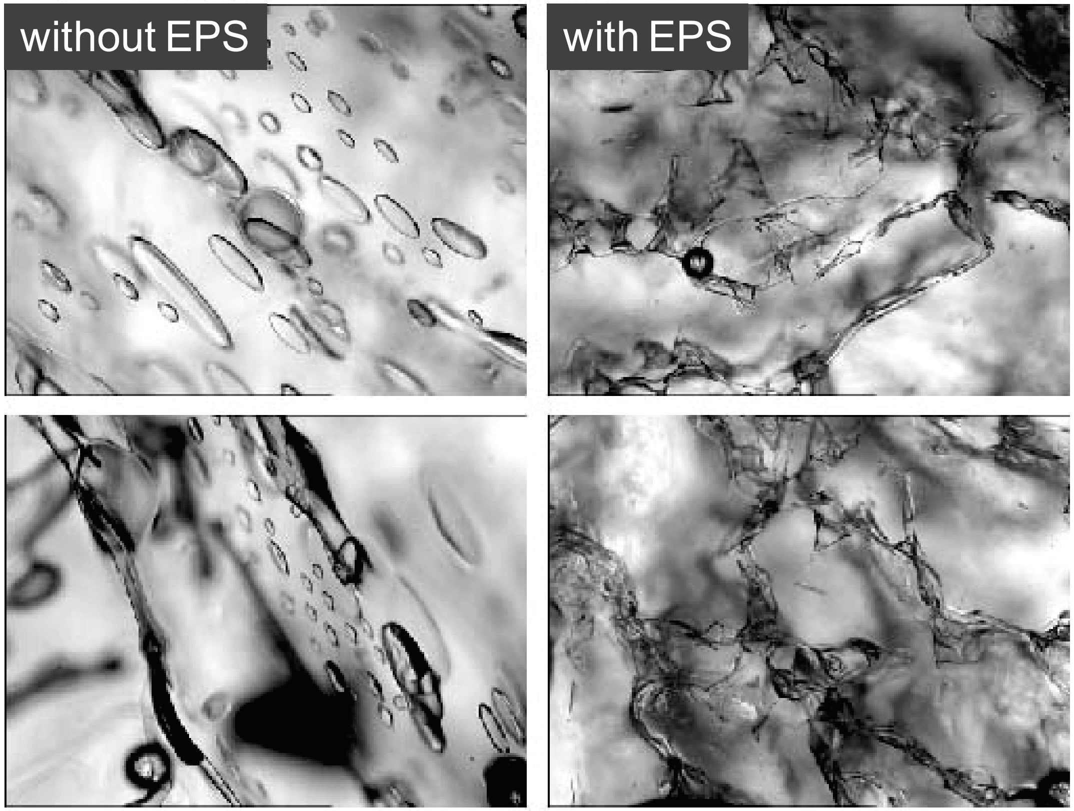
unprecedented look
at thermal evolution
of brine phase and
its connectivity

confirms rule of fives

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

Sea ice algae secrete extracellular polymeric substances (EPS)

EPS changes brine microstructure



ellipsoidal inclusions fractal inclusions

Krembs, Eicken, Deming *PNAS* 2011

numerical model
bounds on fluid
permeability

Steffen, Epshteyn, Zhu, Bowler, Deming, Golden
Multiscale Modeling and Simulation, 2018

How does the biology affect the physics?

Remote sensing of sea ice

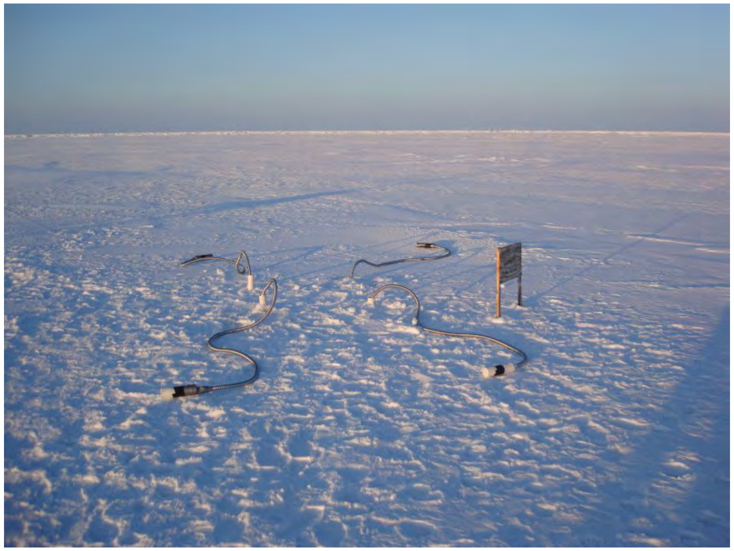
sea ice thickness
ice concentration

INVERSE PROBLEM

Recover sea ice properties from electromagnetic (EM) data

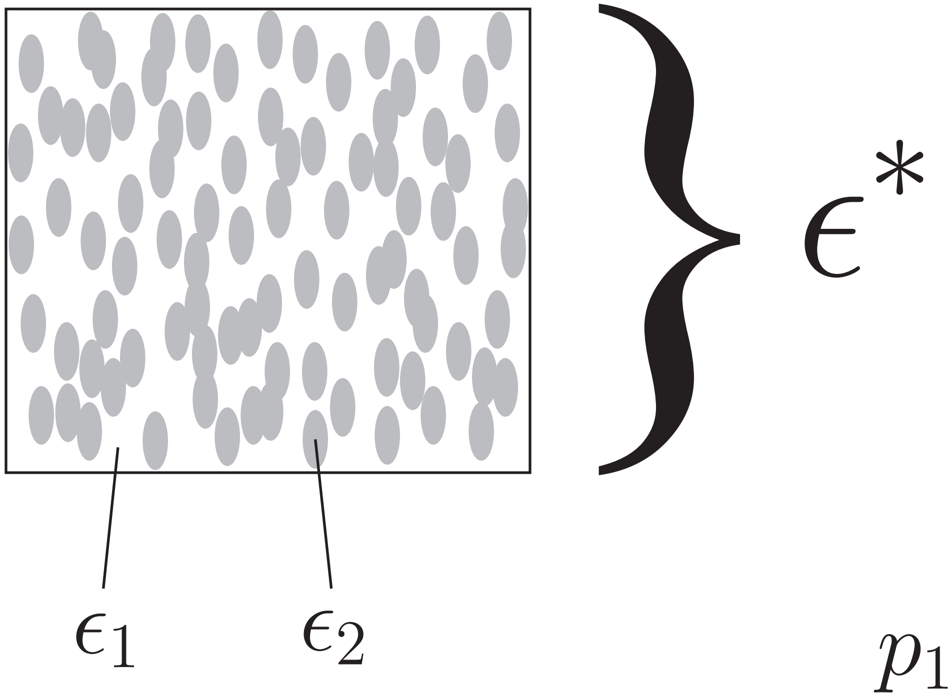
$$\varepsilon^*$$

effective complex permittivity
(dielectric constant, conductivity)



brine volume fraction
brine inclusion connectivity

Effective complex permittivity of a two phase composite in the quasistatic (long wavelength) limit



$$D = \epsilon E$$

$$\nabla \cdot D = 0$$

$$\nabla \times E = 0$$

$$\langle D \rangle = \epsilon^* \langle E \rangle$$

p_1 , p_2 = volume fractions of the components

$$\epsilon^* = \epsilon^* \left(\frac{\epsilon_1}{\epsilon_2} \ , \text{composite geometry} \right)$$

What are the effective propagation characteristics of an EM wave (radar, microwaves) in the medium?

Analytic Continuation Method

Bergman (1978), Milton (1979), Golden and Papanicolaou (1983), Theory of Composites, Milton (2002)

Stieltjes integral representation for homogenized parameter

separates geometry from parameters

geometry

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

material parameters

$$s = \frac{1}{1 - \epsilon_1 / \epsilon_2}$$

μ

- spectral measure of self adjoint operator $\Gamma\chi$
- mass = p_1
- higher moments depend on n-point correlations

$$\Gamma = \nabla(-\Delta)^{-1}\nabla\cdot$$

$\chi =$ characteristic function of the brine phase

$$E = s\,(s + \Gamma\chi)^{-1} e_k$$

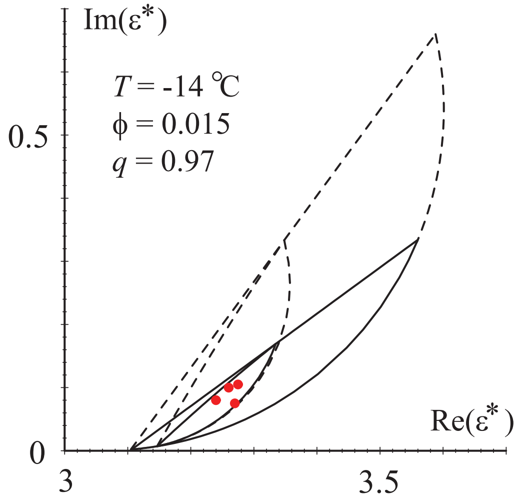
$\Gamma\chi$: microscale $\longrightarrow$ macroscale

$\Gamma\chi$ links scales

Golden and Papanicolaou, Comm. Math. Phys. 1983

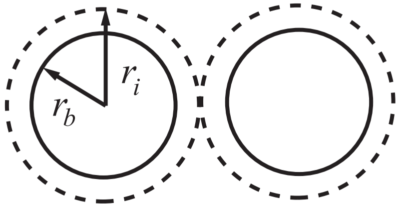
forward and inverse bounds on the complex permittivity of sea ice

forward bounds



4.75 GHz data

matrix particle (Bruno 91)



$$q = r_b / r_i$$

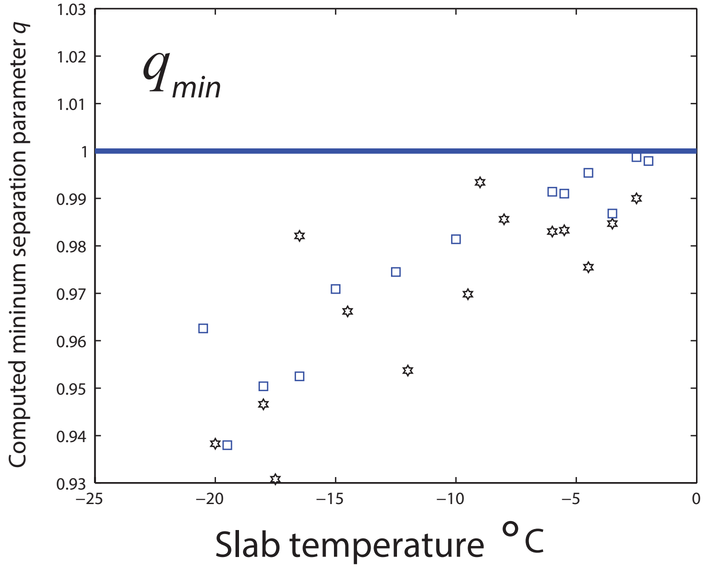
$$0 < q < 1$$

Golden JGR 95, IMA 97

inverse bounds and recovery of brine porosity

Cherkaev and Golden, Waves in Random Media 1998
Gully, Backstrom, Eicken, Golden Physica B, 2007

