# MODELING SEA ICE *in a changing climate*

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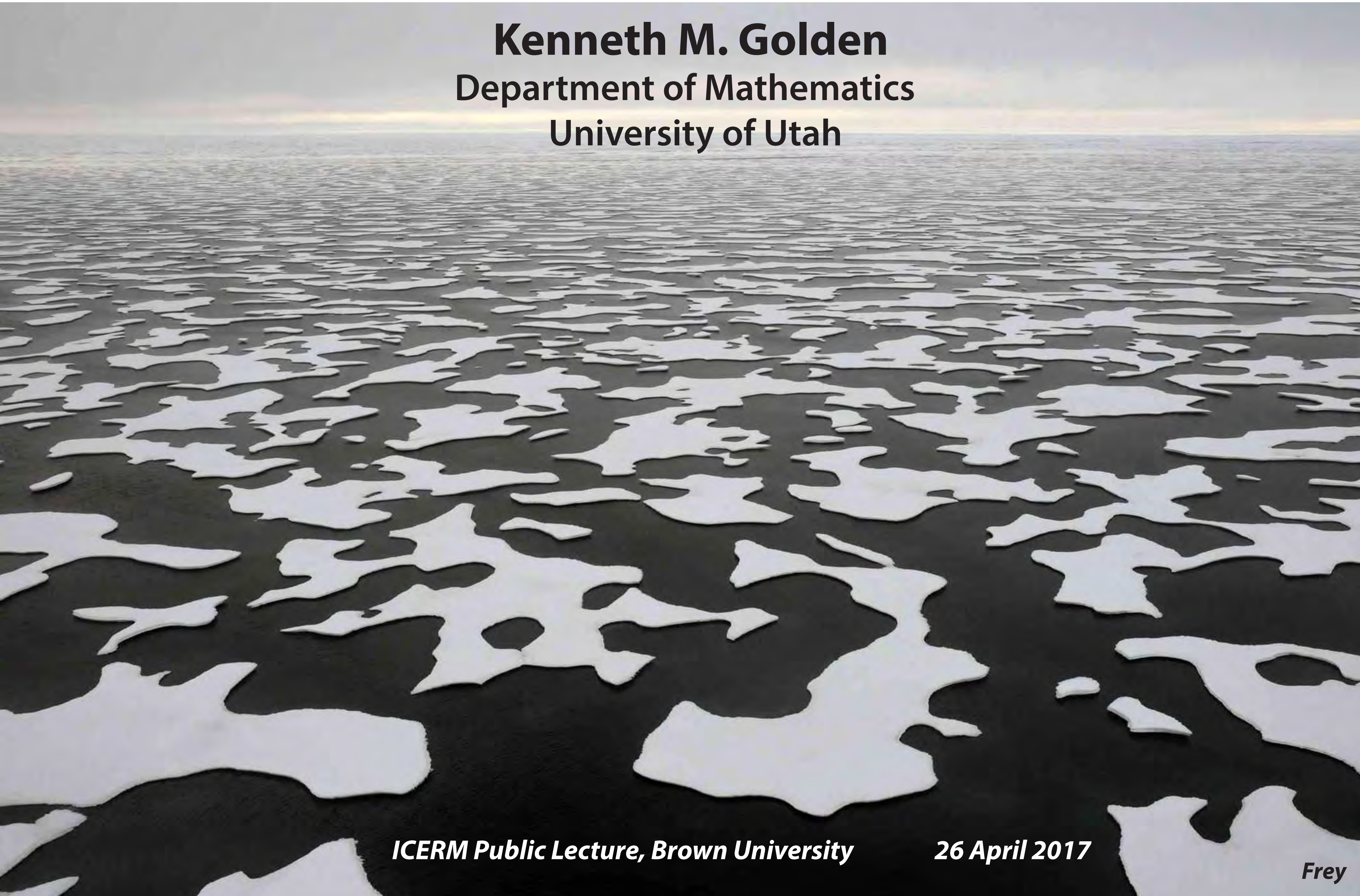
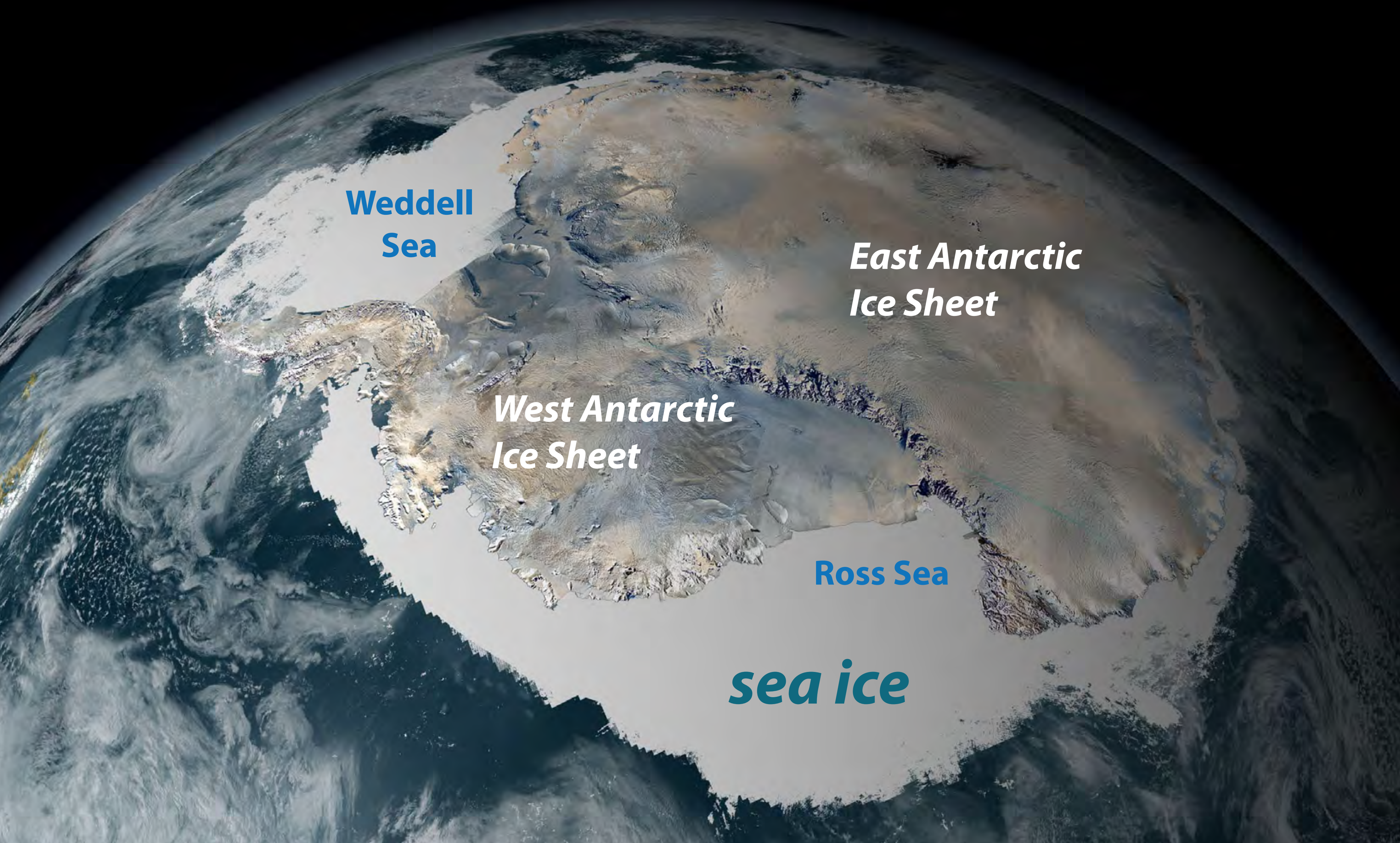


***ICERM Public Lecture, Brown University*** ***26 April 2017***

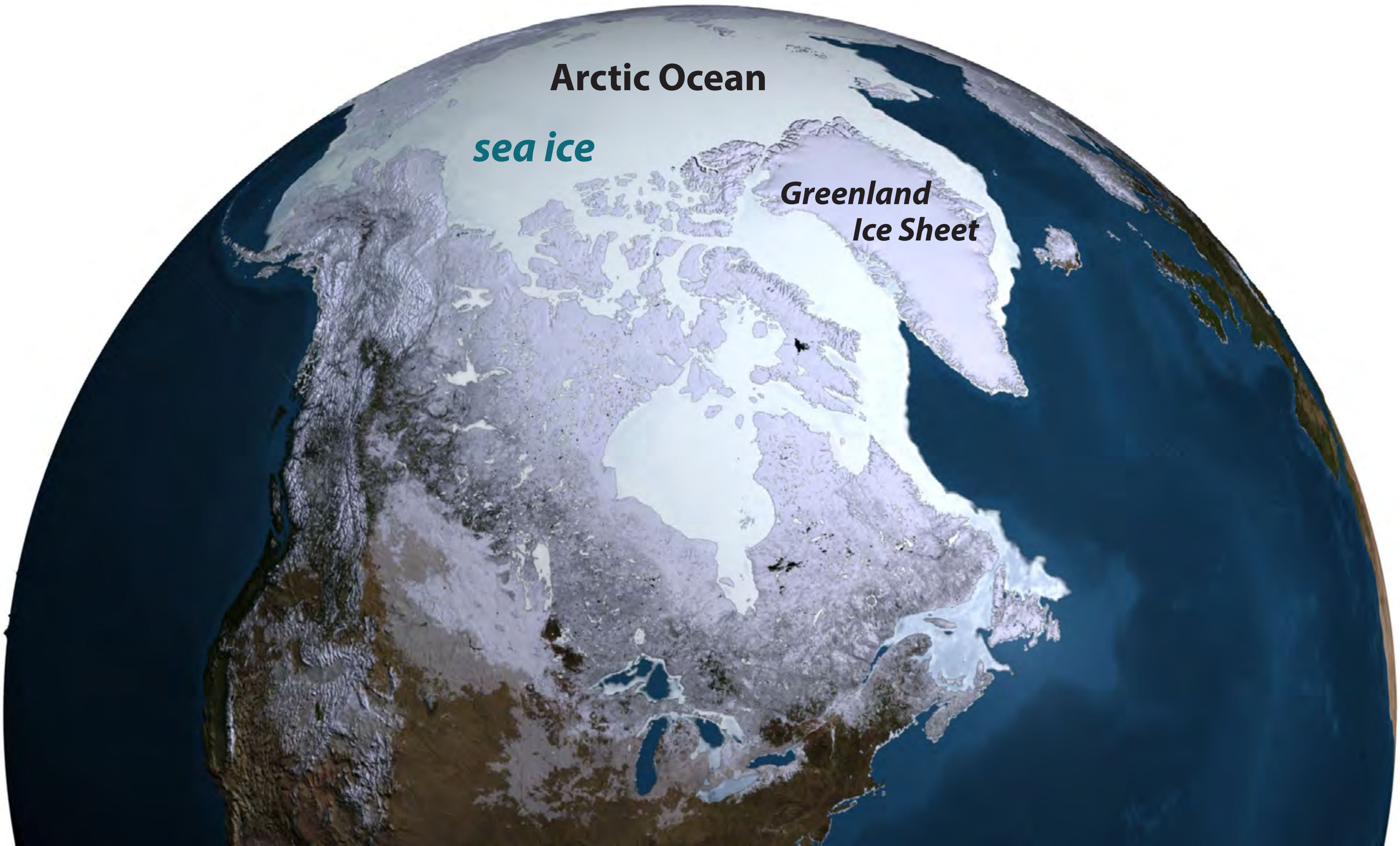
***Frey***

# *ANTARCTICA*

southern cryosphere



# *THE ARCTIC*
# northern cryosphere



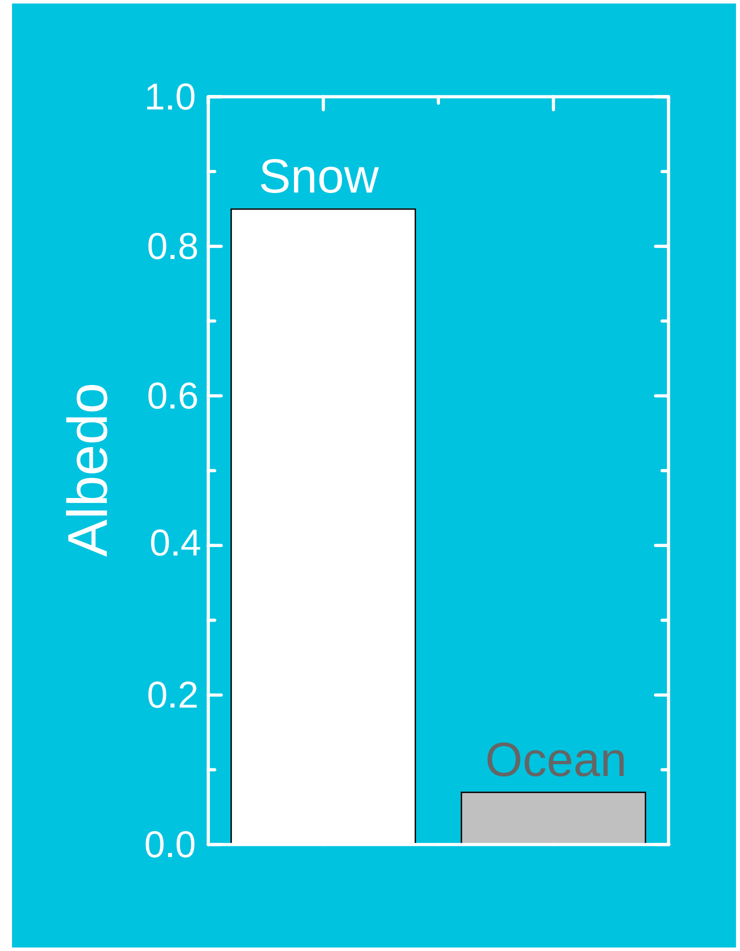
# SEA ICE covers 7 - 10% of earth's ocean surface