inverse bounds



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

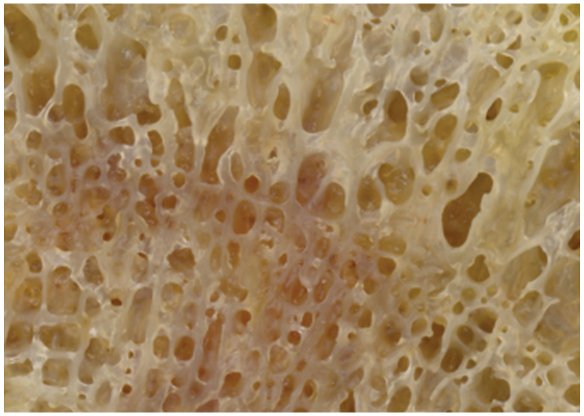
rigorous inverse bound on spectral gap

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

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

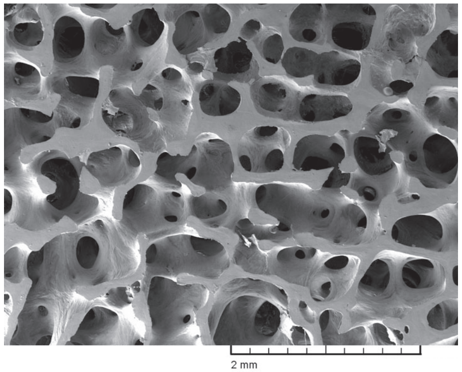
SEA ICE

HUMAN BONE

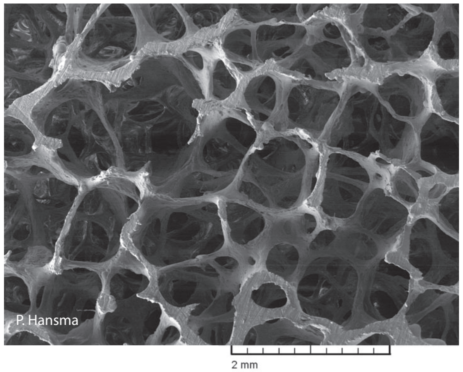


spectral characterization of porous microstructures in human bone

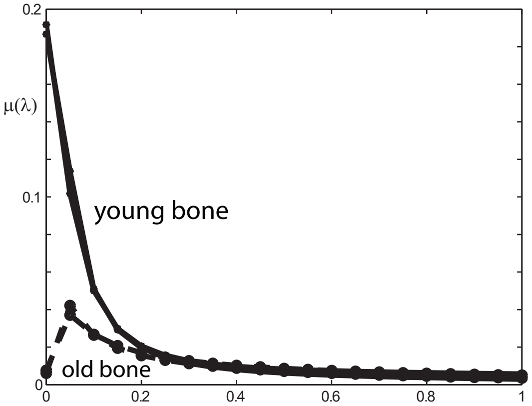
young healthy trabecular bone



old osteoporotic trabecular bone



reconstruct spectral measures from complex permittivity data



use regularized inversion scheme

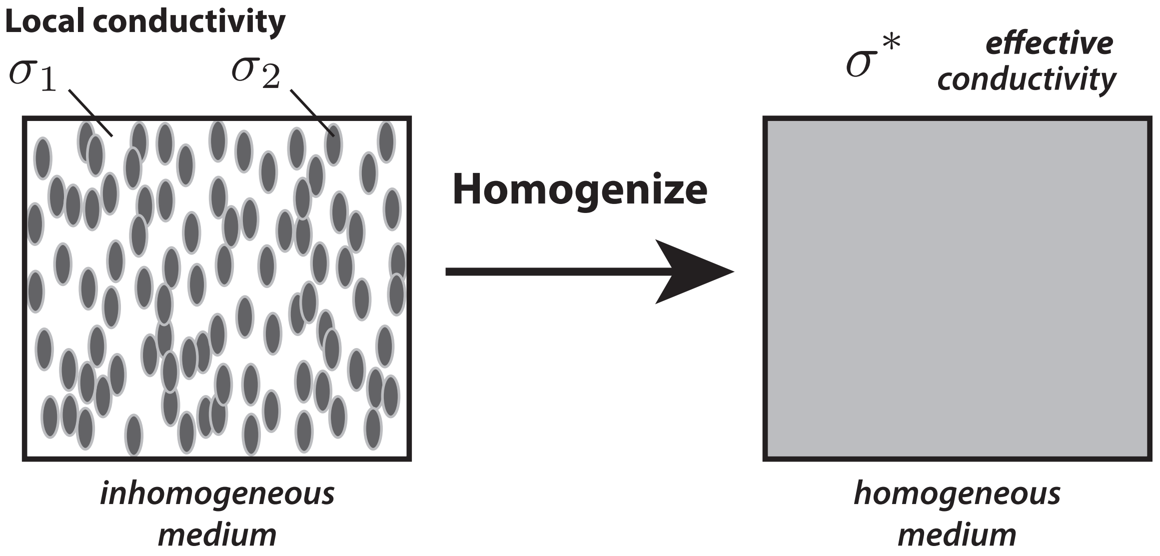
apply spectral measure analysis of brine connectivity and spectral inversion to electromagnetic monitoring of osteoporosis

Golden, Murphy, Cherkaev, J. Biomechanics 2011

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

Homogenization for composite materials

Two-component composites



Local conductivity

σ_1 σ_2

inhomogeneous medium

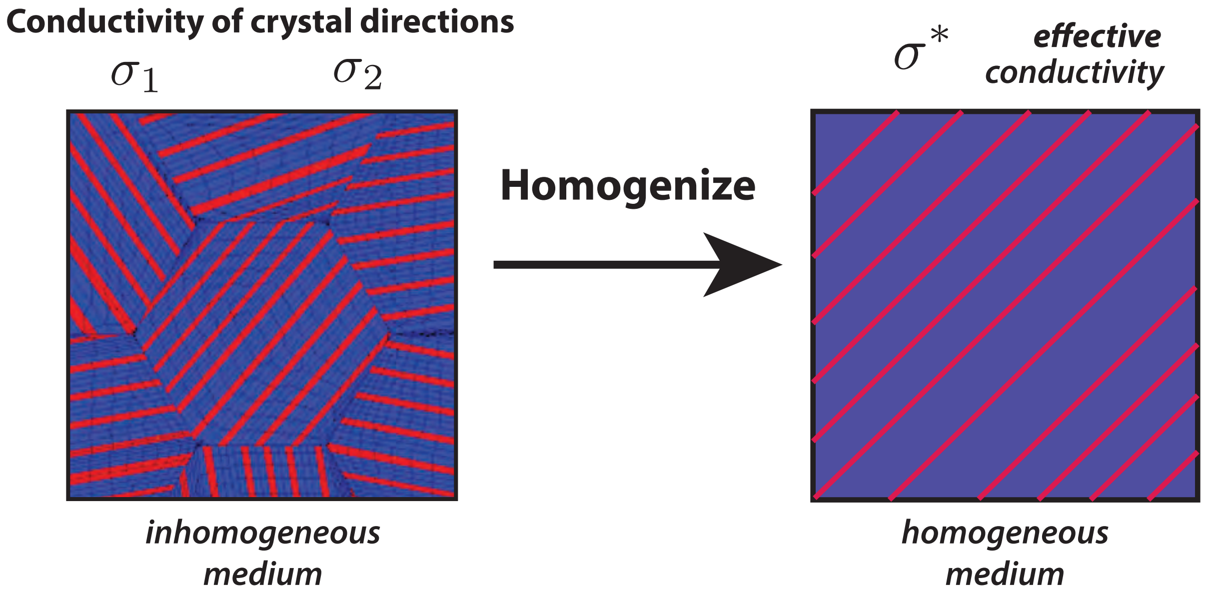
Homogenize

σ^* ***effective conductivity***

homogeneous medium

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

Polycrystalline media



Conductivity of crystal directions

σ_1 σ_2

inhomogeneous medium

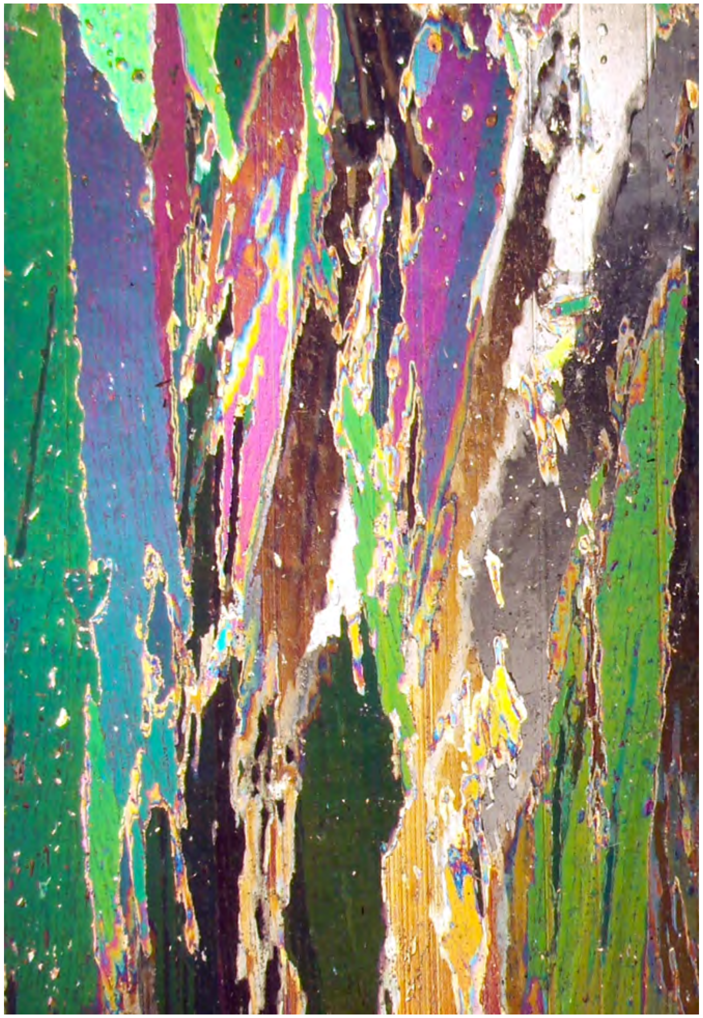
Homogenize

σ^* ***effective conductivity***

homogeneous medium

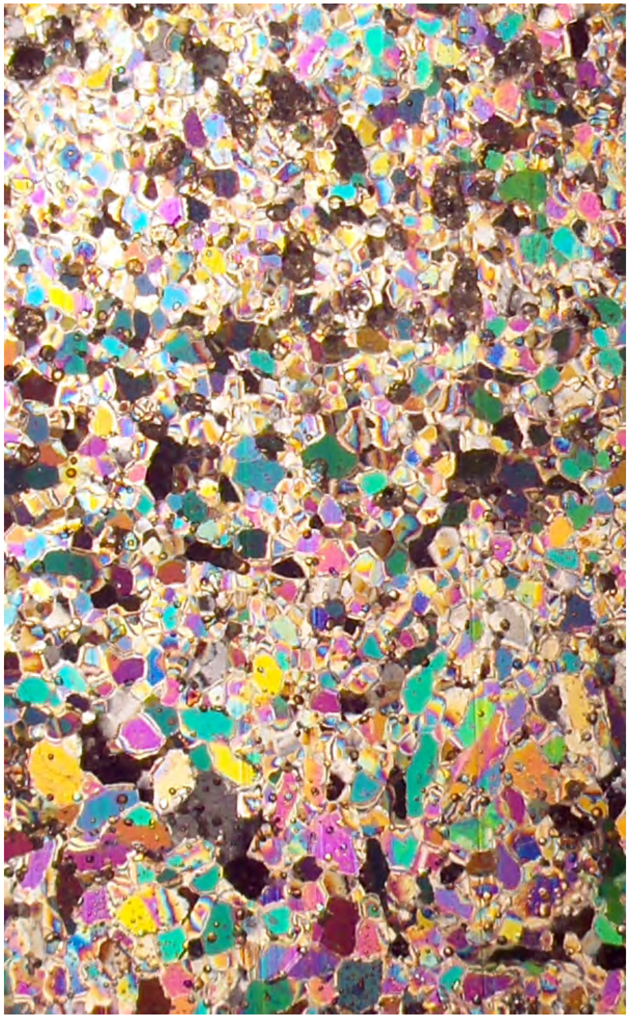
higher threshold for fluid flow in Antarctic granular sea ice

columnar



5%

granular



10%

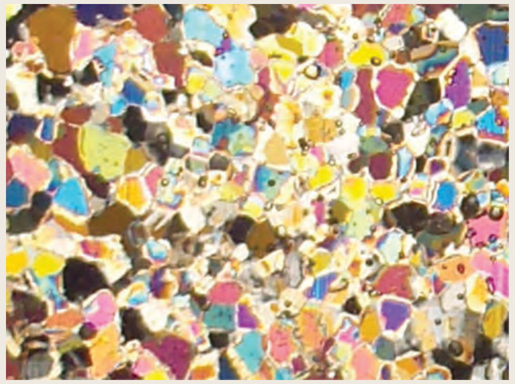
Golden, Sampson, Gully, Lubbers, Tison 2019

Bounds on the complex permittivity of polycrystalline materials by analytic continuation

Adam Gully, Joyce Lin,
Elena Cherkaev, Ken Golden

- **Stieltjes integral representation for effective complex permittivity**

  Milton (1981, 2002), Barabash and Stroud (1999), ...
- **Forward and inverse bounds**
- **Applied to sea ice using two-scale homogenization**
- **Inverse bounds give method for distinguishing ice types using remote sensing techniques**



Proc. Roy. Soc. A 8 Feb 2015

Proc. R. Soc. A | Volume 471 | Issue 2174 | 8 February 2015

ISSN 1364-5021 | Volume 471 | Issue 2174 | 8 February 2015

PROCEEDINGS A

350 YEARS
OF SCIENTIFIC
PUBLISHING

An invited review commemorating 350 years of scientific publishing at the Royal Society

A method to distinguish between different types of sea ice using remote sensing techniques

A computer model to determine how a human should walk so as to expend the least energy

THE
ROYAL
SOCIETY
PUBLISHING

21/01/15 1:47 PM

Rigorous bounds on the complex permittivity tensor of sea ice with polycrystalline anisotropy within the horizontal plane