- 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

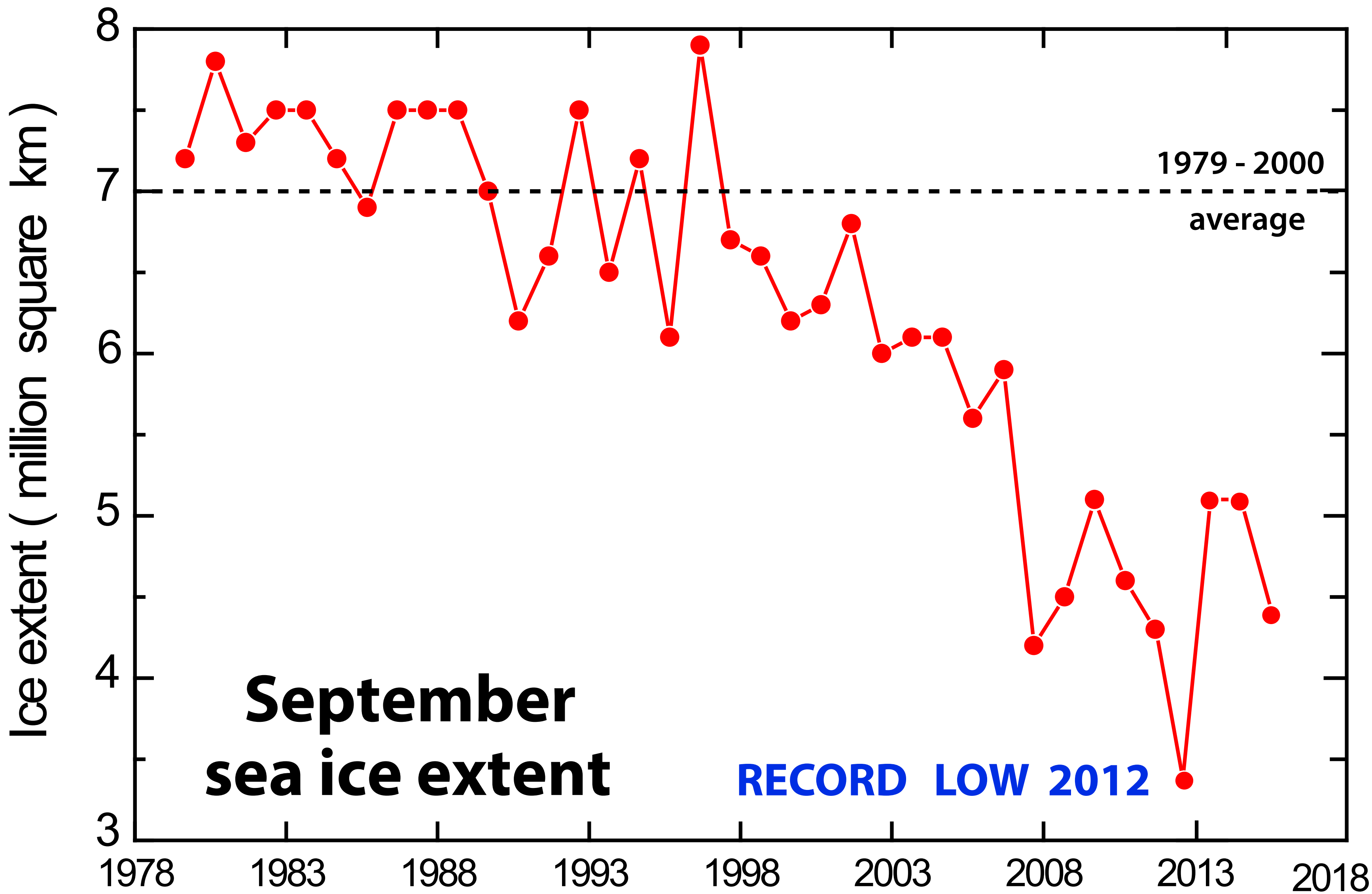





dark water and land absorb

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

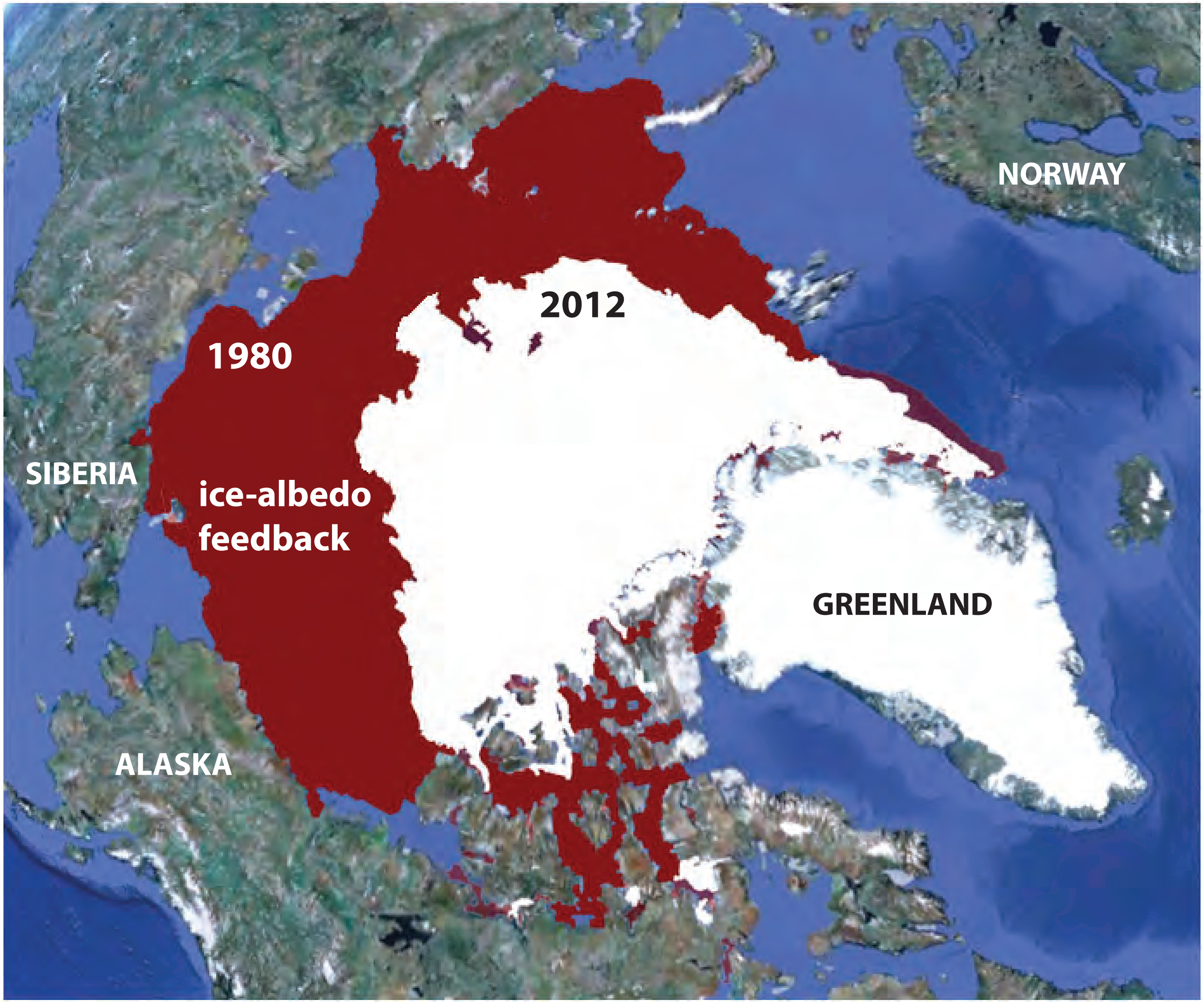
# the summer Arctic sea ice pack is melting




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**

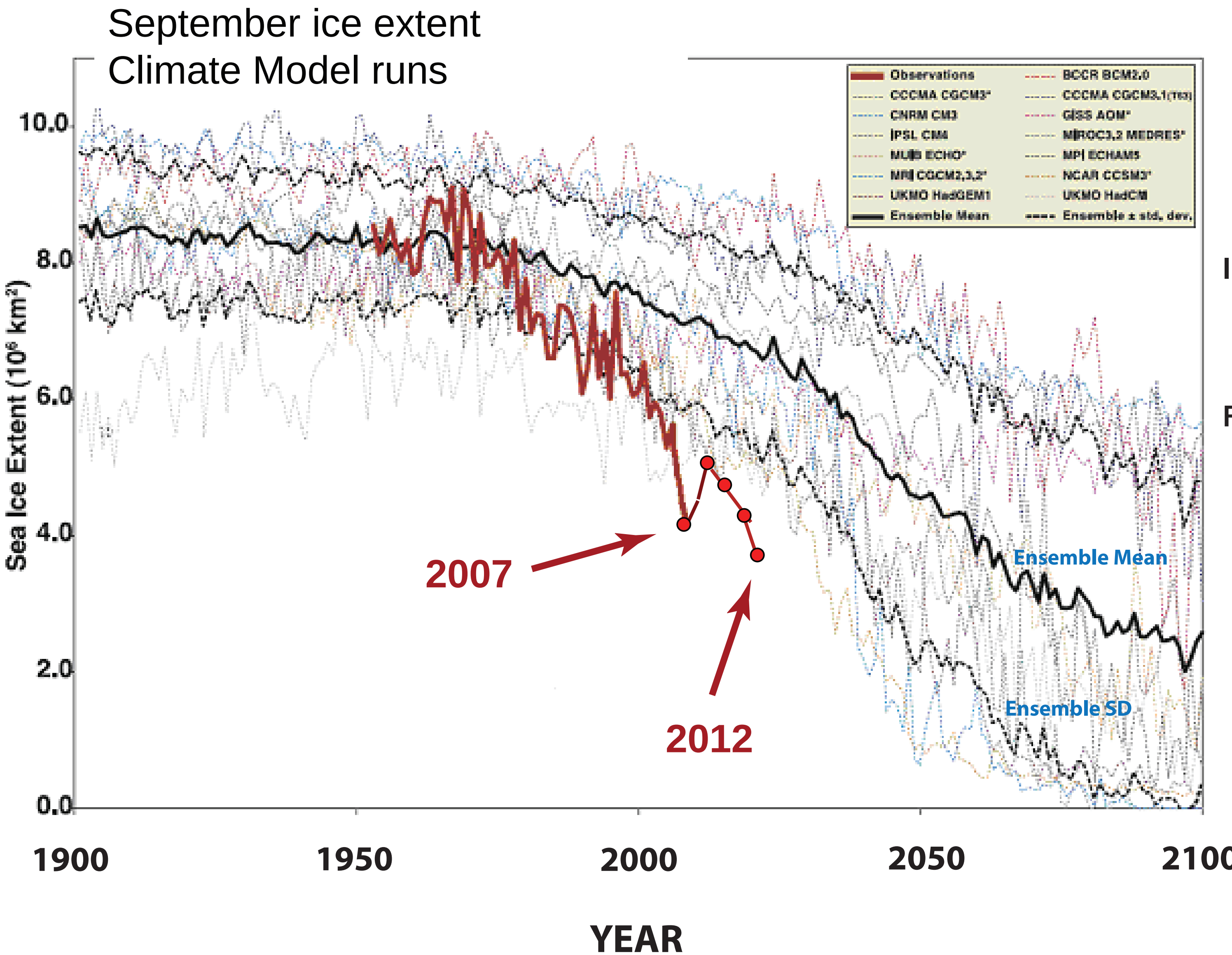



*Perovich*

***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)

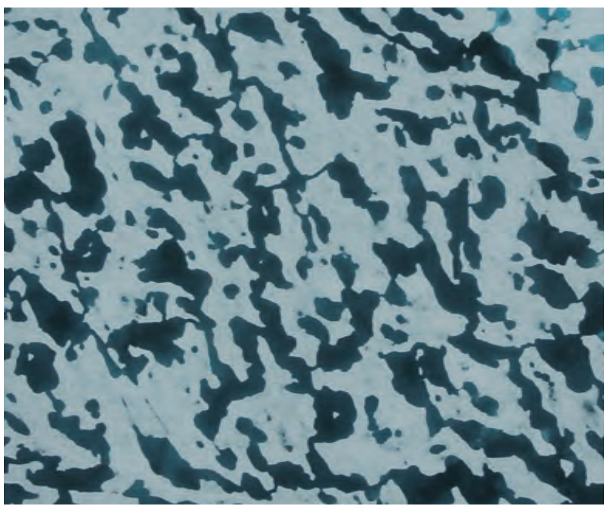
Fourth Assessment AR4, 2007

# challenge

represent sea ice more rigorously in climate models

*account for key processes*

***such as melt pond evolution***



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

Flocco, Schroeder, Feltham, Hunke, *JGR Oceans* 2012

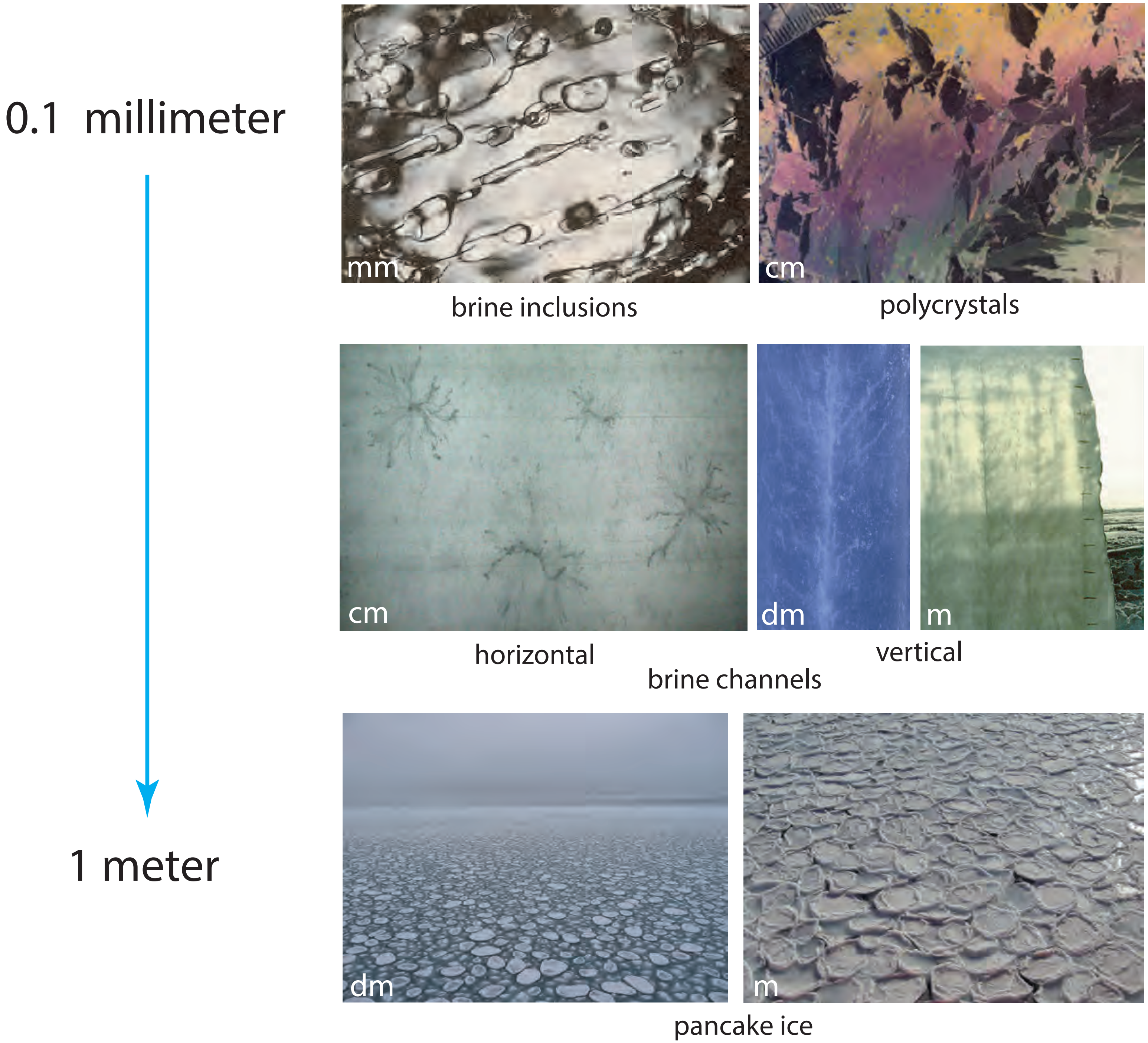
**For simulations with ponds September ice volume is nearly 40% lower.**

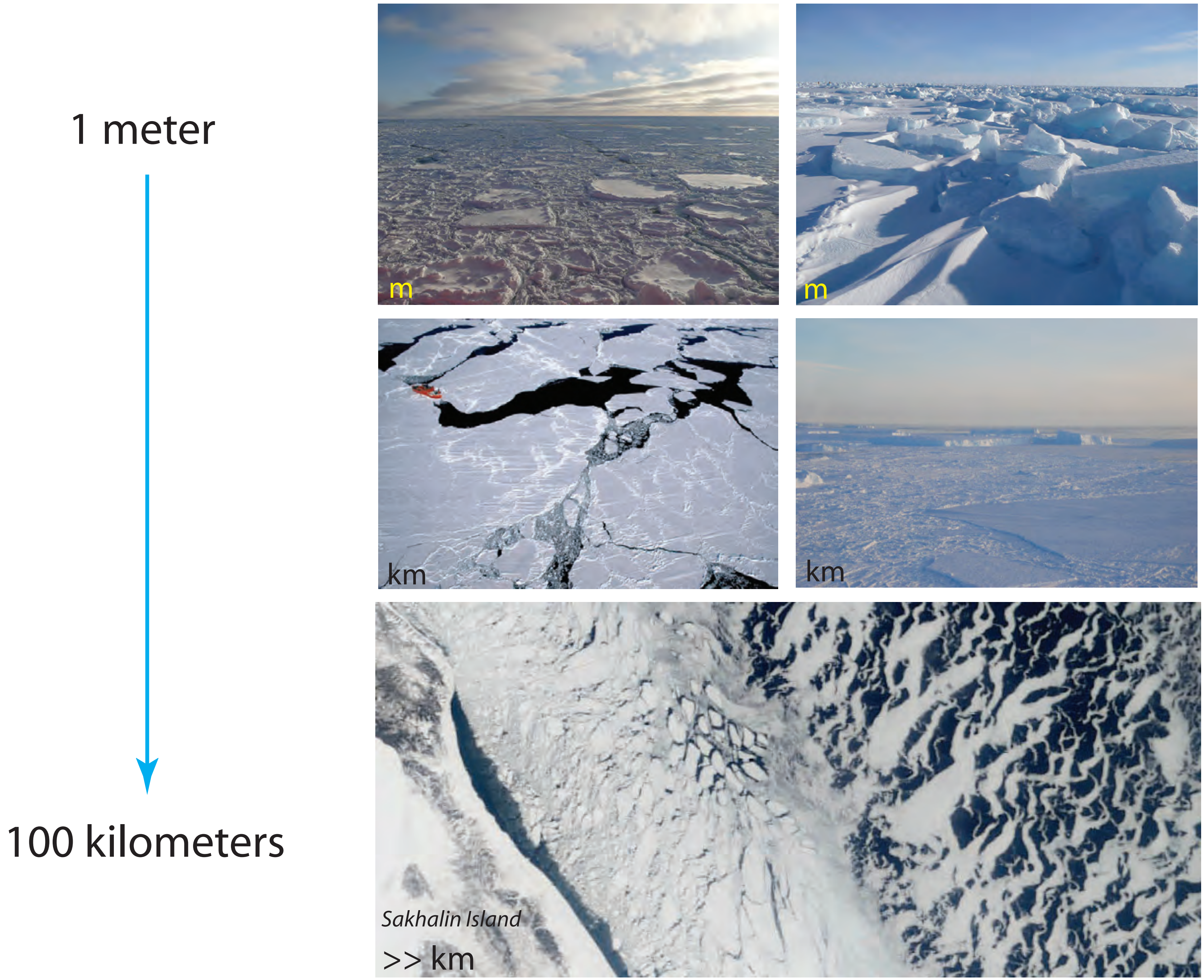
**... and other sub-grid scale structures and processes**

***linkage of scales***

# sea ice is a multiscale composite

## displaying 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. Global climate models and sea ice components

2. Fluid flow through sea ice, percolation

3. Homogenization for composite media
   remote sensing, inversion, advection-diffusion

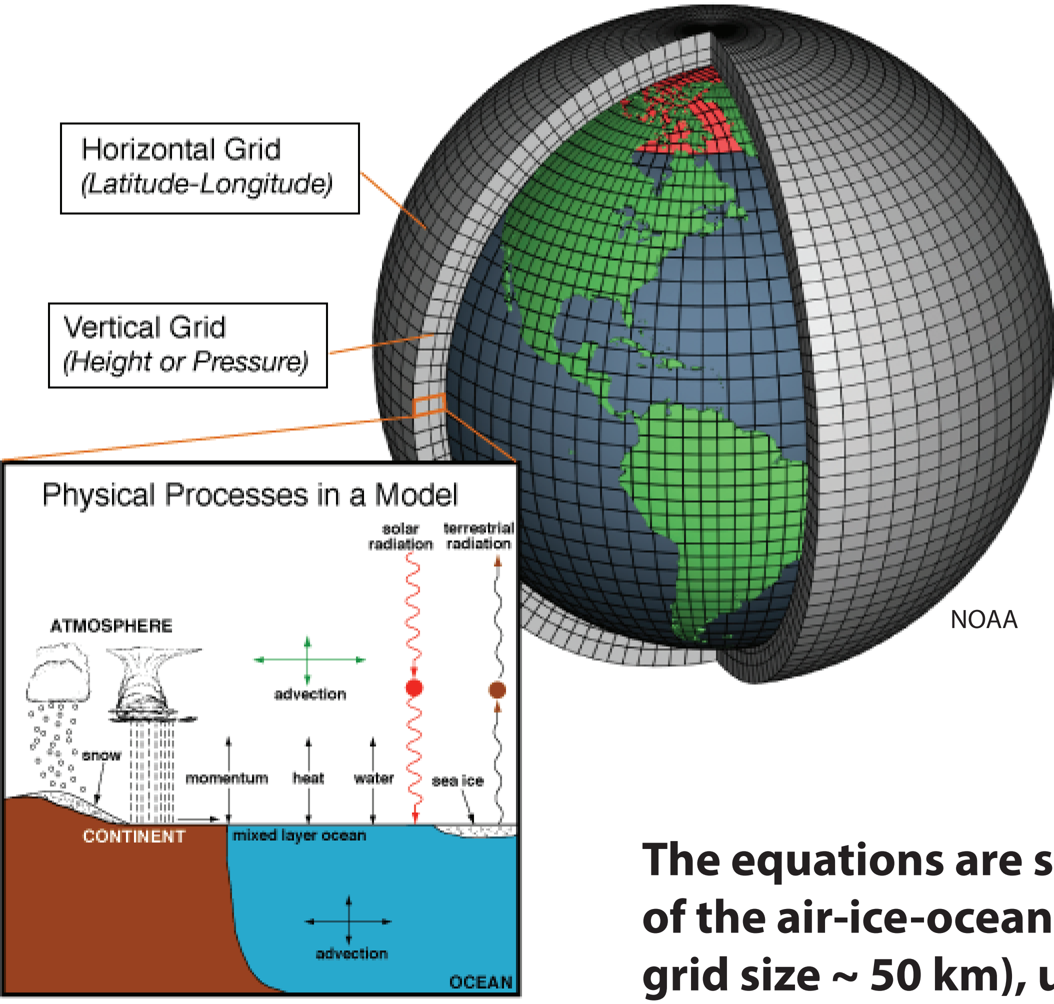
4. Ocean waves and the marginal ice zone (MIZ)

5. Arctic and Antarctic field experiements

6. Evolution of Arctic melt ponds, fractal geometry

***critical behavior*** ***cross-pollination***

# *Global Climate Models*




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

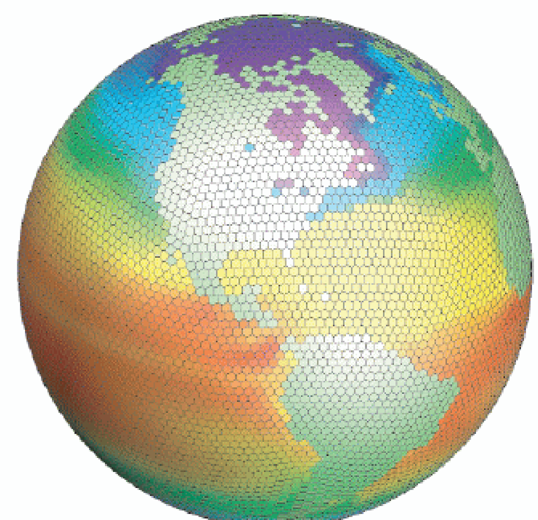
**They describe the state of the ocean, ice, atmosphere, land, and their interactions.**

**The equations are solved on 3-dimensional grids of the air-ice-ocean-land system (with horizontal grid size ~ 50 km), using very powerful computers.**

key challenge :

***incorporating sub - grid scale processes***

**linkage of scales**



Randall *et al.*, 2002

# *sea ice components of GCM's*

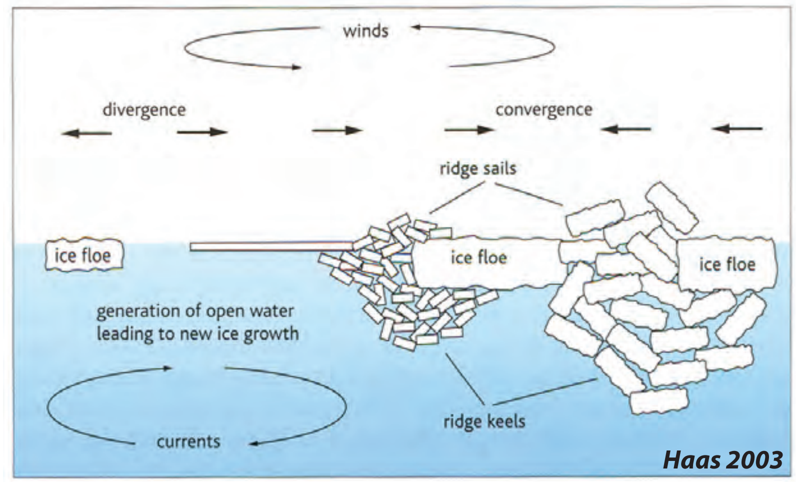
What are the key ingredients -- or ***governing equations***
that need to be solved on grids using powerful computers?

**1. Ice thickness distribution $g(x, y, h, t)$ evolution equation**

(Thorndike *et al.* 1975)

***dynamics***
+
***thermodynamics***

***nonlinear 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**

Coriolis, air and water drag,
floe - floe interactions, ...

***dynamics***

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

***thermodynamics***

evolution of temperature field in ice
brine convection

***+ balance of radiative and thermal fluxes on interfaces***

(Maykut and Untersteiner 1971)

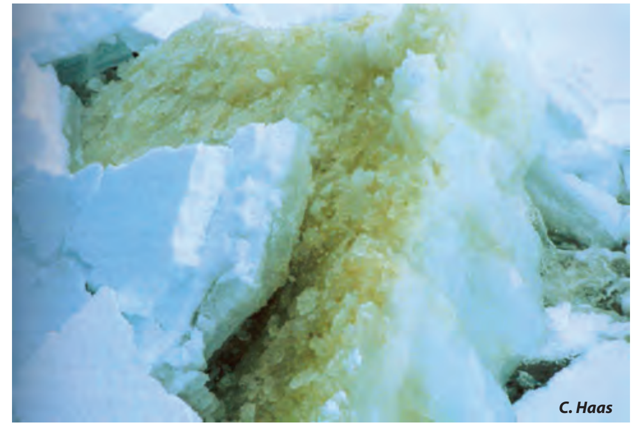
***sea ice microphysics***

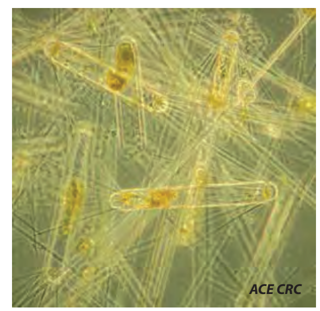
***fluid transport***

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

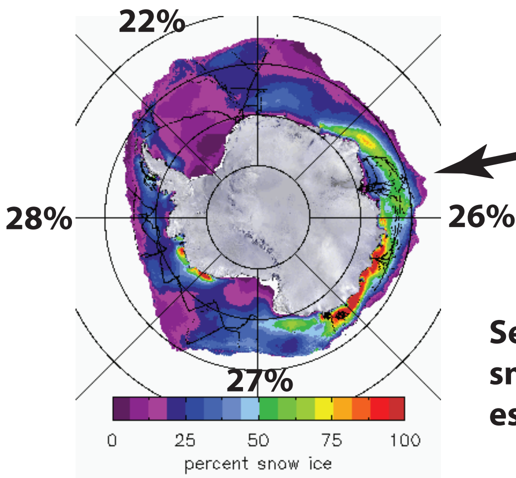
*evolution of Arctic melt ponds and sea ice albedo*


*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, $CO_2$*

# sea ice ecosystem

sea ice algae
support life in the polar oceans

**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***

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

averaged fluid velocity

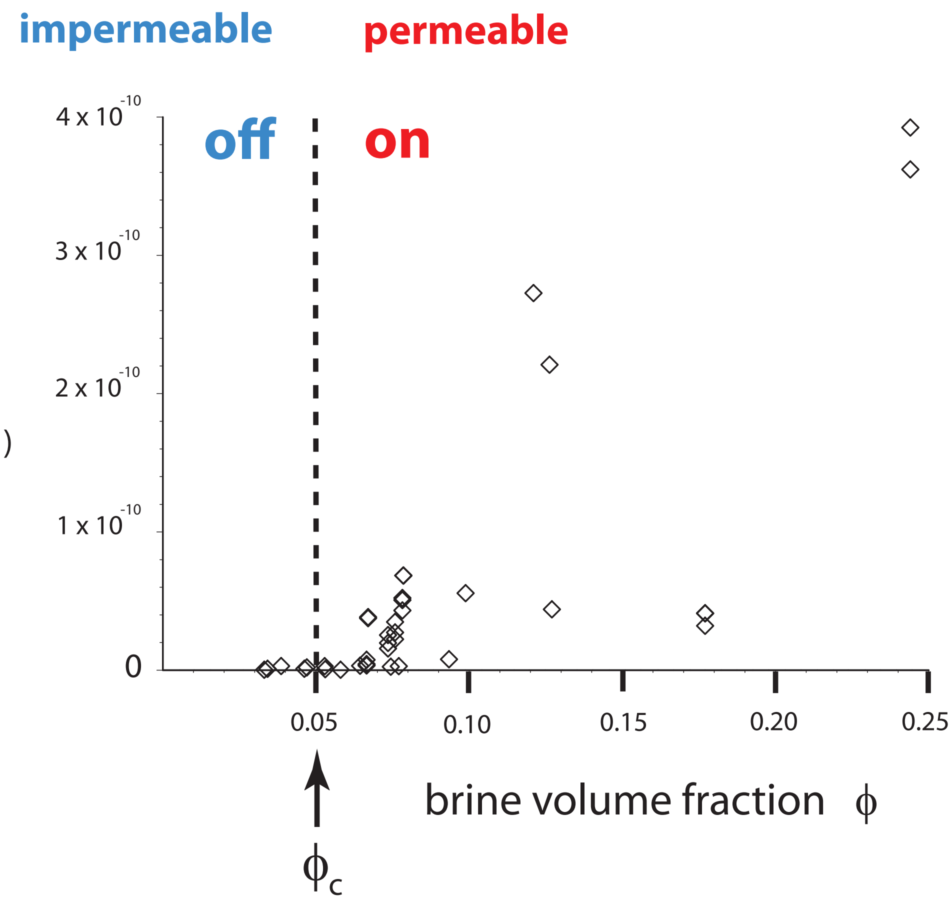
pressure gradient

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

viscosity

$\mathbf{k}$ = fluid permeability tensor

# *Critical behavior of fluid transport in sea ice*




**Arctic field data**

vertical fluid permeability $k$ (m$^2$)