McKenzie McLean, Elena Cherkaev, Ken Golden 2019

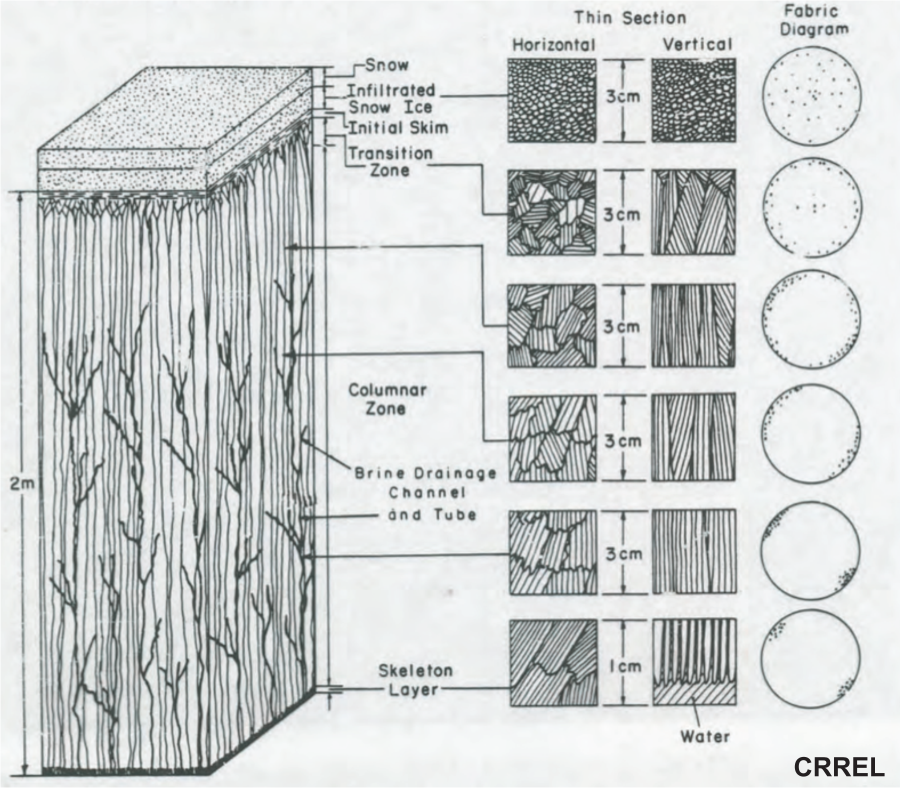
motivated by

Weeks and Gow, 1979: c-axis alignment in Arctic fast ice off Barrow

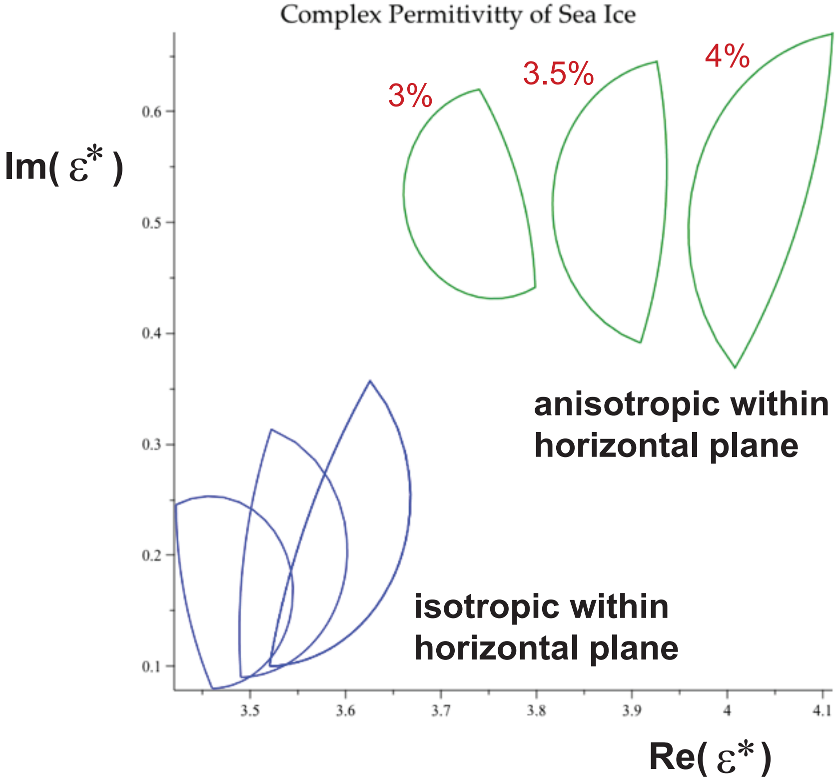
Golden and Ackley, 1981: radar propagation model in aligned sea ice

input: orientation statistics

output: bounds



CRREL

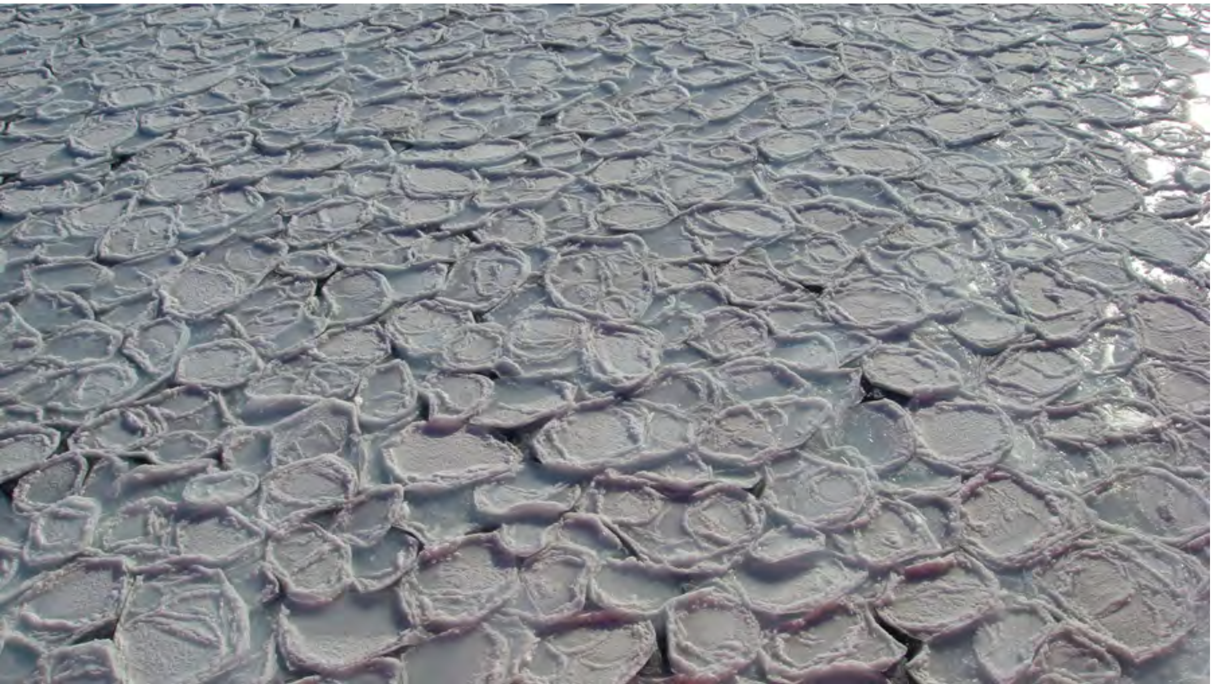


sea ice floe structure

sea ice formation

pancake ice forming in a wave field in the Southern Ocean

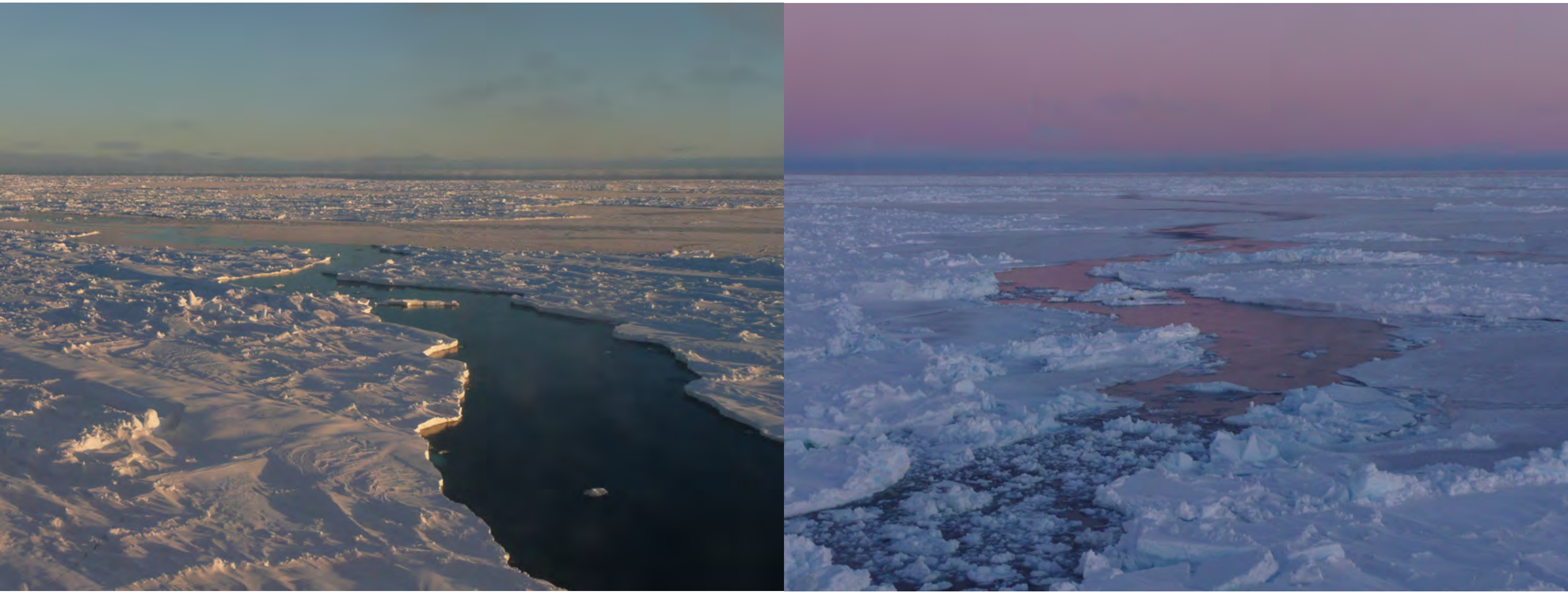
pancake ice



sea ice dynamics

plate tectonics on a fast time scale

leads

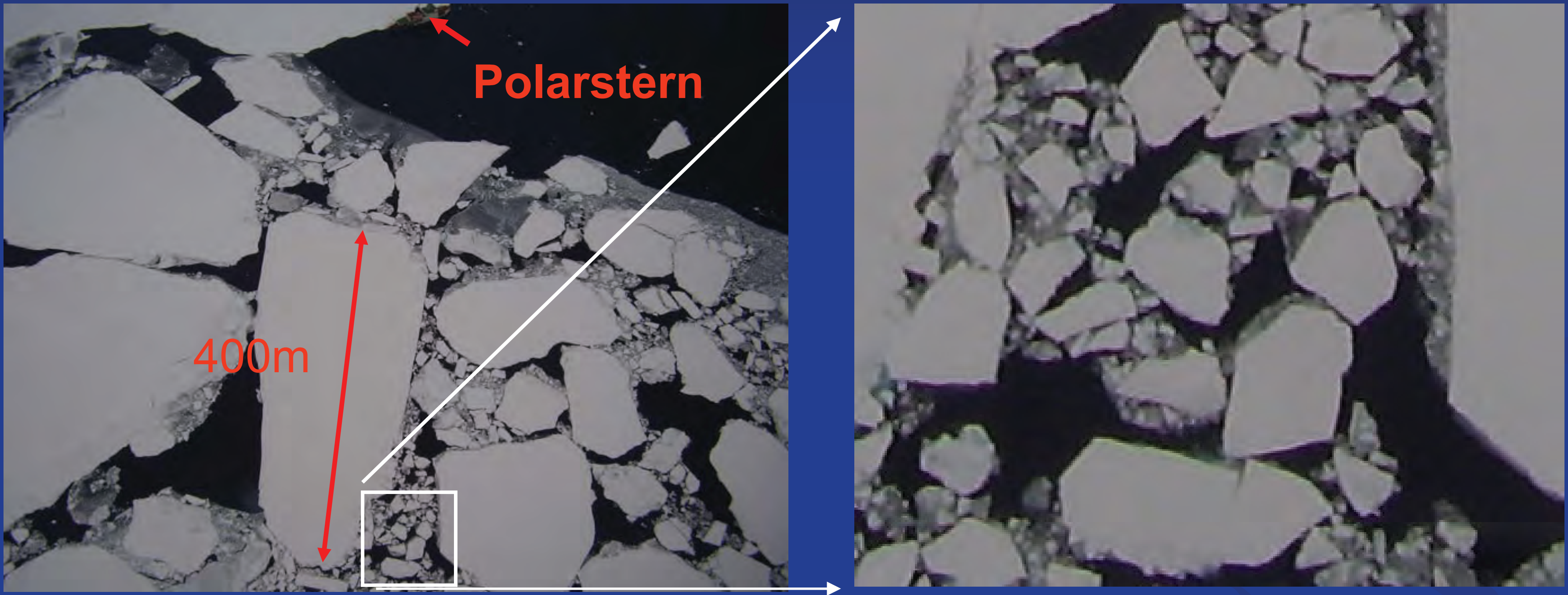


heat flows directly from ocean to atmosphere

The sea ice pack has fractal structure.