***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, *Geophys. Res. Lett.* 2007

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

sea ice algal communities

D. Thomas 2004

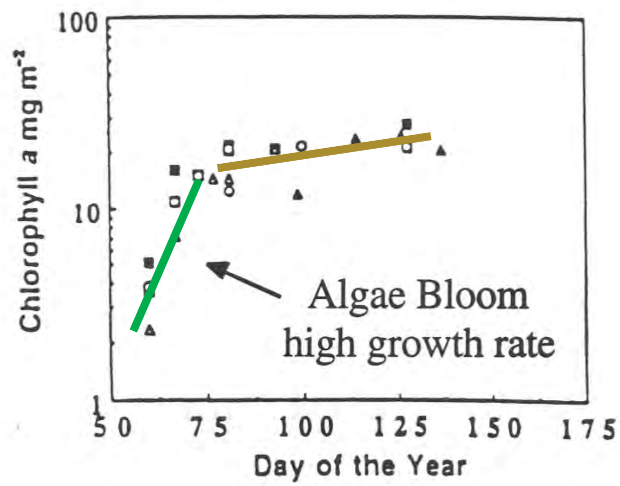
nutrient replenishment
controlled by ice permeability

biological activity turns on
or off according to
***rule of fives***

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

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

***critical behavior of microbial activity***

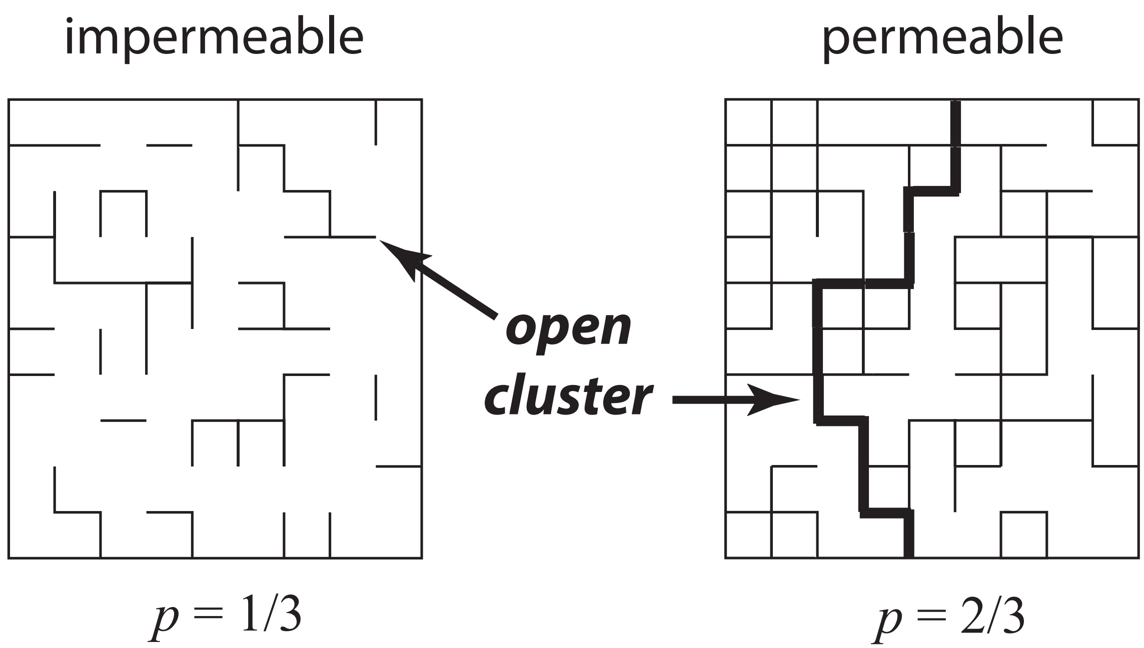



Convection-fueled algae bloom
Ice Station Weddell

## *Why is the rule of fives true?*

# percolation theory

## ***probabilistic theory of connectedness***




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

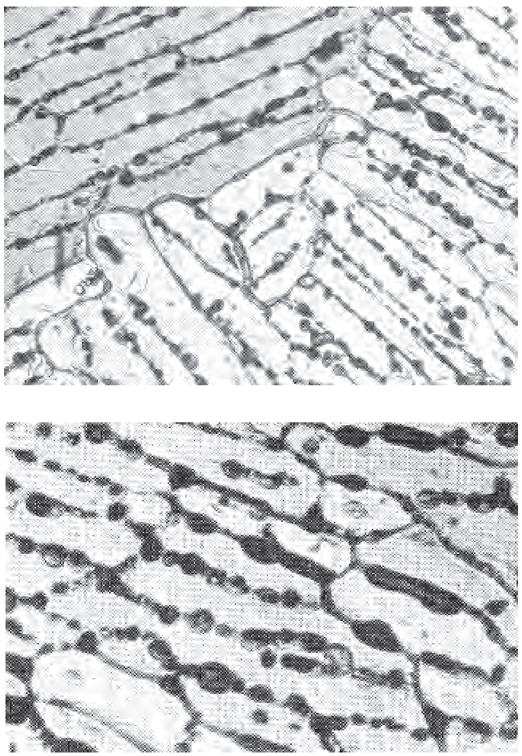
## **percolation threshold**

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

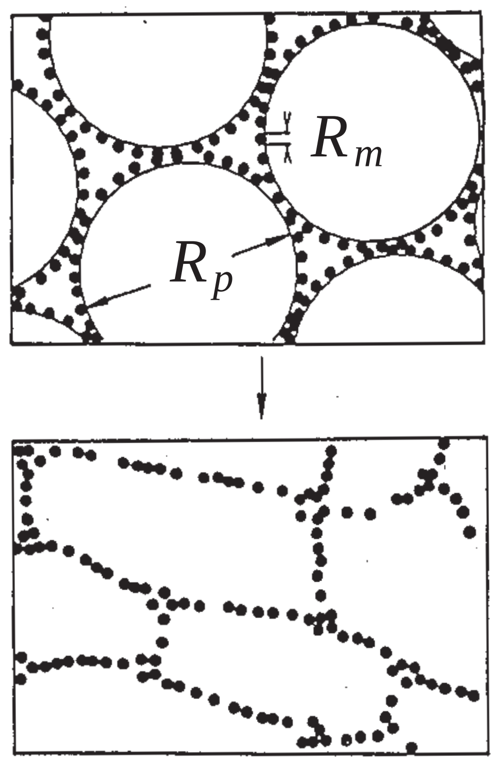
**smallest *p* for which there is an infinite open cluster**

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

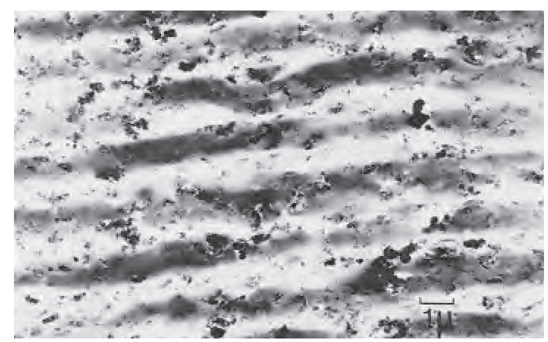
$\phi_c \approx 5\ \%$ Golden, Ackley, Lytle, *Science*, 1998



**sea ice**




**compressed powder**

**radar absorbing composite**

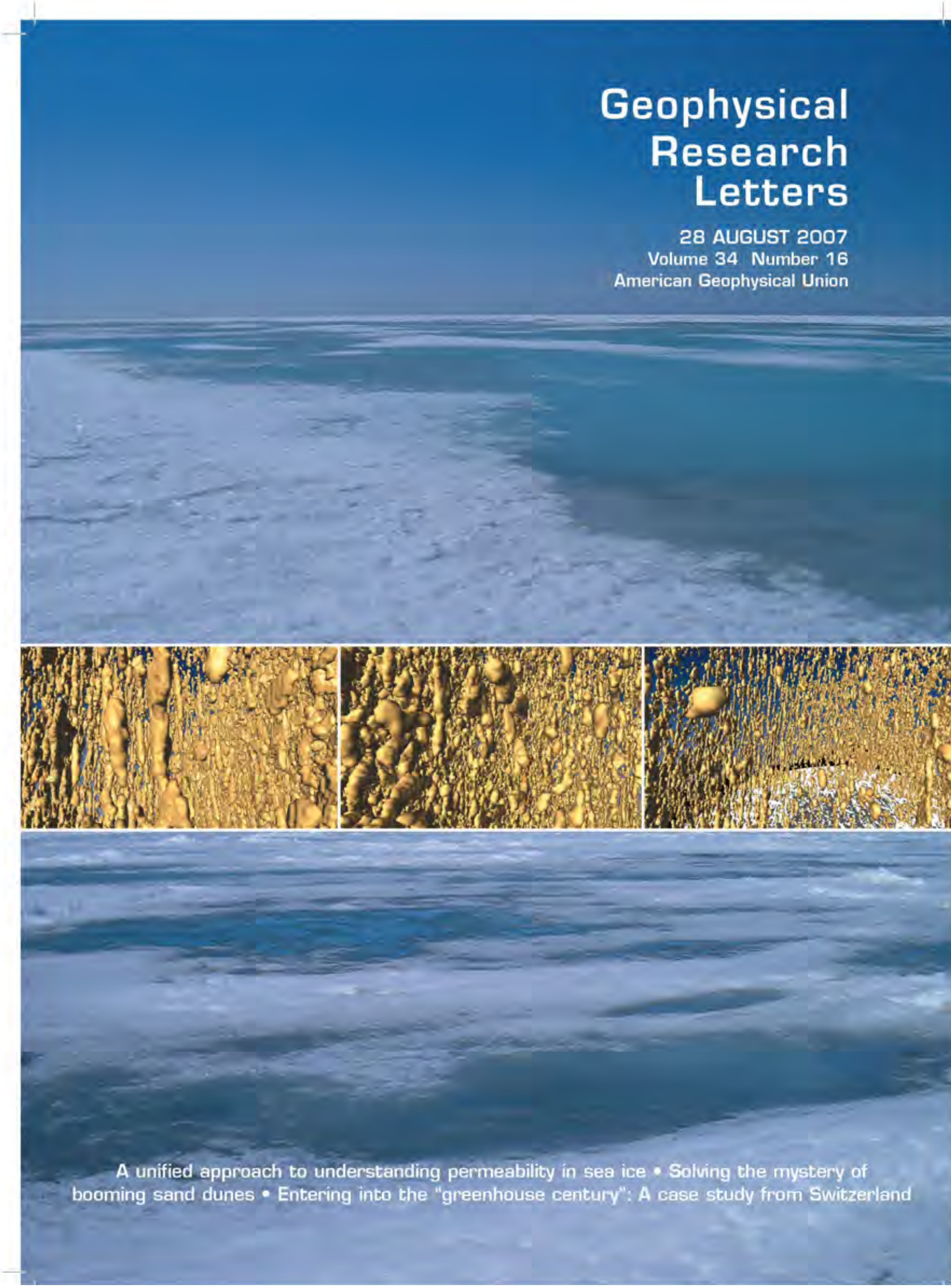
***sea ice is radar absorbing***

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

micro-scale

controls

macro-scale processes




***rigorous bounds***
***percolation theory***
***hierarchical model***
***network model***

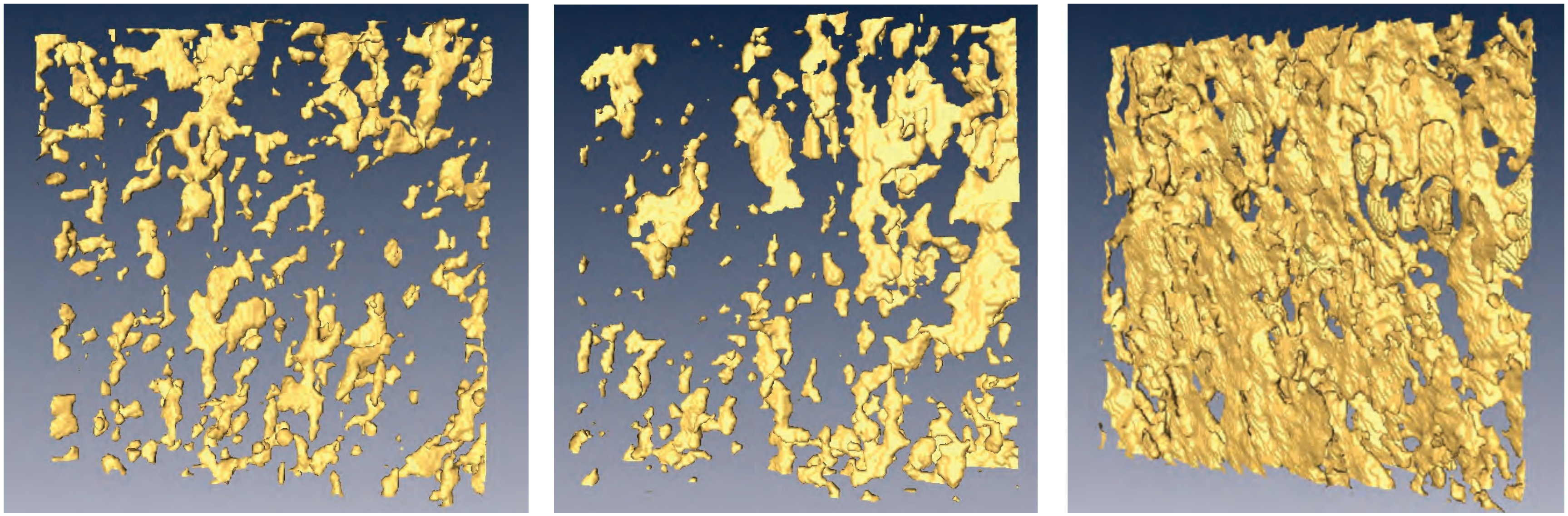
***field data***

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*

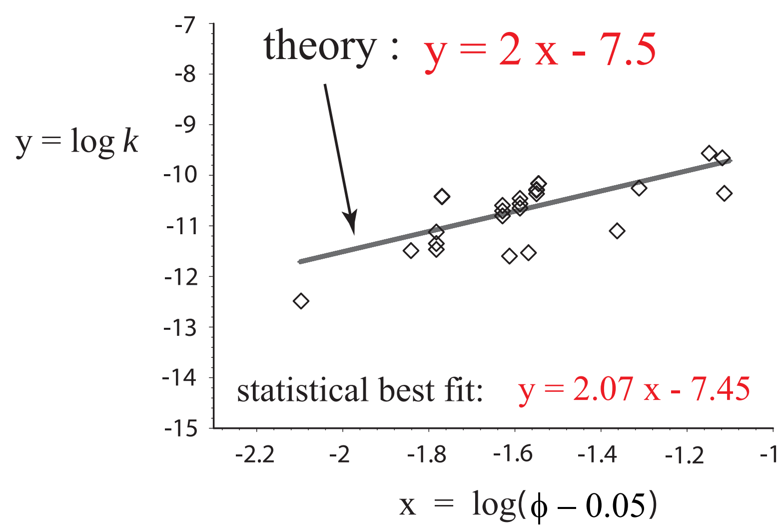
# lattice and continuum percolation theories yield:

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

critical exponent $t$

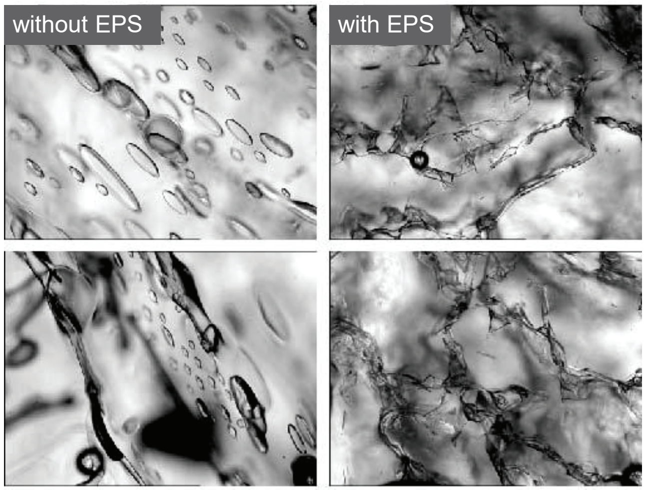
$$k_0 = 3 \times 10^{-8}\ m^2$$

- 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 $k_0$

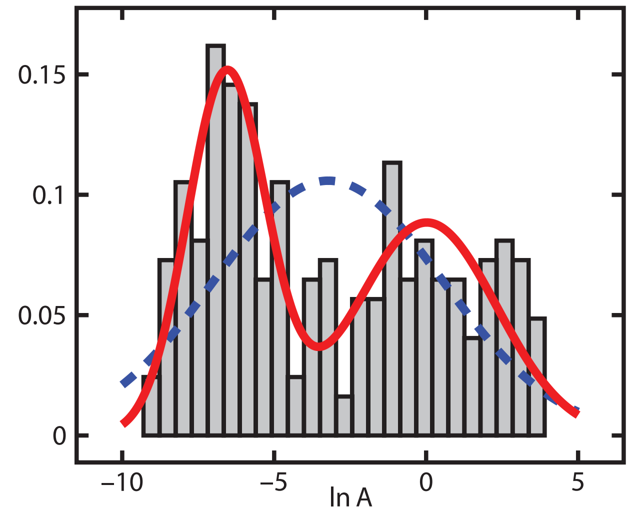


## Sea ice algae secrete extracellular polymeric substances (EPS).

# How does EPS affect fluid transport?




Krembs, Eicken, Deming, PNAS 2011

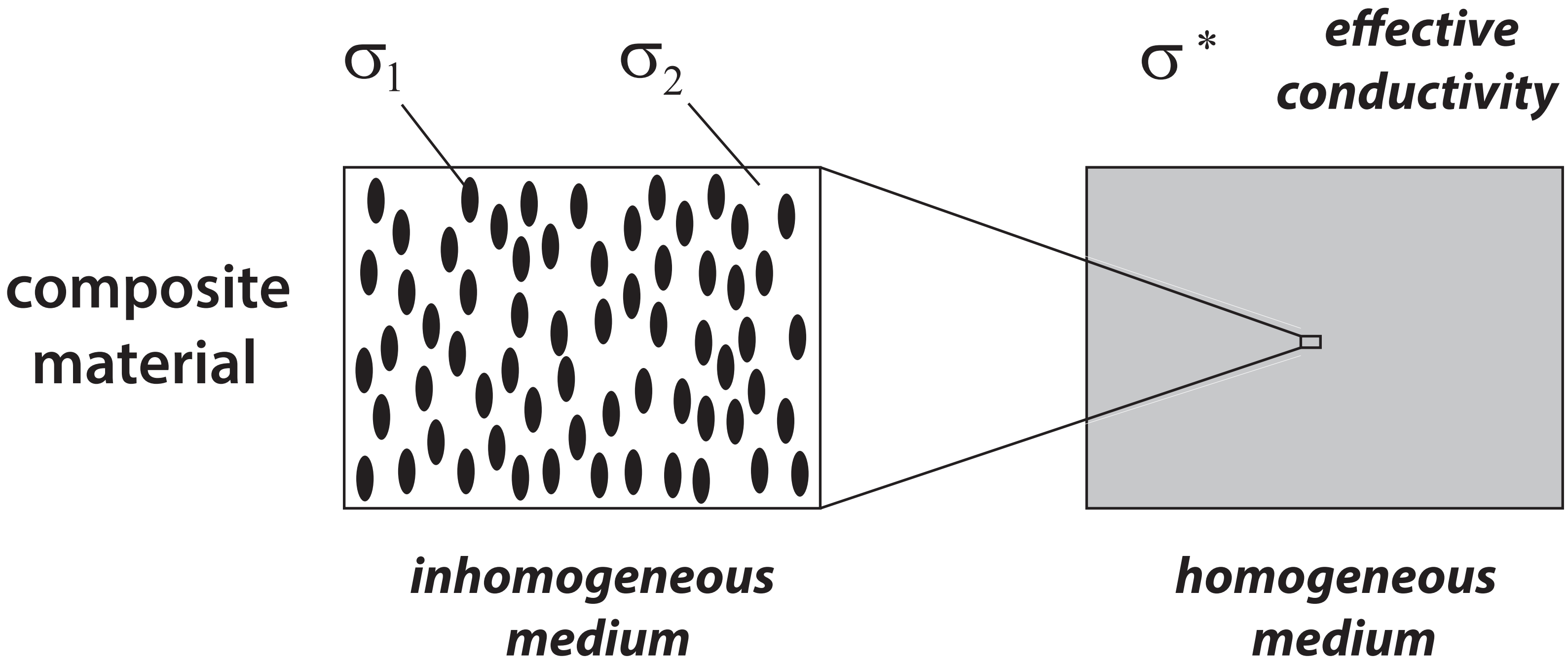



- **Bimodal** lognormal distribution for brine inclusions
- Develop new random pipe network with bimodal distribution; Update numerical methods to handle larger variances in sizes.
- Results predict observed drop in fluid permeability *k*.
- Rigorous bound on *k* for bimodal distribution of pore sizes

***Steffen, Epshteyn, Zhu, Bowler, Deming, Golden 2017***

## How does the biology affect the physics?

# *HOMOGENIZATION*

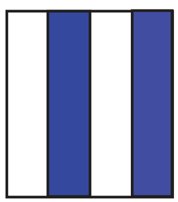



**find the homogeneous medium which behaves macroscopically the same as the inhomogeneous medium**

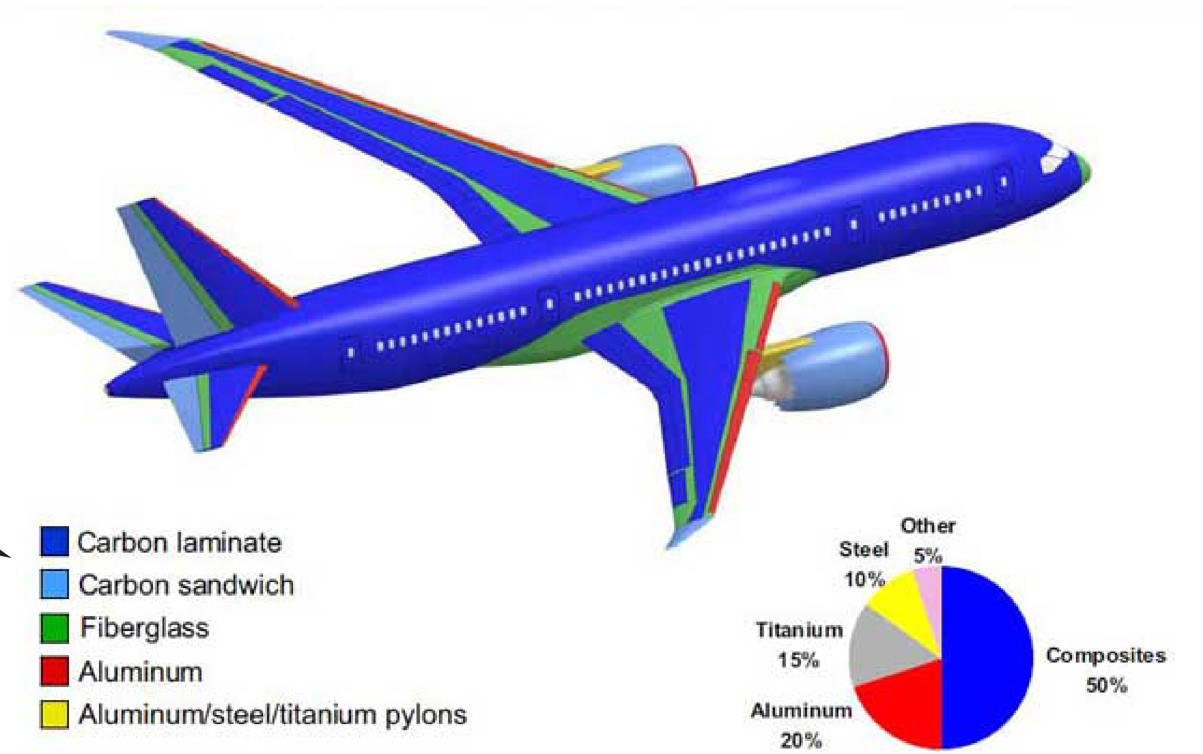
*Maxwell 1873 : effective conductivity of a dilute suspension of spheres*
*Einstein 1906 : effective viscosity of a dilute suspension of rigid spheres in a fluid*

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

# Composite materials in the Boeing 787 Dreamliner



**laminate structures display optimal properties**

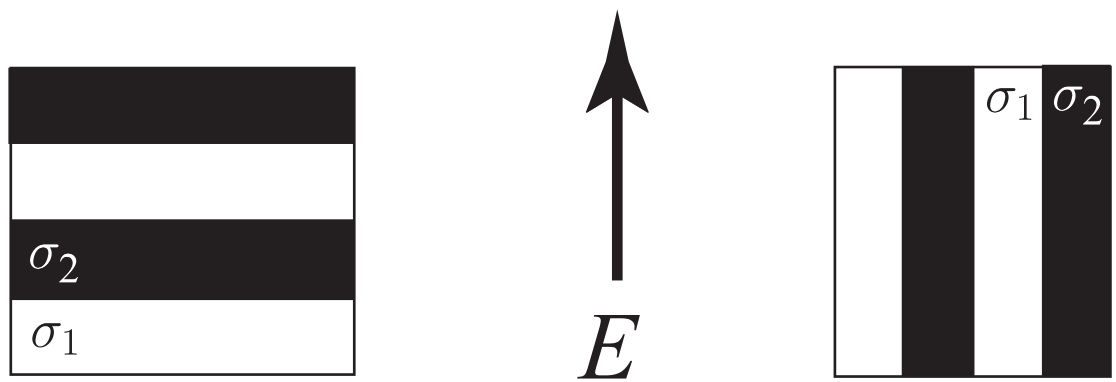


# arithmetic and harmonic mean bounds on transport properties

effective electrical conductivity $\sigma^*$ for two phase composite of $\sigma_1$ and $\sigma_2$

***optimal bounds*** on $\sigma^*$ for known volume fractions $p_1$ and $p_2$ :

$$\frac{1}{\frac{p_1}{\sigma_1} + \frac{p_2}{\sigma_2}} \leq \sigma^* \leq p_1\sigma_1 + p_2\sigma_2$$




**applied electric field**

***optimal designs are laminates***

**Wiener 1912, .....**

# Remote sensing of sea ice

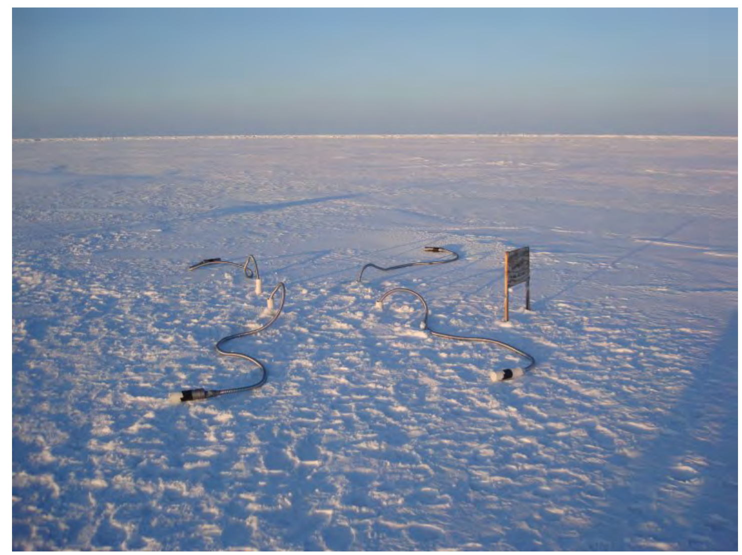
*sea ice thickness*
*ice concentration*

## *INVERSE PROBLEM*

Recover sea ice properties from electromagnetic (EM) data

$\varepsilon^*$

effective complex permittivity
(dielectric constant, conductivity)

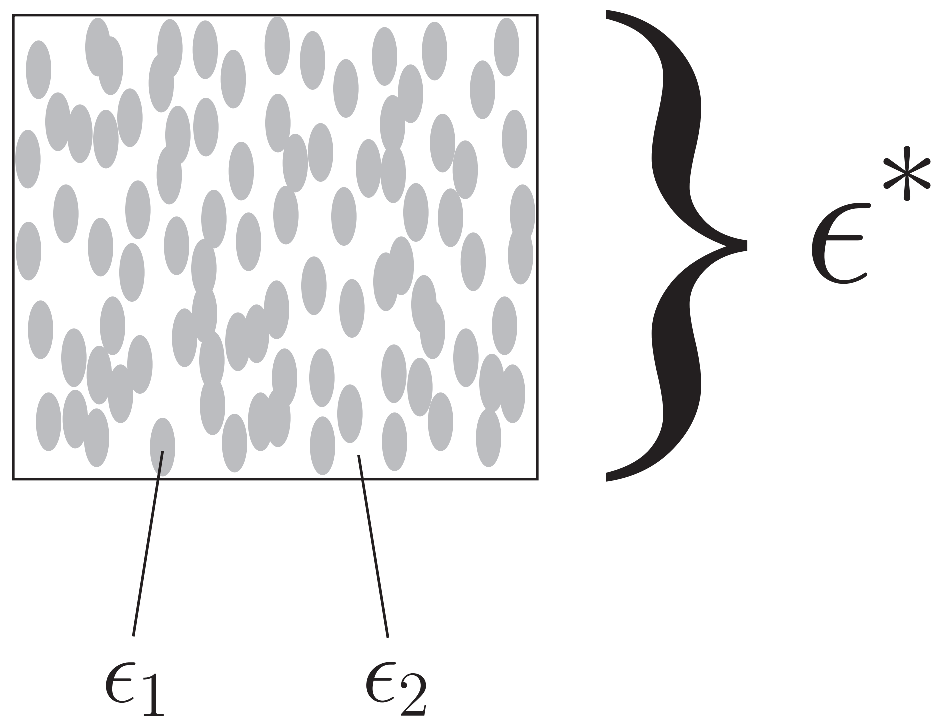


*brine volume fraction*
*brine inclusion connectivity*

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

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

***HOMOGENIZATION***




$p_1$ , $p_2$ = volume fractions of brine and ice

# ***Theory of Effective Electromagnetic Behavior of Composites***

## analytic continuation method

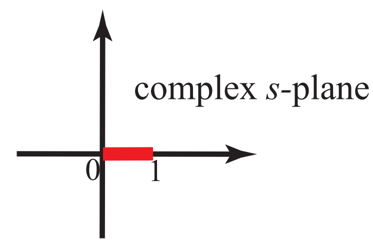
***Forward Homogenization*** Bergman (1978), Milton (1979), Golden and Papanicolaou (1983)
*Theory of Composites*, Milton (2002)

***composite geometry*** **(spectral measure $\mu$)** → $\varepsilon^*$

## Stieltjes integral representation

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

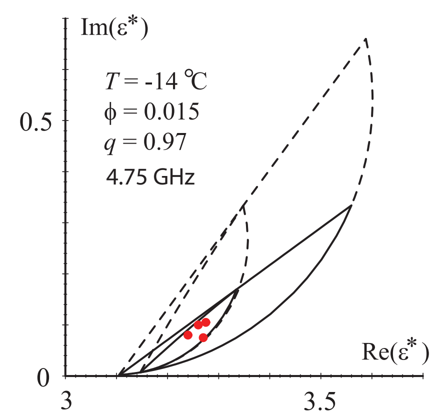
$$s = \frac{1}{1 - \epsilon_1 / \epsilon_2}$$




$\mu$

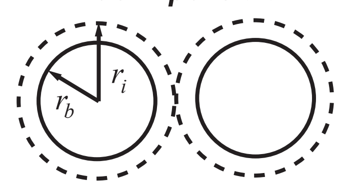
- spectral measure of self adjoint operator $\chi\,\Gamma\,\chi$
- mass $= p_1$
- higher moments depend on $n$-point correlations

Golden and Papanicolaou 1983




**bounds on the complex permittivity of sea ice**

***matrix particle***




$q = r_b / r_i$

$0 < q < 1$

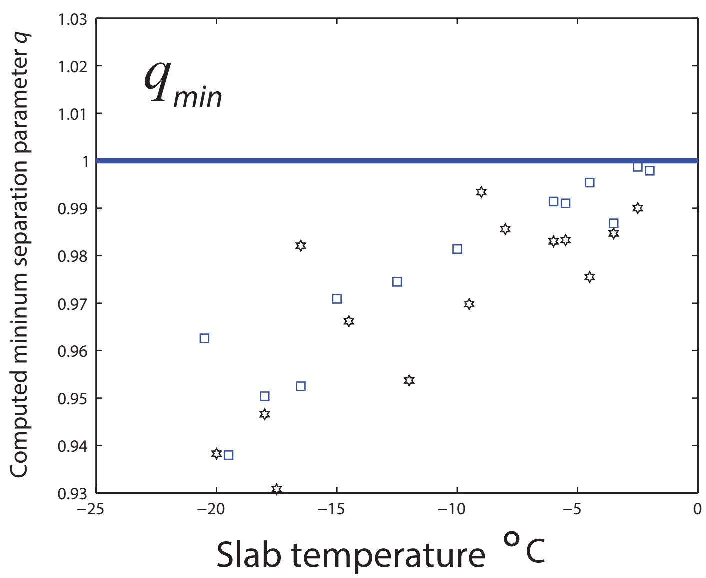
***Golden 1995, 1997***

# *Inverse Homogenization*

Cherkaev and Golden (1998), Day and Thorpe (1999), Cherkaev (2001)
McPhedran, McKenzie, Milton (1982), *Theory of Composites*, Milton (2002)

$\varepsilon^*$ ⟶ ***composite geometry***
**(spectral measure $\mu$)**

**recover brine volume fraction, brine connectivity, etc.**




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

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

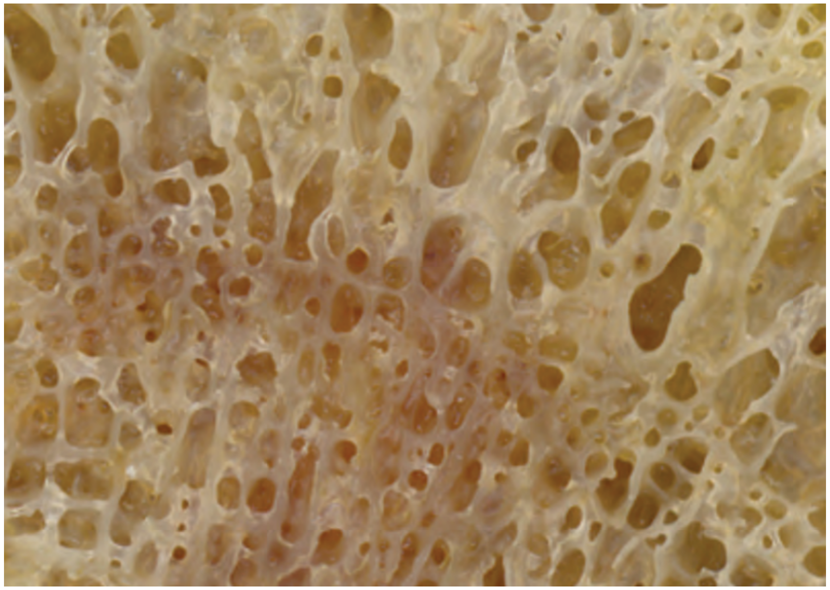
**rigorous inverse bound**
**on spectral gap**

**inverse bounds and recovery of brine porosity**

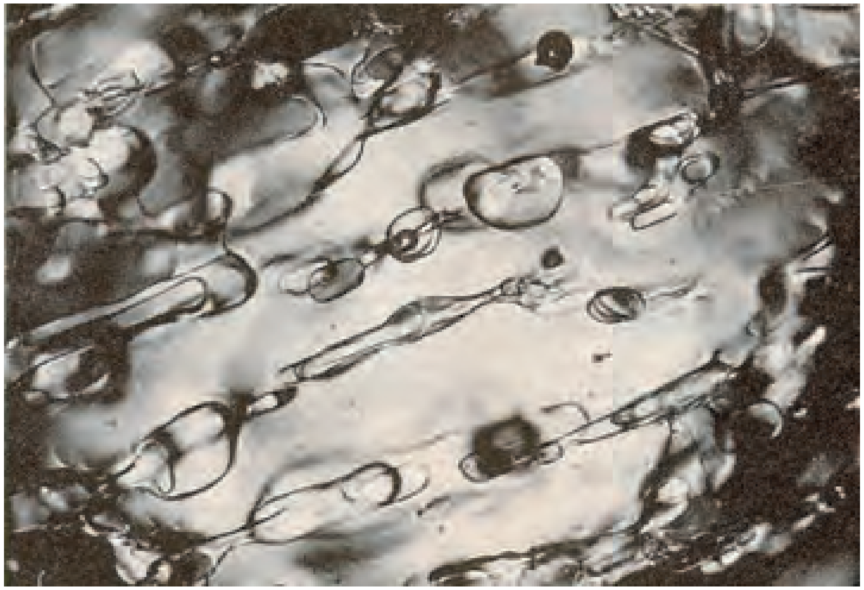
***Gully, Backstrom, Eicken, Golden***
***Physica B, 2007***

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

**HUMAN BONE**



**SEA ICE**



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

***Golden, Murphy, Cherkaev, J. Biomechanics 2011***

# direct calculation of spectral measure

- depends only on the composite geometry
- discretization of microstructural image gives binary network
- fundamental operator becomes a random matrix
- spectral measure computed from eigenvalues and eigenvectors

once we have the spectral measure $\mu$
it can be used in Stieltjes integrals for other transport coefficients:

**electrical and thermal conductivity, complex permittivity, magnetic permeability, effective diffusion**

→ *cross-property relations and inversions; spectral statistics*

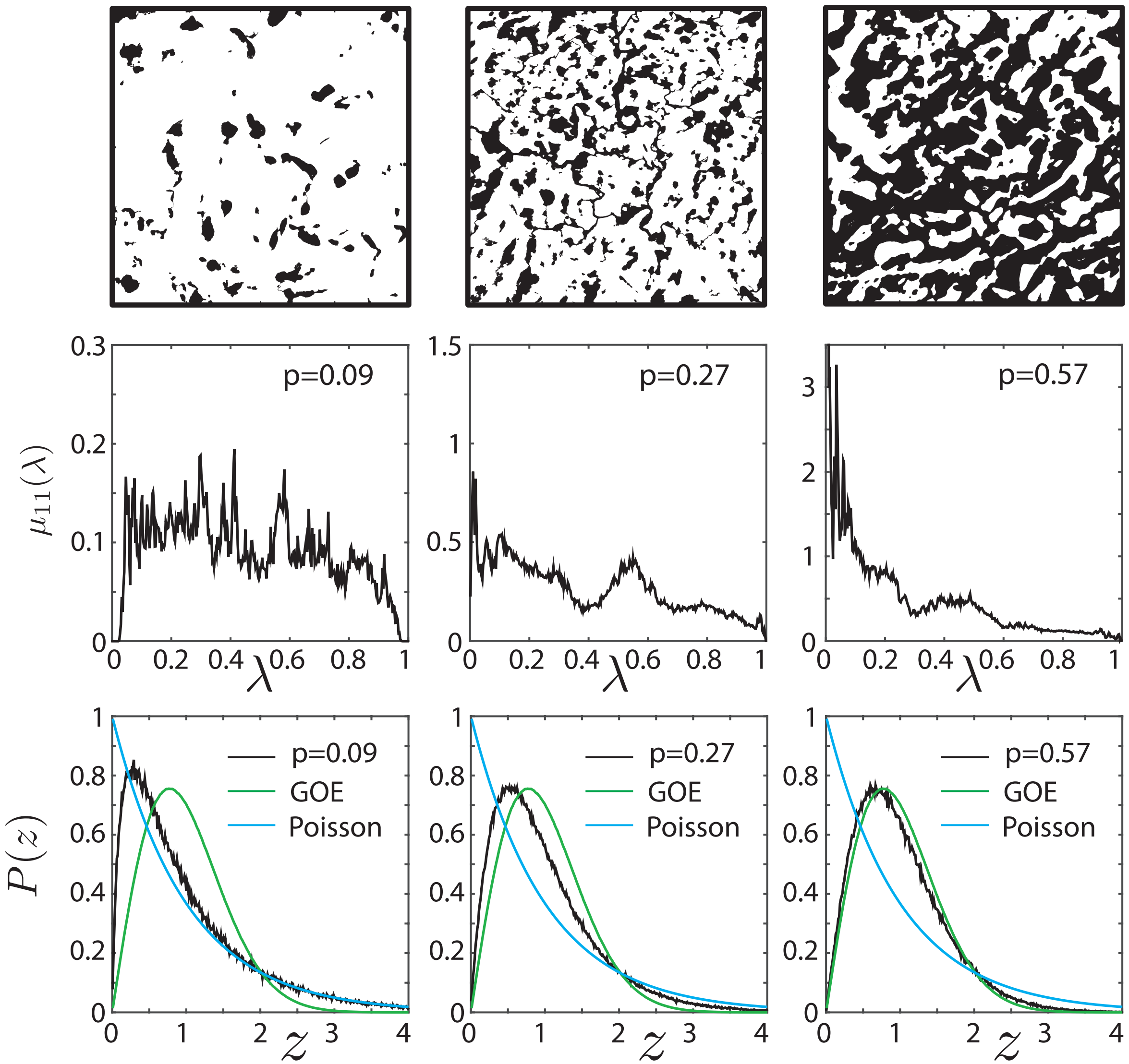
earlier studies of spectral measures

Day and Thorpe 1996
Helsing, McPhedran, Milton 2011

# Spectral computations for Arctic melt ponds

**spectral measures**

**eigenvalue spacing distributions**

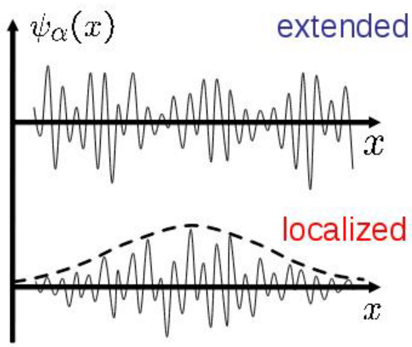



**uncorrelated** → **level repulsion**

**TRANSITION**

**Ben Murphy**
**Elena Cherkaev**
**Ken Golden**
**2016**

***eigenvalue statistics for transport tend toward the UNIVERSAL Wigner-Dyson distribution as the "conducting" phase percolates***




metal / insulator transition

**localization**

*Anderson 1958*
*Mott 1949*
*Shklovshii et al 1993*
*Evangelou 1992*

**Anderson transition in wave physics:**
**quantum, optics, acoustics, water waves, ...**

**we find a surprising analog**

***Anderson transition for classical transport in composites***

*Murphy, Cherkaev, Golden   Phys. Rev. Lett.   2017*

**PERCOLATION TRANSITION** → **transition to universal eigenvalue statistics (GOE) extended states, mobility edges**

**-- but without wave interference or scattering effects ! --**

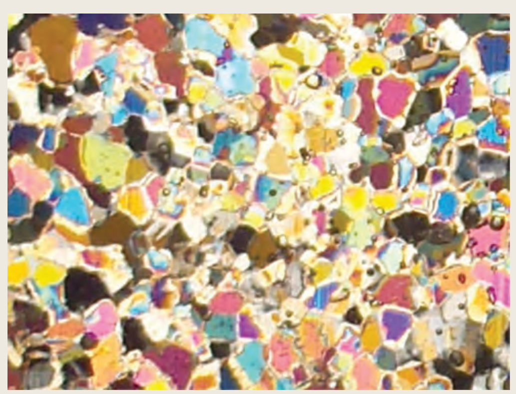
# Bounds on the complex permittivity of polycrystalline materials by analytic continuation