Self-similarity of sea ice floes

Weddell Sea, Antarctica

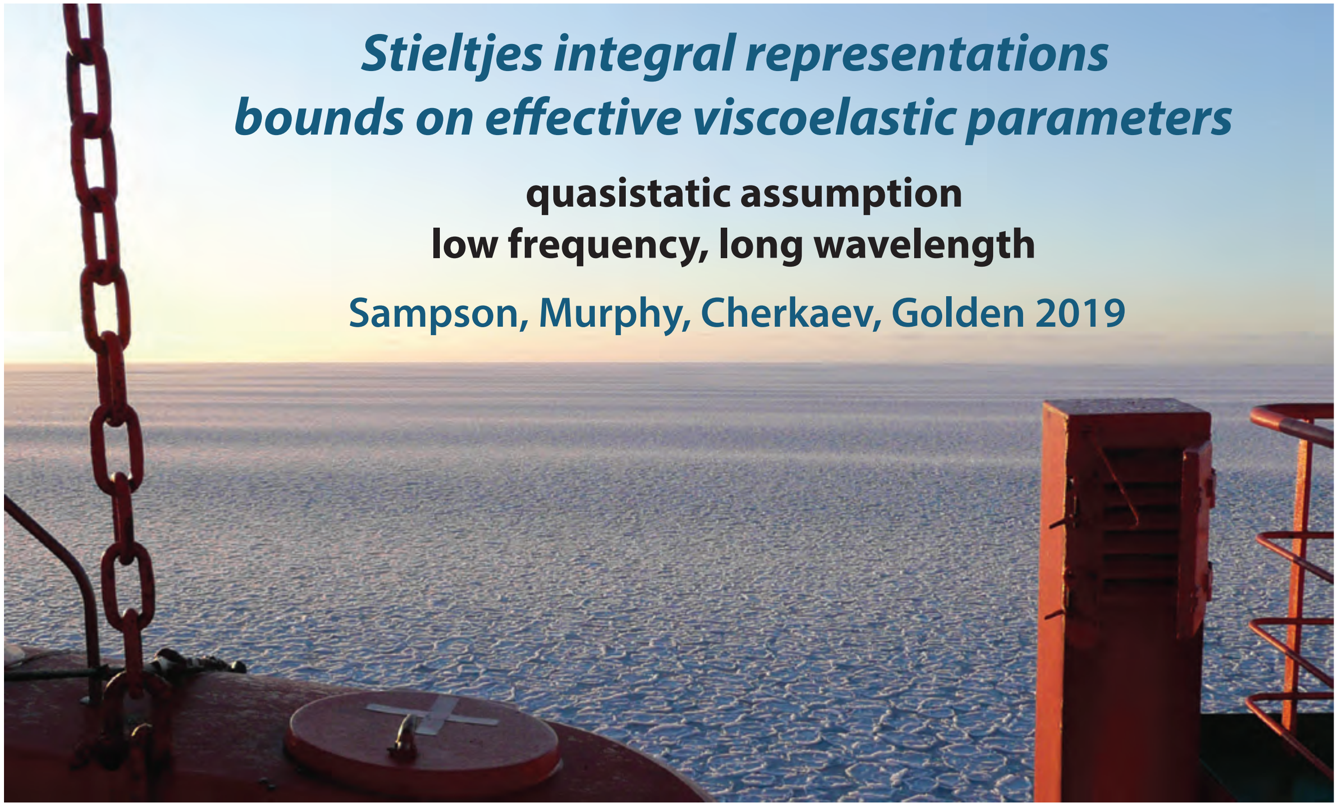


fractal dimensions of Okhotsk Sea ice pack
smaller scales D~1.2, larger scales D~1.9

Toyota, *et al. Geophys. Res. Lett.* 2006

Rothrock and Thorndike, *J. Geophys. Res. 1984*

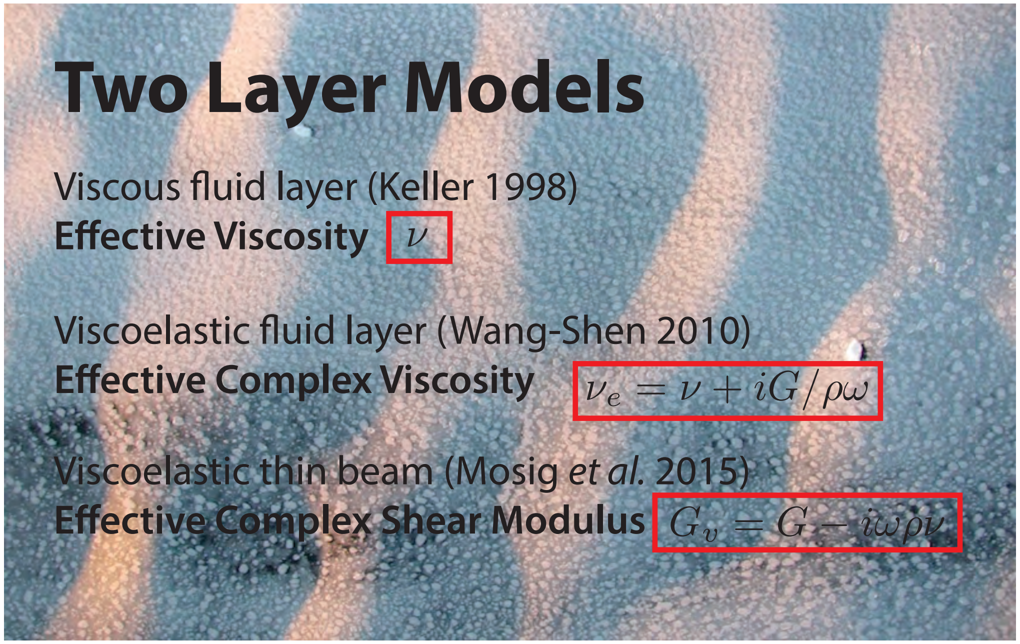
wave propagation in the marginal ice zone



Stieltjes integral representations
bounds on effective viscoelastic parameters

quasistatic assumption
low frequency, long wavelength

Sampson, Murphy, Cherkaev, Golden 2019



Two Layer Models

Viscous fluid layer (Keller 1998)
Effective Viscosity $\boxed{\nu}$

Viscoelastic fluid layer (Wang-Shen 2010)
Effective Complex Viscosity $\boxed{\nu_e = \nu + iG/\rho\omega}$

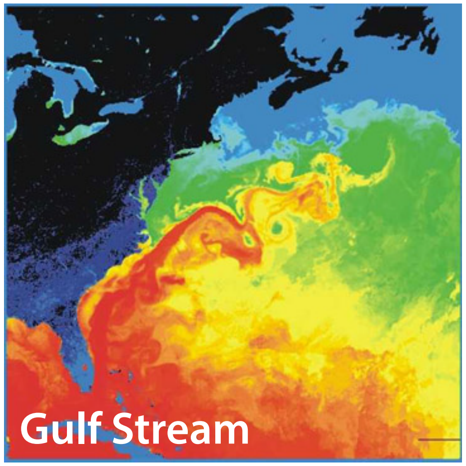
Viscoelastic thin beam (Mosig *et al.* 2015)
Effective Complex Shear Modulus $\boxed{G_v = G - i\omega\rho\nu}$

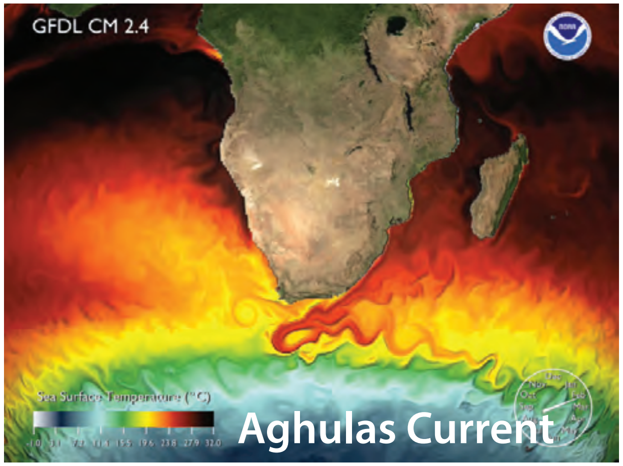
NASA Ice Bridge Movie

advection enhanced diffusion

effective diffusivity

sea ice floes diffusing in ocean currents
diffusion of pollutants in atmosphere
salt and heat transport in ocean
heat transport in sea ice with convection





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

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

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

$$\Big\downarrow \quad \textit{homogenize}$$

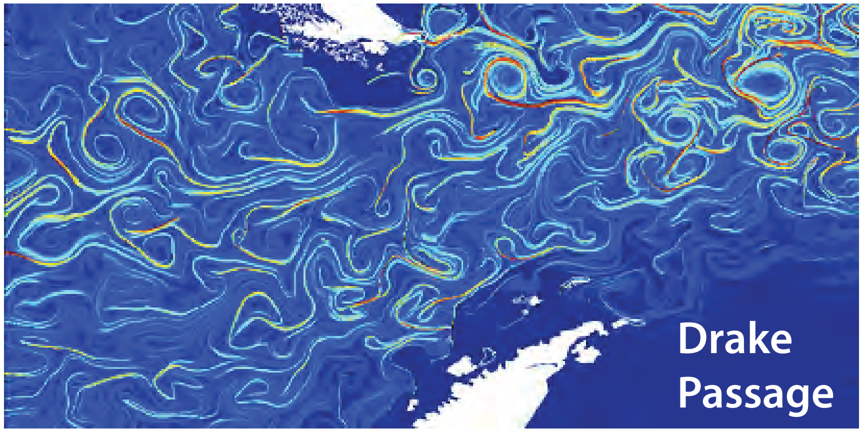
$$\frac{\partial \overline{T}}{\partial t} = \kappa^* \Delta \overline{T}$$

κ^* *effective diffusivity*

Stieltjes integral for κ^* with spectral measure

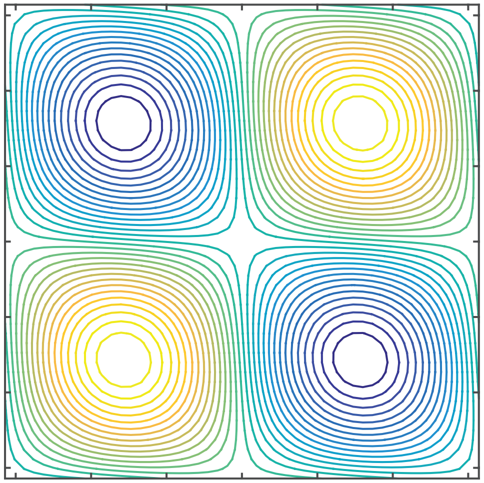
Avellaneda and Majda, PRL 89, CMP 91

Murphy, Cherkaev, Xin, Zhu, Golden, *Ann. Math. Sci. Appl.* 2017
Murphy, Cherkaev, Zhu, Xin, Golden, *J. Math Phys.* 2019

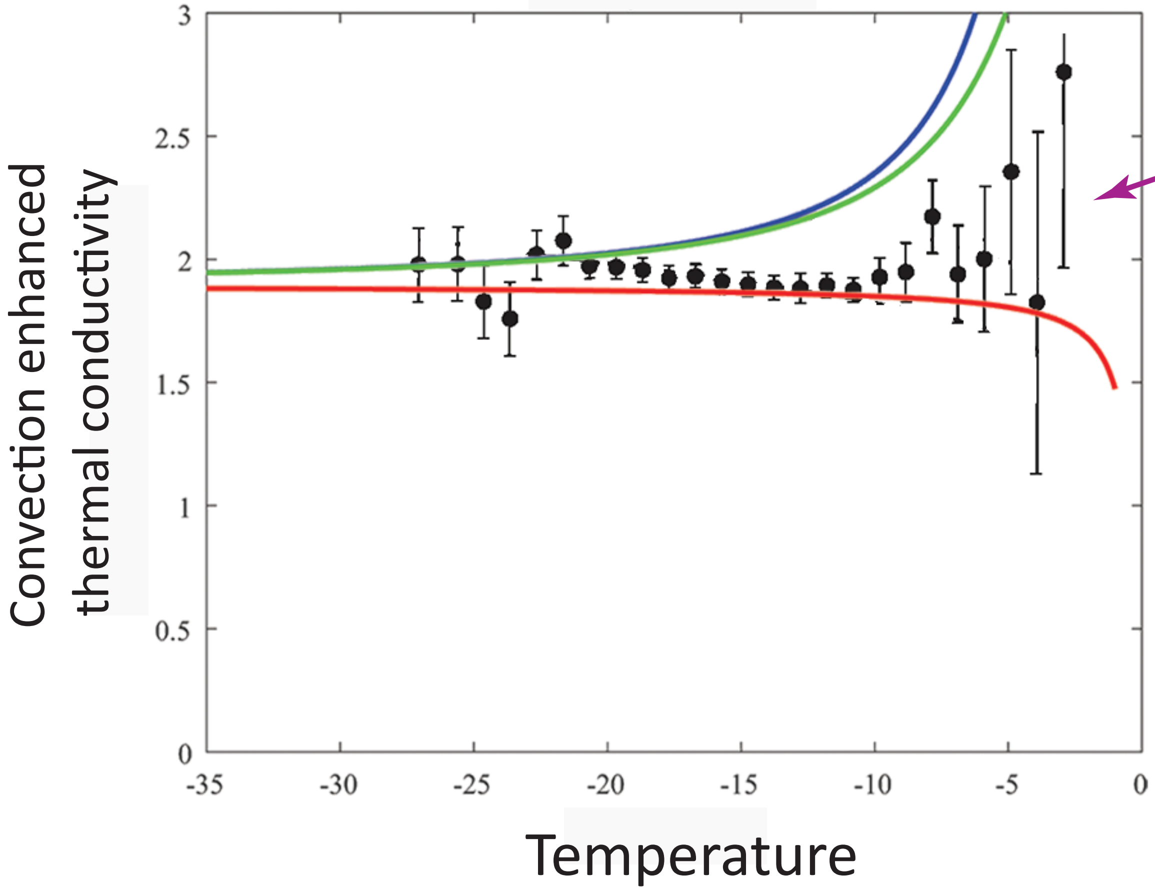


Rigorous bounds on convection enhanced thermal conductivity of sea ice

Kraitzman, Hardenbrook, Dinh, Murphy, Zhu, Cherkaev, Golden 2019



cat’s eye flow model for
brine convection cells



data
Trodahl
et al. 2001

rigorous Padé bounds from Stieltjes integral +
analytical calculations of moments of measure

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***
2014	***Arctic***	***Chukchi Sea***

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of the American Mathematical Society

May 2009

Volume 56, Number 5

Climate Change and the Mathematics of Transport in Sea Ice

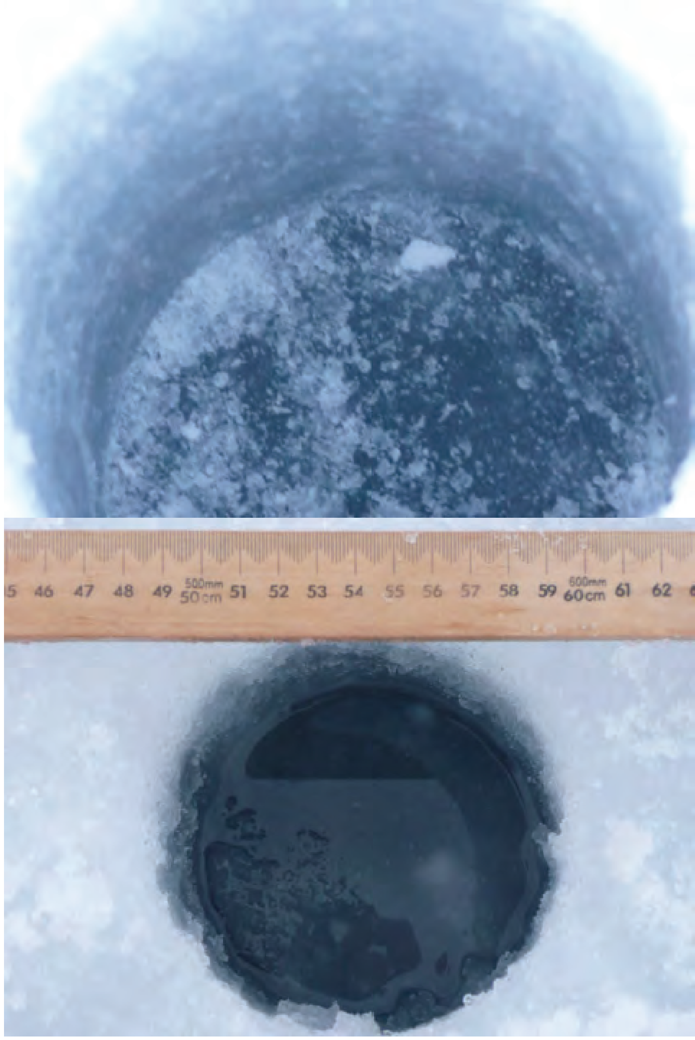
page 562

Mathematics and the Internet: A Source of Enormous Confusion and Great Potential

page 586

Real analysis in polar coordinates (see page 613)

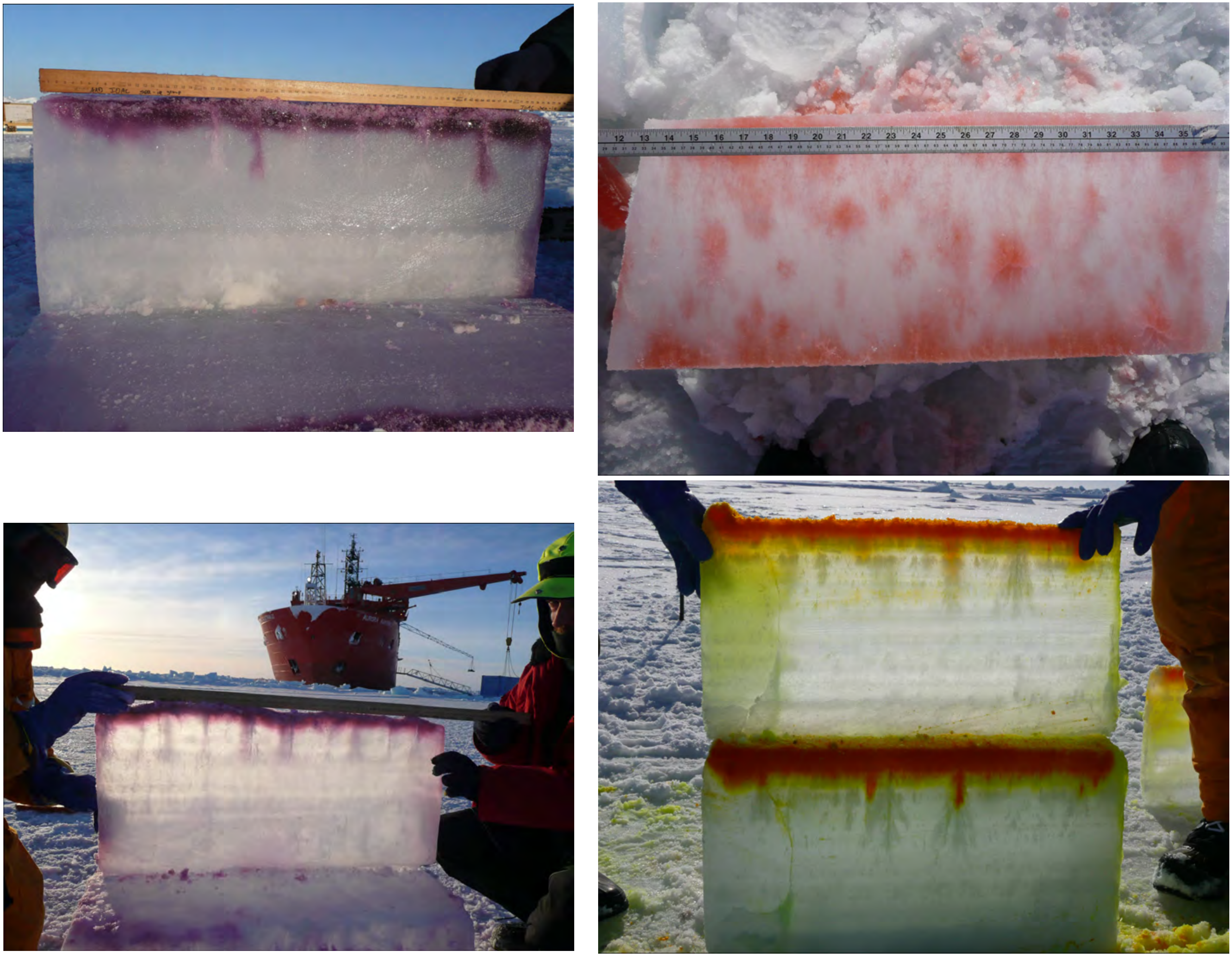
photo by Jan Lieser



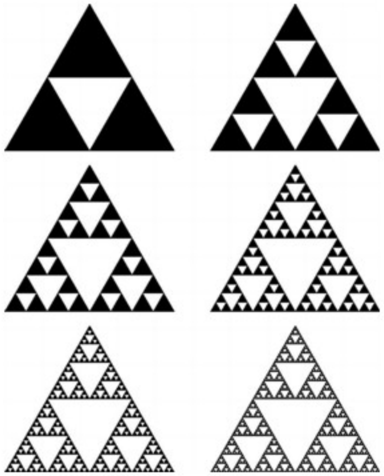
measuring fluid permeability of Antarctic sea ice

SIPEX 2007

tracers flowing through inverted sea ice blocks



fractals and multiscale structure



melt pond formation and albedo evolution:

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

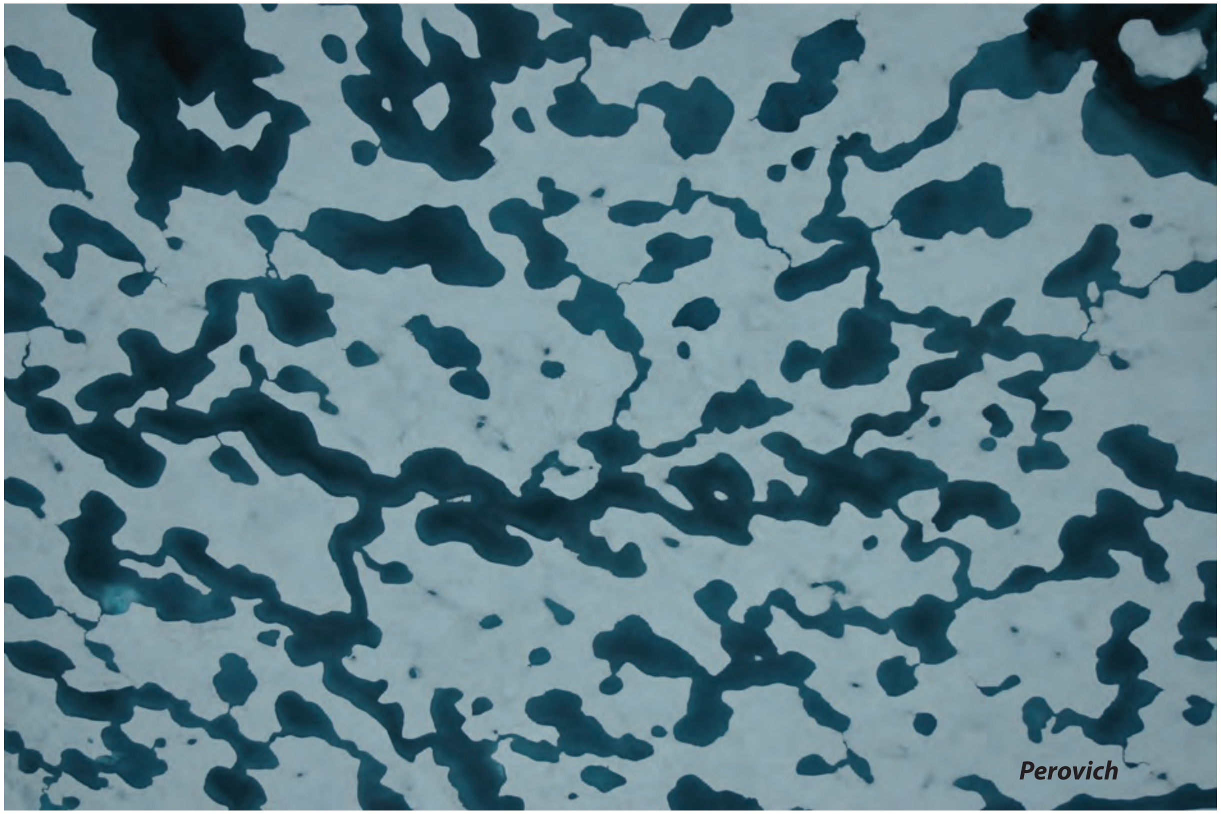
numerical models of melt pond evolution, including topography, drainage (permeability), etc.