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**

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

Proc. R. Soc. A | 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

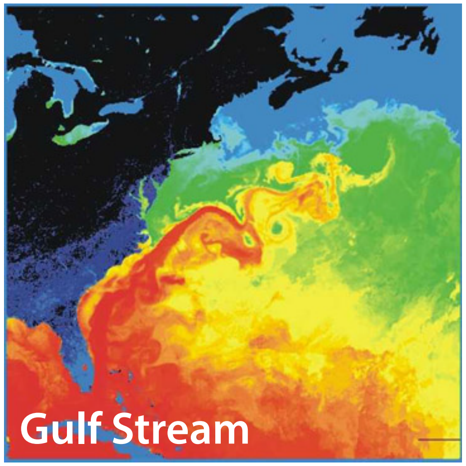
THE ROYAL SOCIETY PUBLISHING

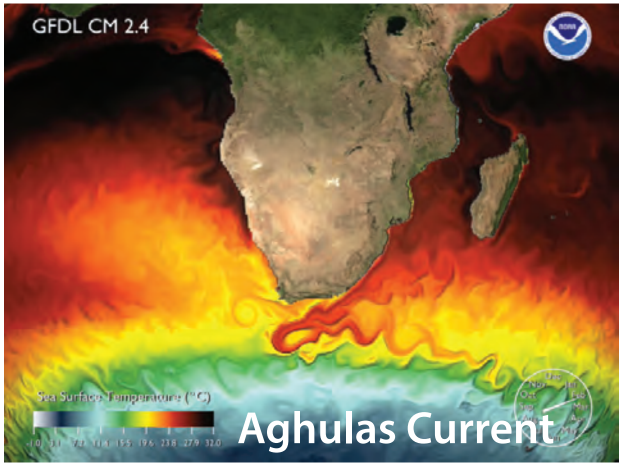
21/01/15 1:47 PM

# advection enhanced diffusion

## effective diffusivity

tracers, buoys diffusing in ocean eddies
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** $\vec{u}$

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

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

***homogenize***

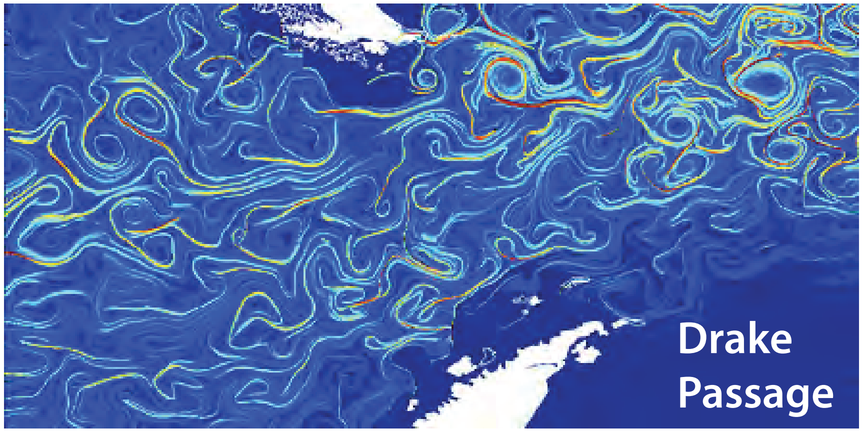
$$\frac{\partial \overline{T}}{\partial t} = \kappa^* \Delta \overline{T}$$

$\kappa^*$ ***effective diffusivity***

***Stieltjes integral for*** $\kappa^*$ ***with spectral measure***

***Avellaneda and Majda, PRL 89, CMP 91***

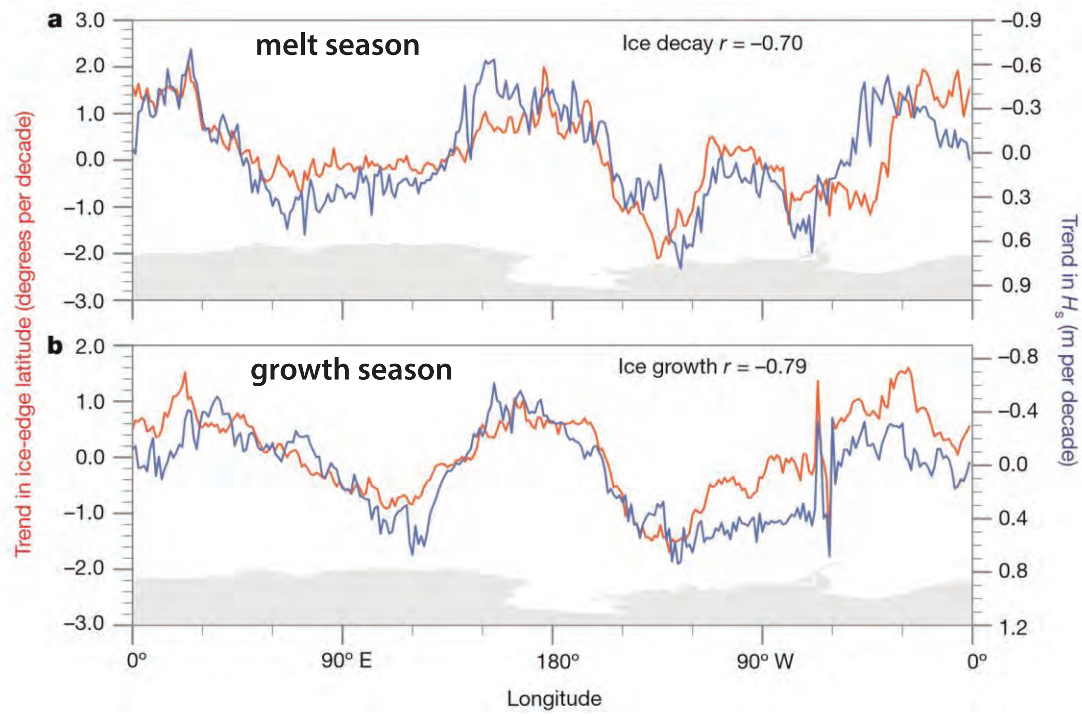
Murphy, Cherkaev, Xin, Zhu, Golden, *Ann. Math. Sci. Appl.* 2017
Murphy, Cherkaev, Zhu, Xin, Golden, 2017




# Storm-induced sea-ice breakup and the implications for ice extent

Kohout et al., *Nature* 2014

- during three large-wave events, significant wave heights did not decay exponentially, enabling large waves to persist deep into the pack ice.
- large waves break sea ice much farther from the ice edge than would be predicted by the commonly assumed exponential decay



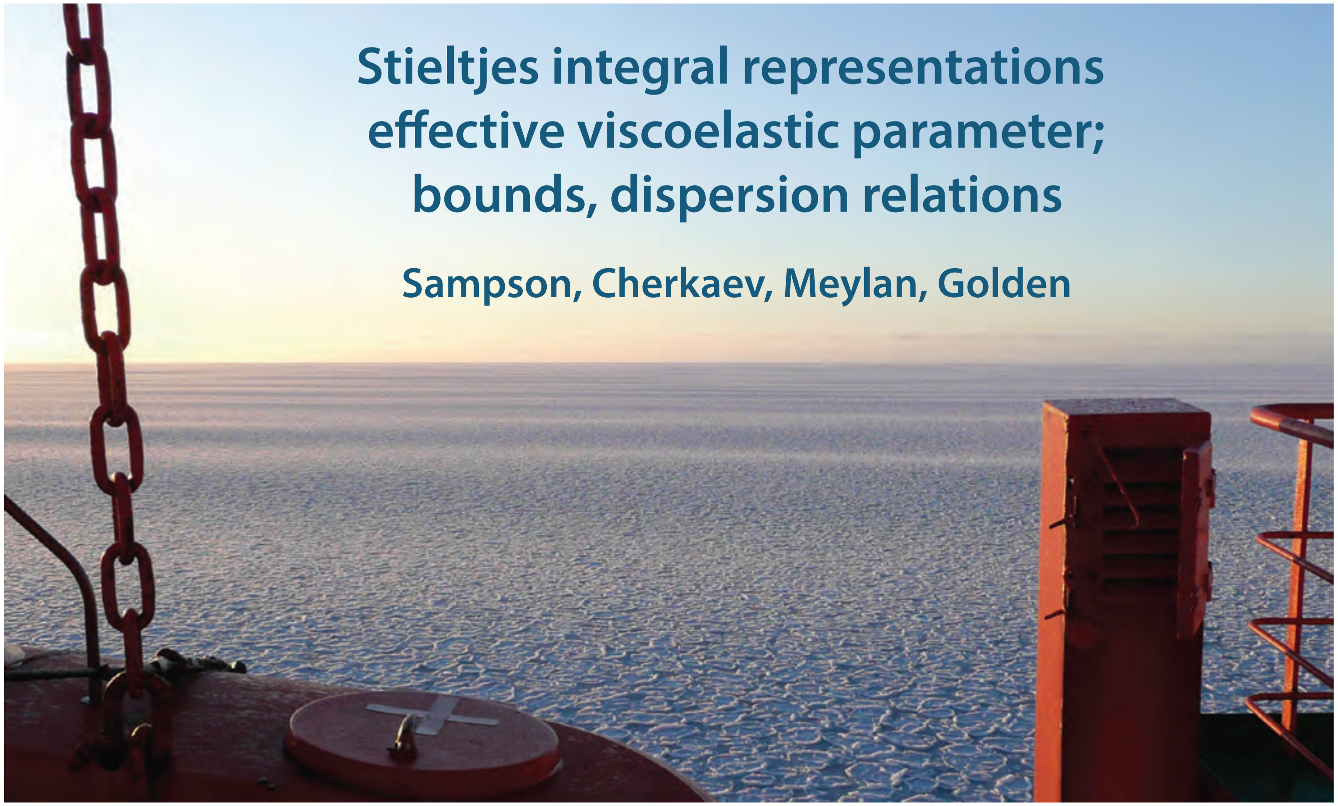

*ice extent compared with significant wave height*

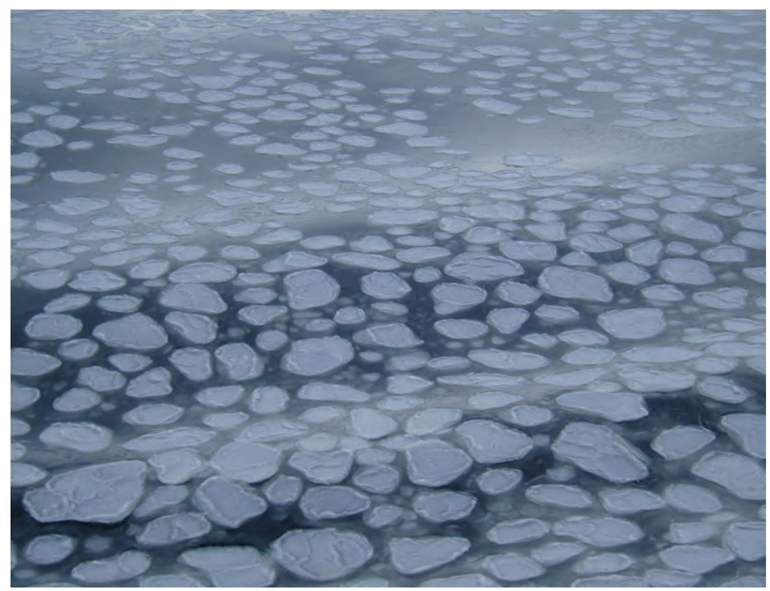
**Waves have strong influence on both the floe size distribution and ice extent.**

***ocean swells propagating through a vast field of pancake ice***

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

# wave propagation in the marginal ice zone

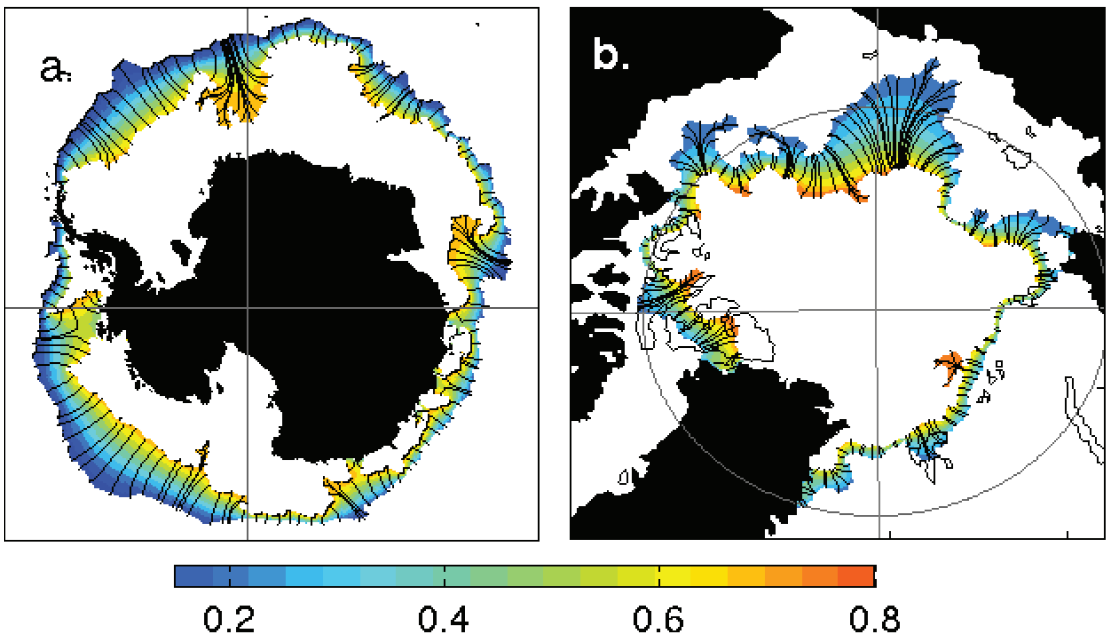


# Marginal Ice Zone

## 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

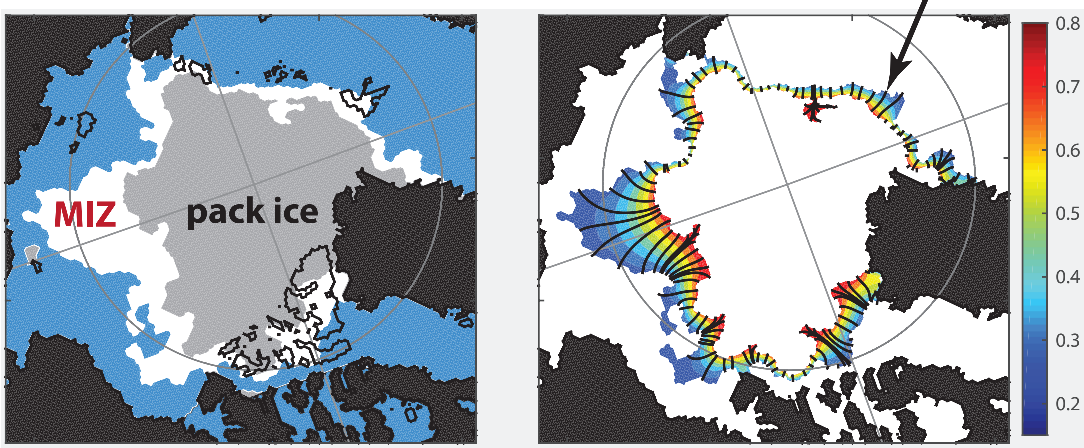
**How to objectively measure the "width" of this complex, non-convex region?**