Lüthje, Feltham, Taylor, Worster 2006

Flocco, Feltham 2007

Skyllingstad, Paulson, Perovich 2009

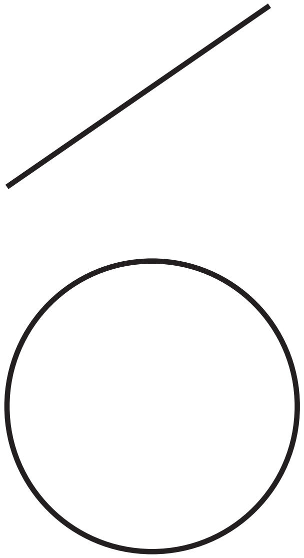
Flocco, Feltham, Hunke 2012


Perovich

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

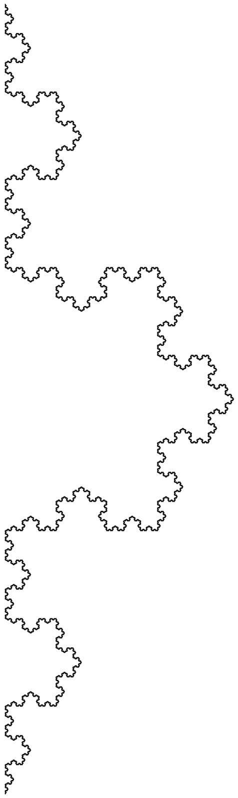
fractal curves in the plane

they wiggle so much that their dimension is >1



simple curves

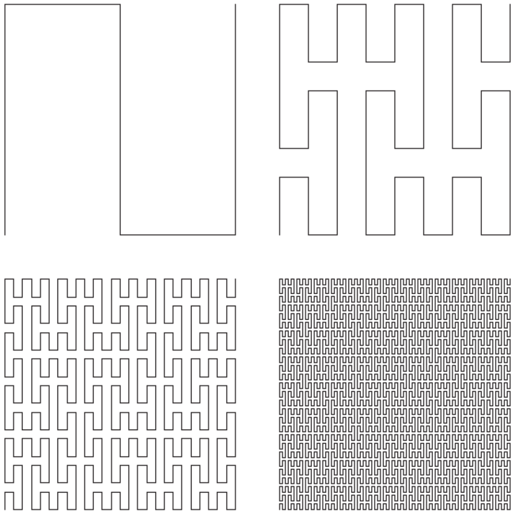
$D = 1$

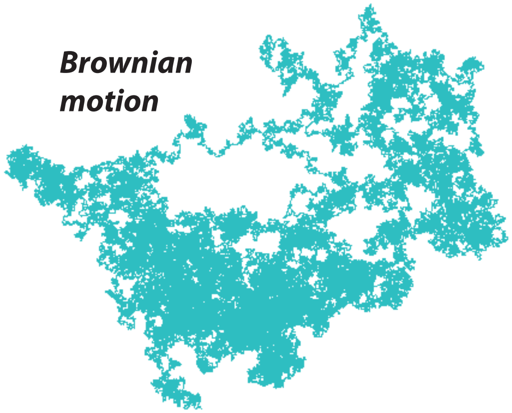


Koch snowflake

$D = 1.26$

Peano curve





Brownian motion

space filling curves

$D = 2$

30th Congressional District, Texas, 1991-1996

clouds exhibit fractal behavior from 1 to 1000 km

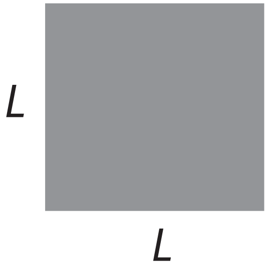
use ***perimeter-area*** data to find that cloud and rain boundaries are fractals

$$D \approx 1.35$$

S. Lovejoy, Science, 1982

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

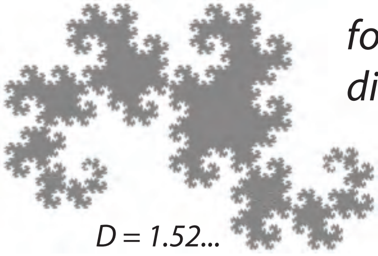
simple shapes



$A = L^2$

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

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



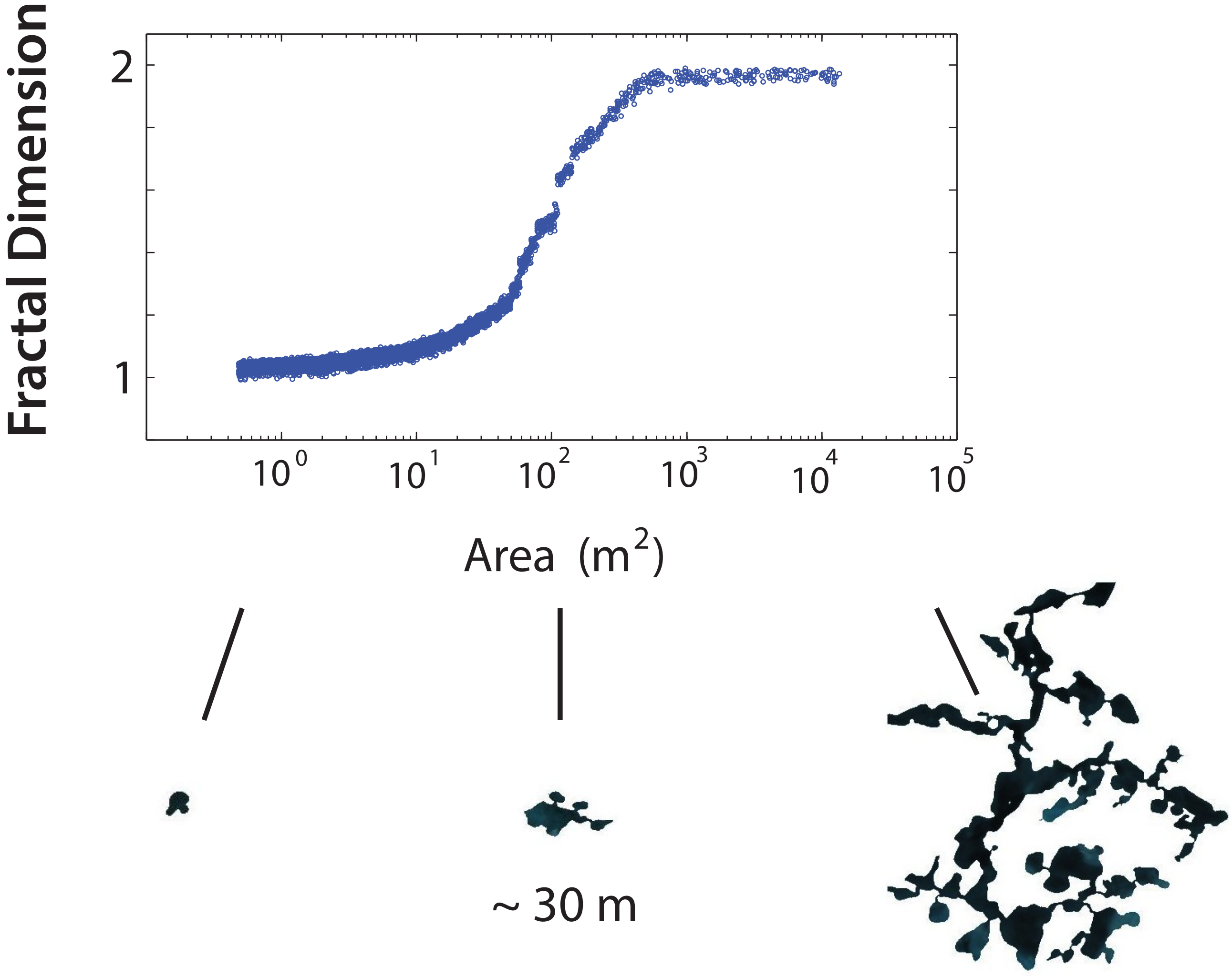
for fractals with dimension D

Transition in the fractal geometry of Arctic melt ponds

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

The Cryosphere, 2012

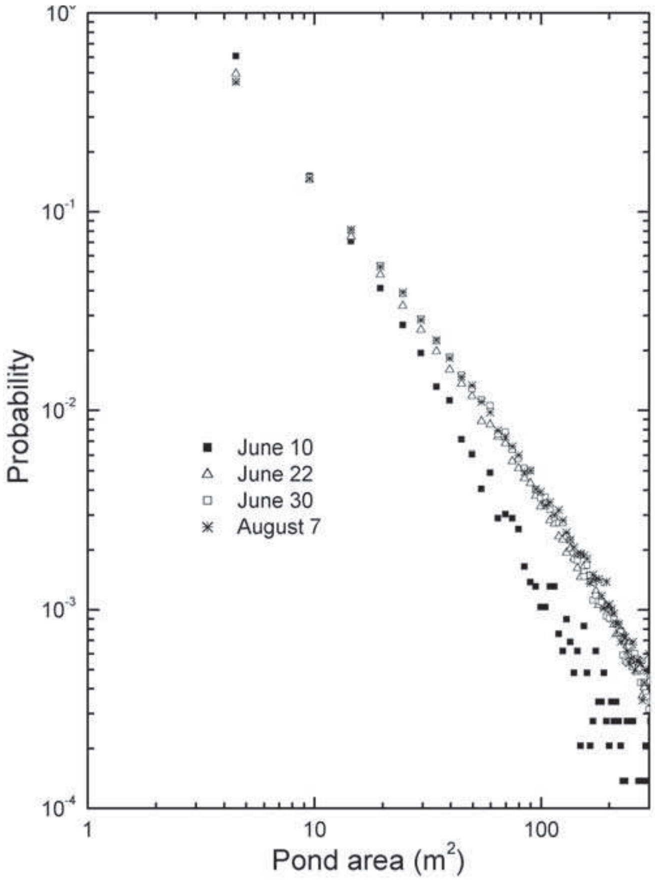
complexity grows with length scale



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

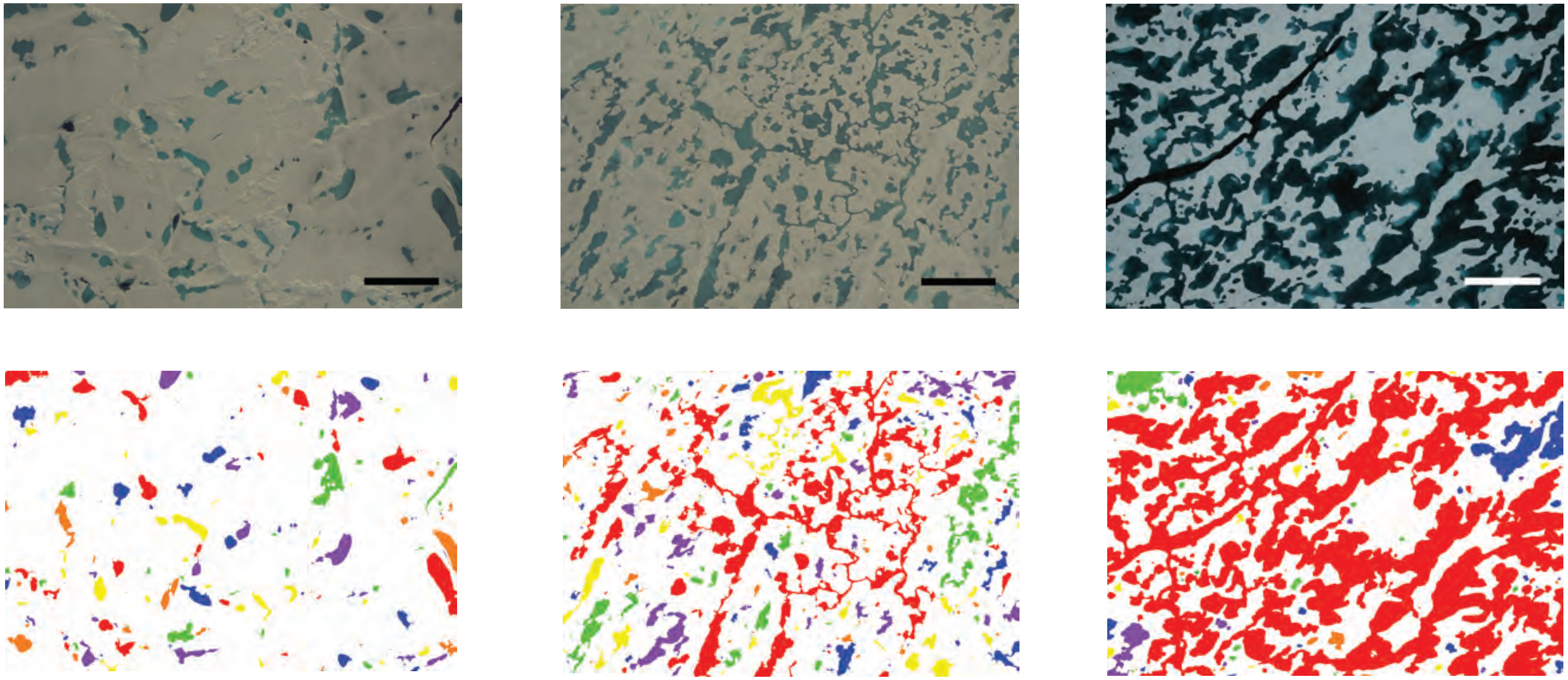
Power law scaling of pond size distribution

Image analysis reveals that the probability distribution of the pond area exhibits power law scaling with exponent about -3/2.



[Perovich, Tucker & Ligett, JGR, 2002]

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



melt pond percolation

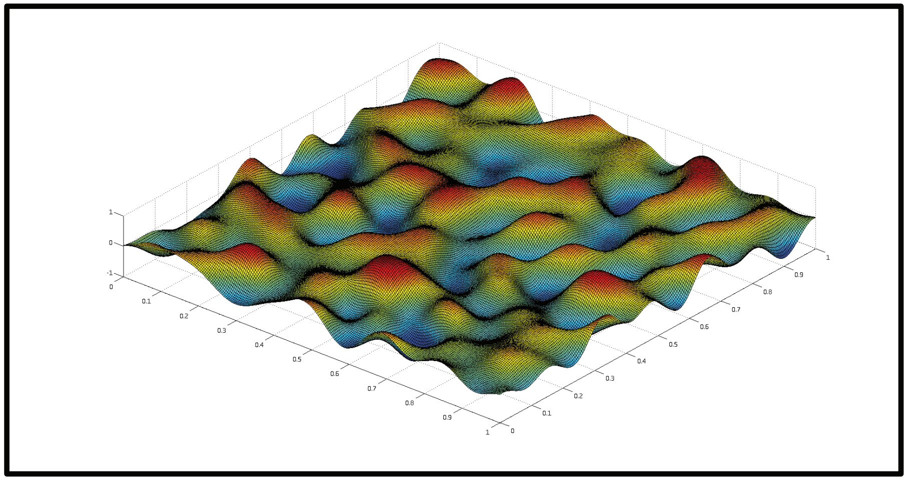
results on percolation threshold, correlation length, cluster behavior

Anthony Cheng (Hillcrest HS), Dylan Webb (Skyline HS), Court Strong, Ken Golden

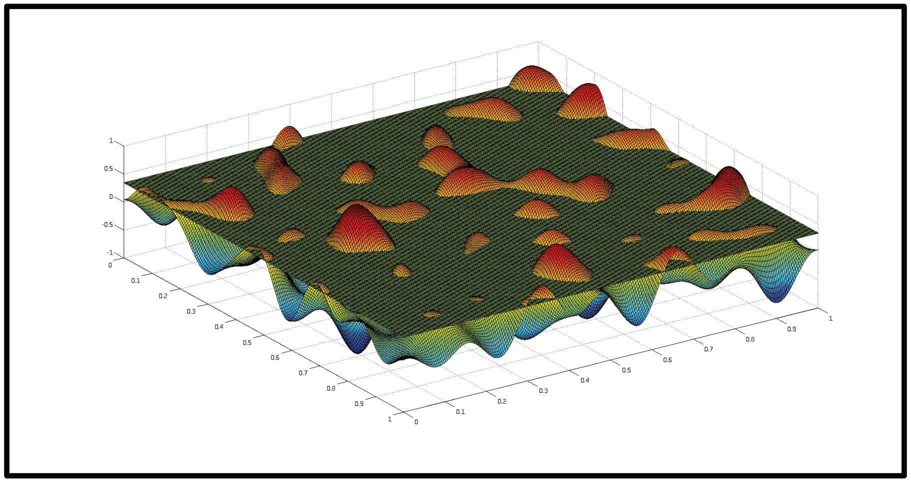
Continuum percolation model for melt pond evolution

level sets of random surfaces

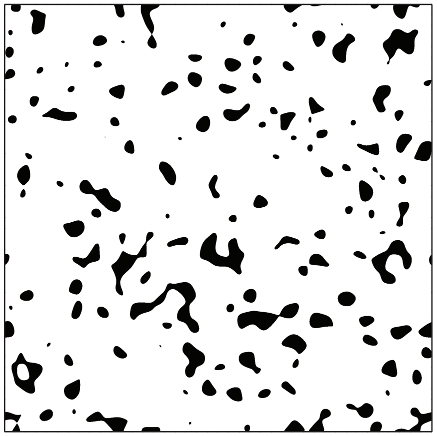
Brady Bowen, Court Strong, Ken Golden, J. Fractal Geometry 2018

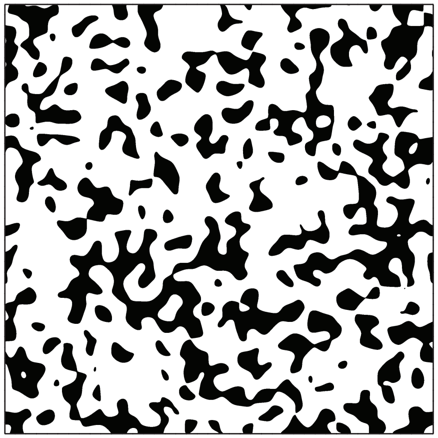


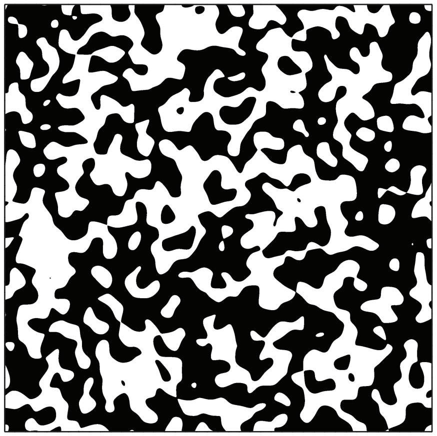
random Fourier series representation of surface topography



intersections of a plane with the surface define melt ponds

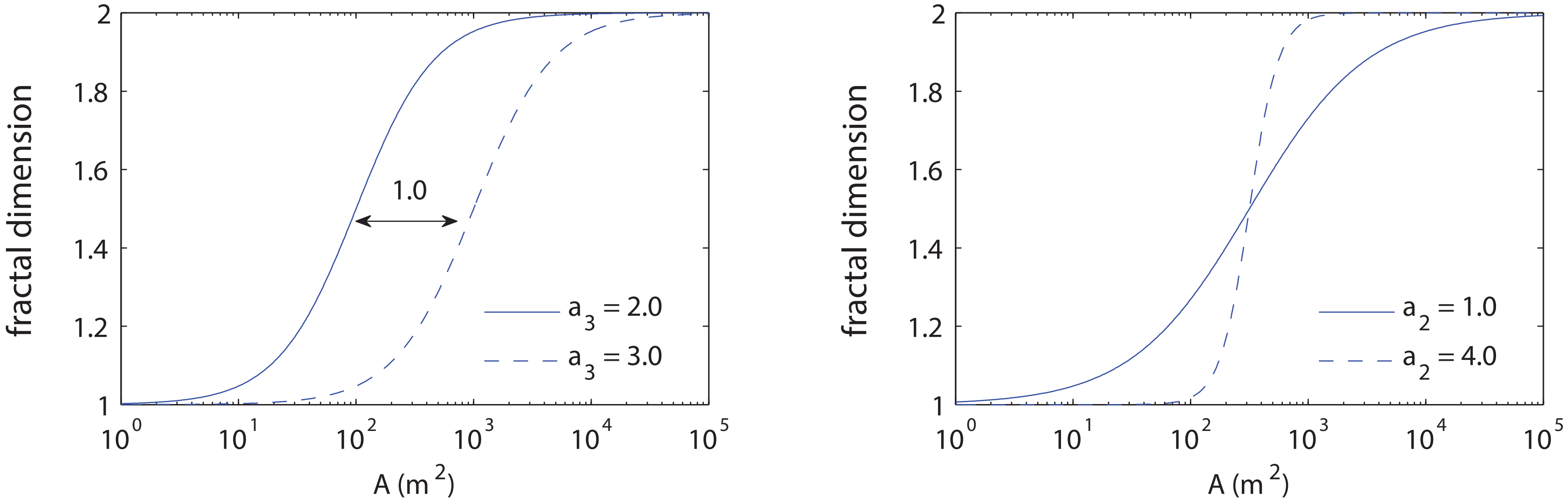




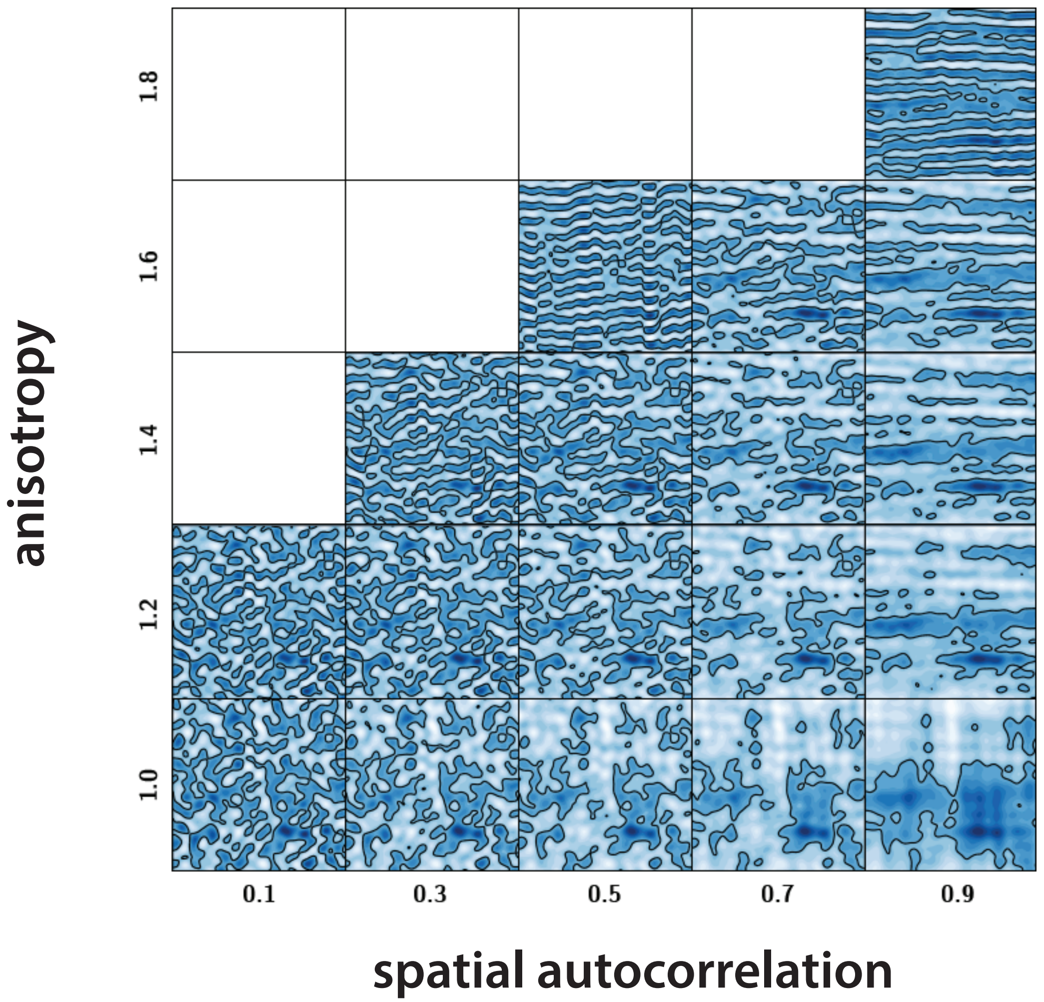


electronic transport in disordered media   *diffusion in turbulent plasmas*   *Isichenko, Rev. Mod. Phys., 1992*

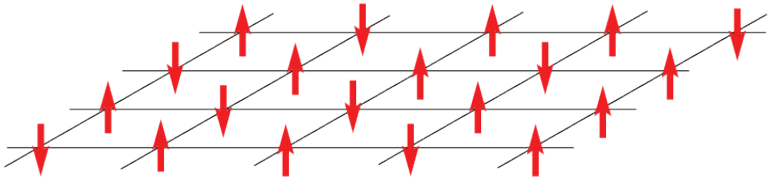
fractal dimension curves depend on statistical parameters defining random surface



Coefficients of Fourier surface chosen to produce topography with given autocorrelation and anisotropy



Ising Model for a Ferromagnet



$$s_i = \begin{cases} +1 & \text{spin up} \\ -1 & \text{spin down} \end{cases}$$

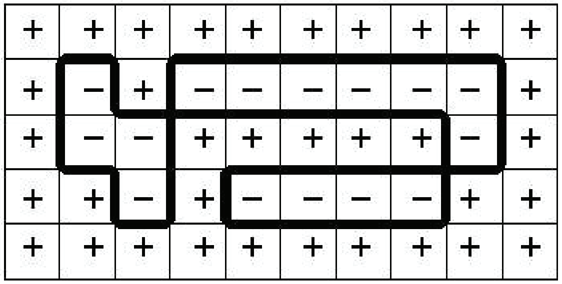
applied magnetic field

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

nearest neighbor Ising Hamiltonian

for any configuration $\omega \in \Omega = \{-1, 1\}^N$ of the spins

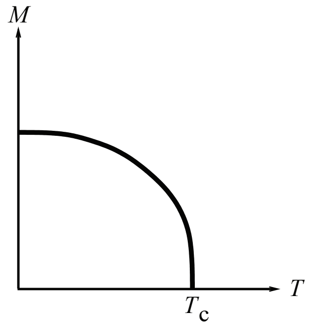
ferromagnetic interaction $J \geq 0$



+	+	+	+	+	+	+	+	+	+
+	−	+	−	−	−	−	−	−	+
+	−	−	+	+	+	+	+	−	+
+	+	−	+	−	−	−	−	+	+
+	+	+	+	+	+	+	+	+	+

magnetization

$$M(T,H) = \lim_{N\to\infty} \frac{1}{N} \left\langle \sum_j s_j \right\rangle = -\frac{\partial f}{\partial H}$$

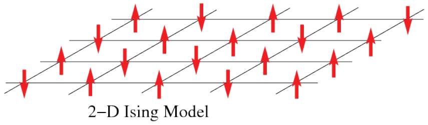


Curie point
critical temperature

homogenized parameter
like effective conductivity

Ising model for ferromagnets ⟶ Ising model for melt ponds

Ma, Sudakov, Strong, Golden 2019


2–D Ising Model

$$\mathcal{H}_\omega = -J \sum_{<i,j>}^{N} s_i s_j - \sum_{i}^{N} H_i \, s_i \qquad s_i = \left\{ \begin{array}{llll} \uparrow & +1 & \text{water} & \text{(spin up)} \\ \downarrow & -1 & \text{ice} & \text{(spin down)} \end{array} \right.$$

random magnetic field represents snow topography

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

pond coverage $\frac{(M+1)}{2}$

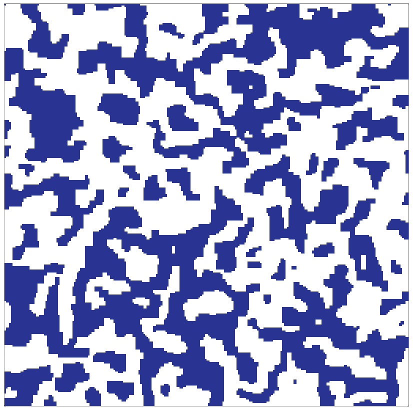
~ albedo

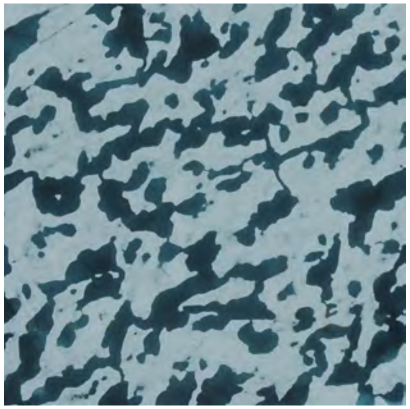
only nearest neighbor patches interact

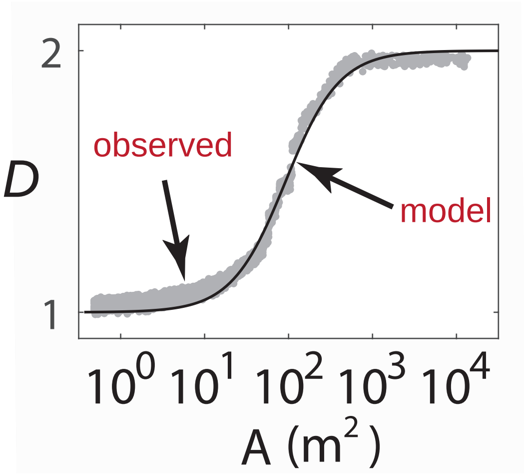
Starting with random initial configurations, as Hamiltonian energy is minimized by Glauber spin flip dynamics, system "flows" toward metastable equilibria.

Melt ponds are metastable islands of like spins.

Order from Disorder


Ising model


melt pond photo **(Perovich)**



pond size distribution exponent

observed	-1.5
	(Perovich, *et al.* 2002)
model	-1.58

ONLY MEASURED INPUT = LENGTH SCALE (GRID SIZE) from snow topography data

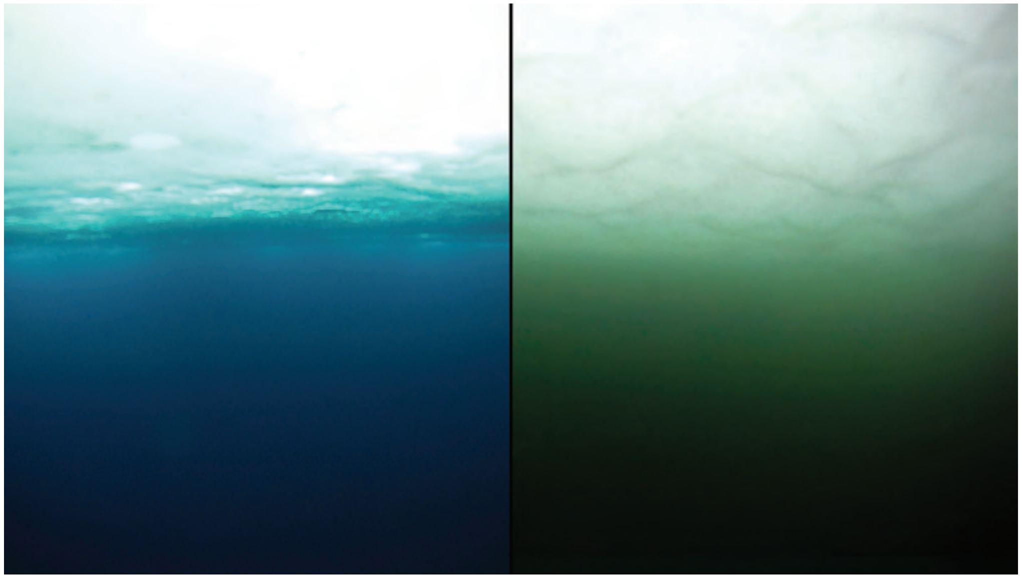
2011 massive under-ice algal bloom

Arrigo et al., *Science* 2012

melt ponds act as

WINDOWS

allowing light through sea ice



no bloom

bloom

Have we crossed into a new ecological regime?

The frequency and extent of sub-ice phytoplankton blooms in the Arctic Ocean

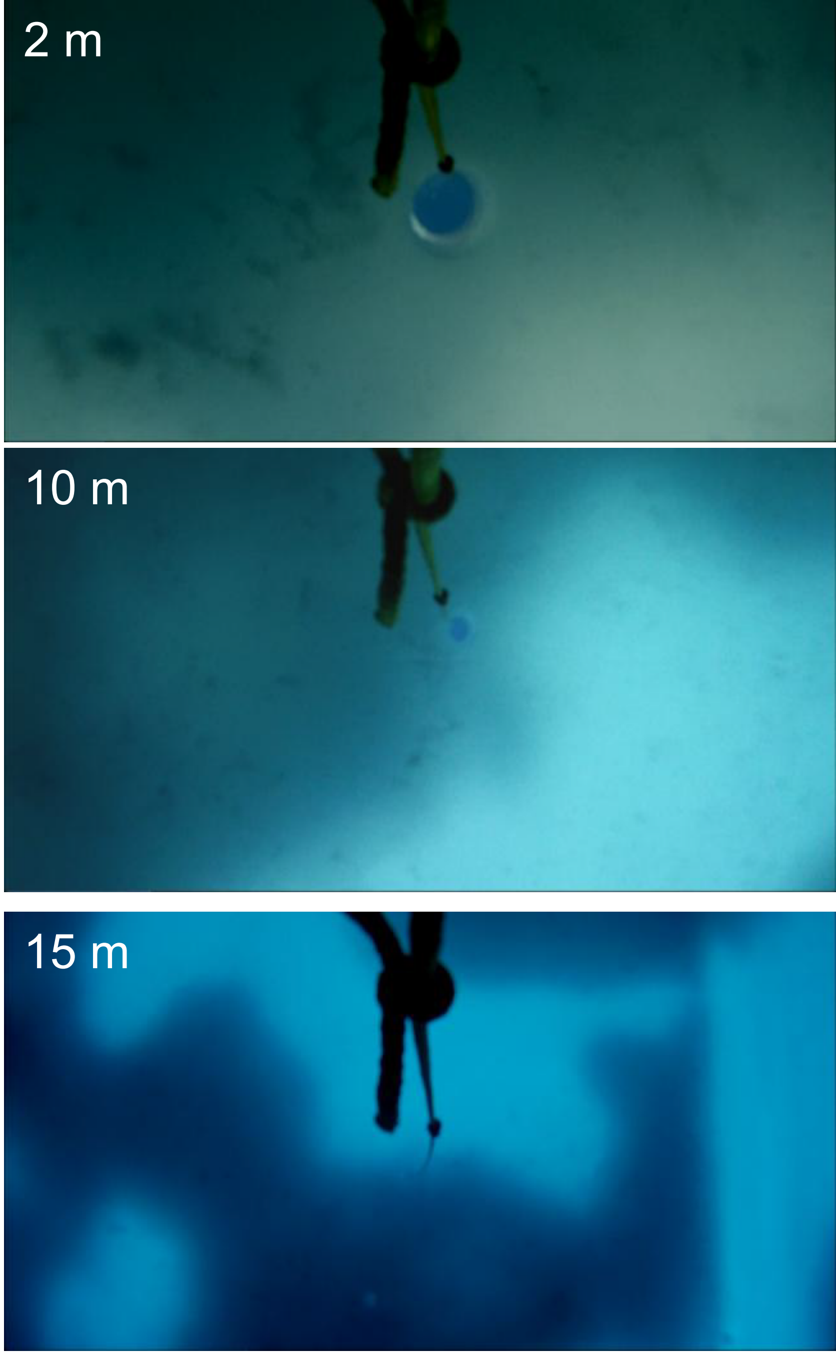
Horvat, Rees Jones, Iams, Schroeder, Flocco, Feltham, ***Science Advances***, 2017

The distribution of solar energy under ponded sea ice

Horvat, Flocco, Rees Jones, Roach, Golden, 2019

(2015 AMS MRC)

the view from underneath →



melt ponds are WINDOWS

light reaches the upper ocean

Perovich

The Melt Pond Conundrum:

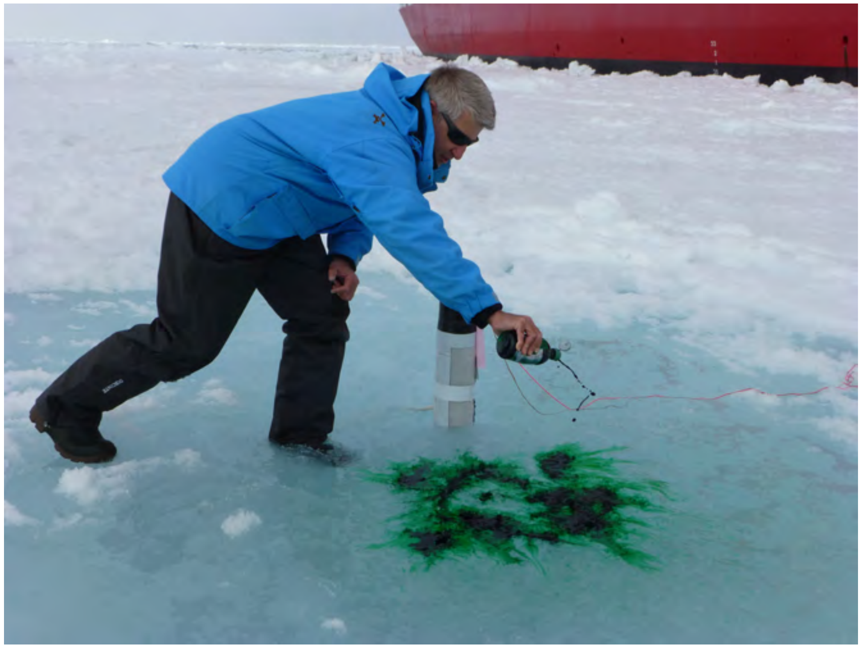
How can ponds form on top of sea ice that is highly permeable?

C. Polashenski, K. M. Golden, D. K. Perovich, E. Skyllingstad, A. Arnsten, C. Stwertka, N. Wright

Percolation Blockage: A Process that Enables Melt Pond Formation on First Year Arctic Sea Ice

J. Geophys. Res. Oceans 2017

2014 Study of Under Ice Blooms in the Chuckchi Ecosystem (SUBICE)
aboard USCGC Healy



Conclusions

1. **Sea ice forms complex patterns over a wide range of scales.**

2. Homogenization and statistical physics help link information on microstructural patterns to larger scale effective behavior; advancing how sea ice is represented in climate models.

3. ***Stieltjes integral representations*** provide powerful methods for homogenization of sea ice structures and processes.

4. Melt ponds display fascinating fractal behavior; statistical physics models (percolation, Ising) account for observations.

5. This work is helping to improve projections of the fate of Earth’s sea ice packs and the ecosystems they support.

THANK YOU

Office of Naval Research

Arctic and Global Prediction Program

Applied and Computational Analysis Program

National Science Foundation

Division of Mathematical Sciences

Division of Polar Programs

United States Coast Guard

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

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.

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.

A file photo of the Aurora Australis in Antarctica.

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 ....”