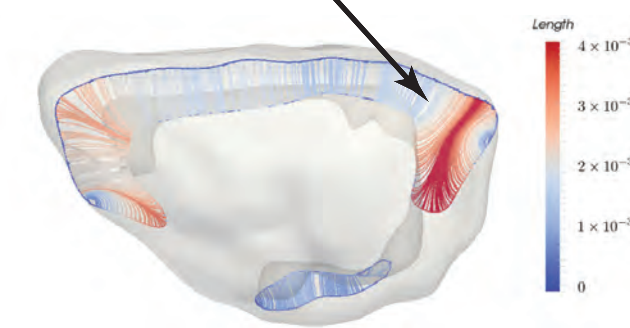
# Objective method for measuring MIZ width motivated by medical imaging and diagnostics

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

**streamlines of a solution to Laplace's equation**

"average" lengths of streamlines




**Arctic Marginal Ice Zone**

**crossection of the cerebral cortex of a rodent brain**

***analysis of different MIZ WIDTH definitions***

Strong, Foster, Cherkaev, Eisenman, Golden
*J. Atmos. Oceanic Tech.* 2017

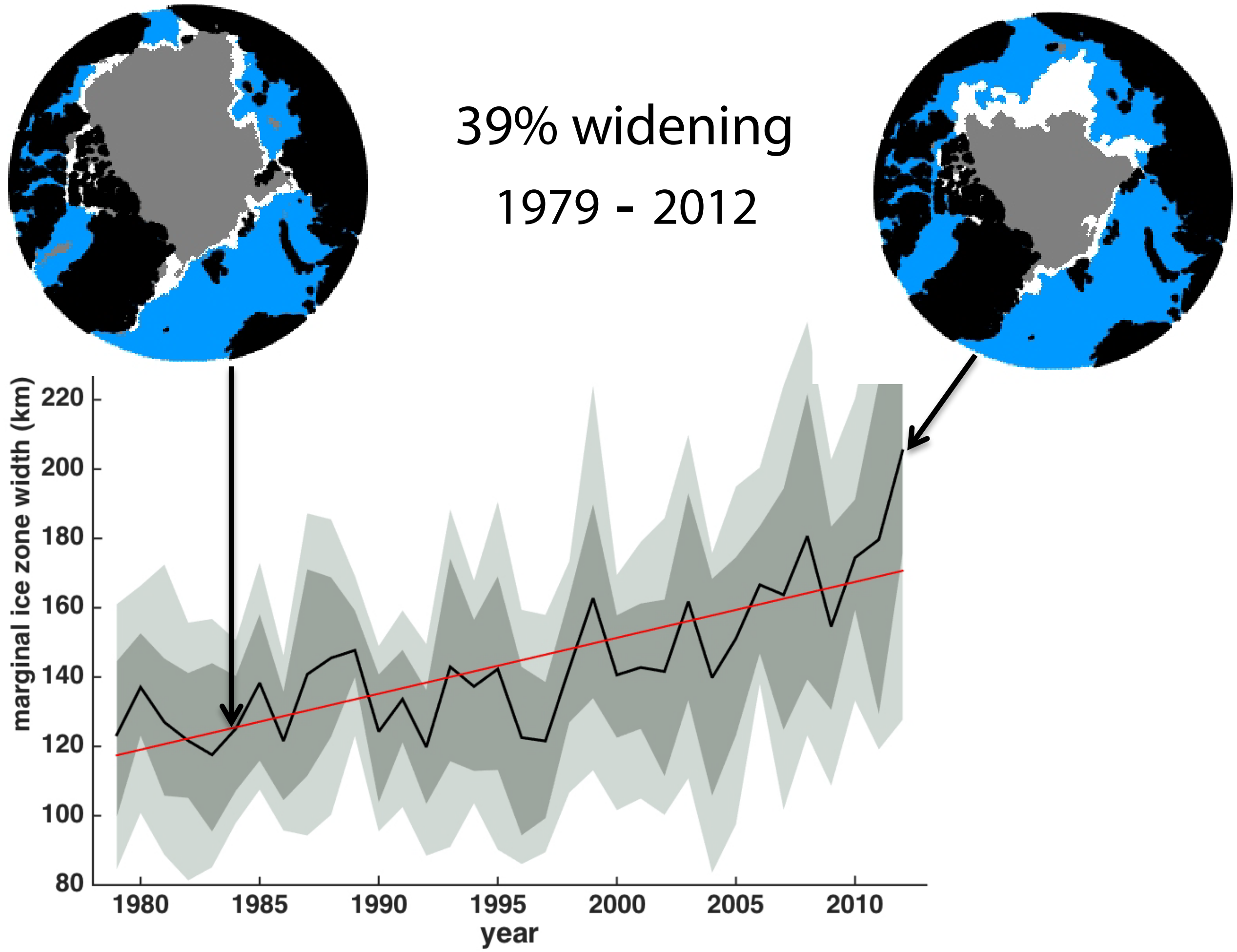
Strong and Golden
*Society for Industrial and Applied Mathematics News*, April 2017

# MIZ width increasing

39% widening

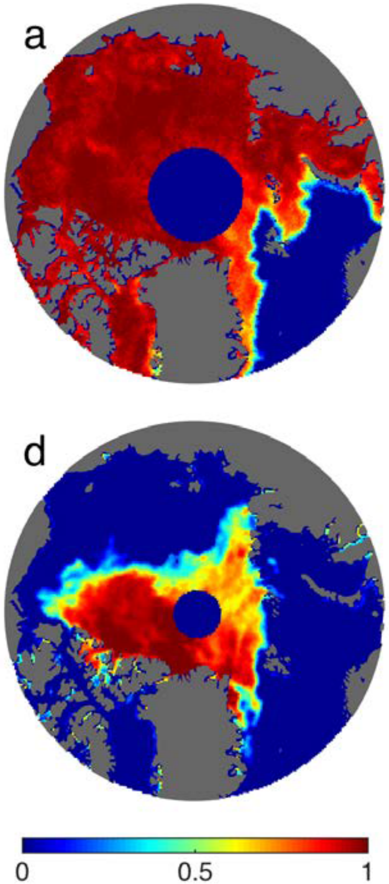
1979 - 2012

July-Sep




Strong and Rigor, *Geophysical Research Letters*, 2013

# Filling the polar data gap




Gap radius: 611 km
06 January 1985

Gap radius: 311 km
30 August 2007

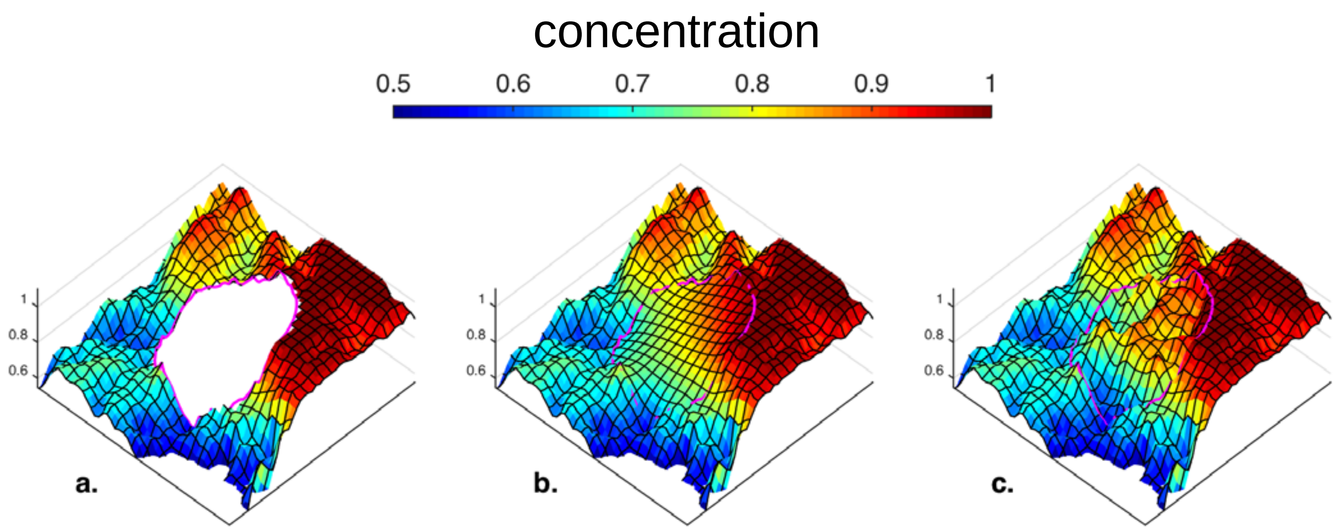
Examples of "polar data gap" where orbiting satellites do not measure sea ice concentration

gap region conventionally assumed ice-covered for sea ice extent calculations

***given recent losses this assumption may no longer be valid***

Strong and Golden, *Remote Sensing*, 2016.

# Filling the polar data gap




polar data gap
30 August 2007

$$\nabla^2\psi = 0$$

$$f(\lambda,\phi) = \psi(\lambda,\phi) + \Omega(\lambda,\phi)$$

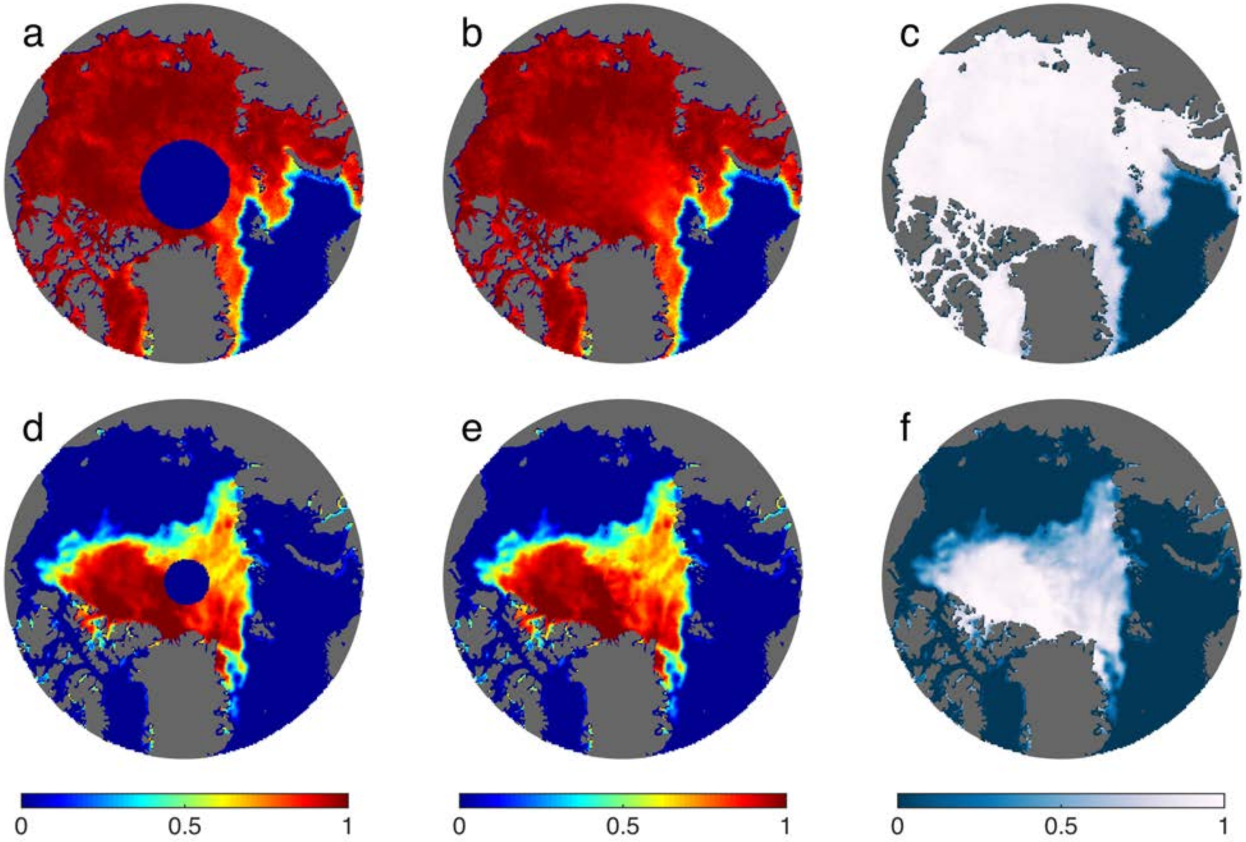
$\Omega$ simulates realistically autocorrelated deviations from $\psi$ via convolution of random noise with a Gaussian function

Strong and Golden, *Remote Sensing,* 2016.

# Filling the polar data gap

Gap radius: 611 km
06 January 1985

Gap radius: 311 km
30 August 2007




Strong and Golden, *Remote Sensing,* 2016.

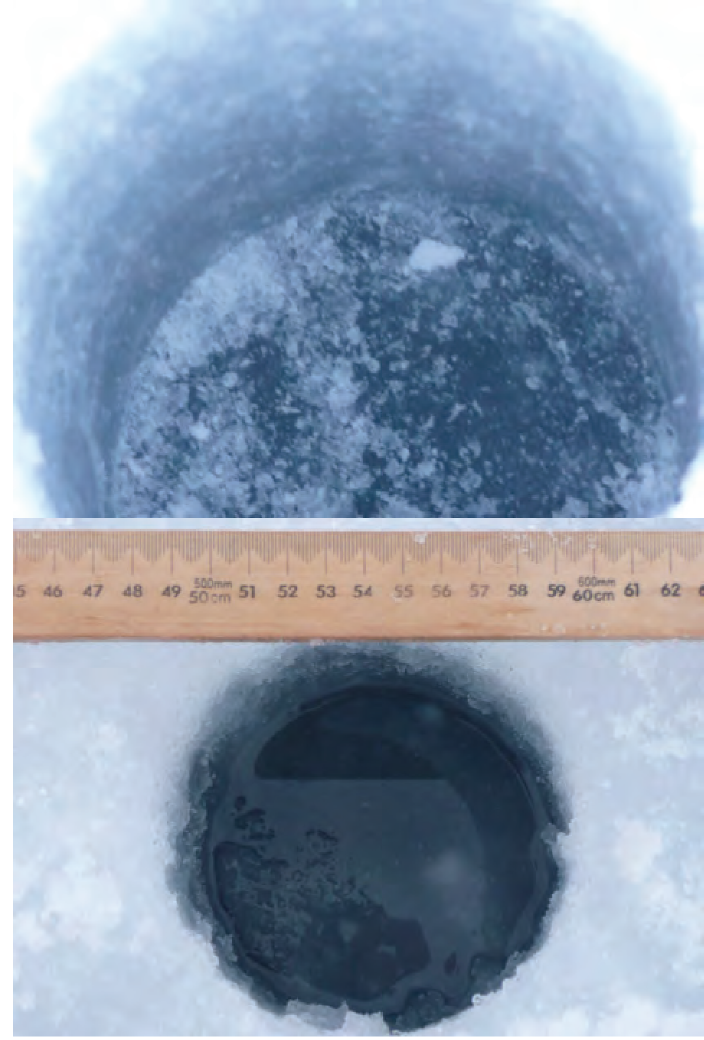
# Arctic and Antarctic field experiments

## *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*** |


*photo by Jan Lieser*

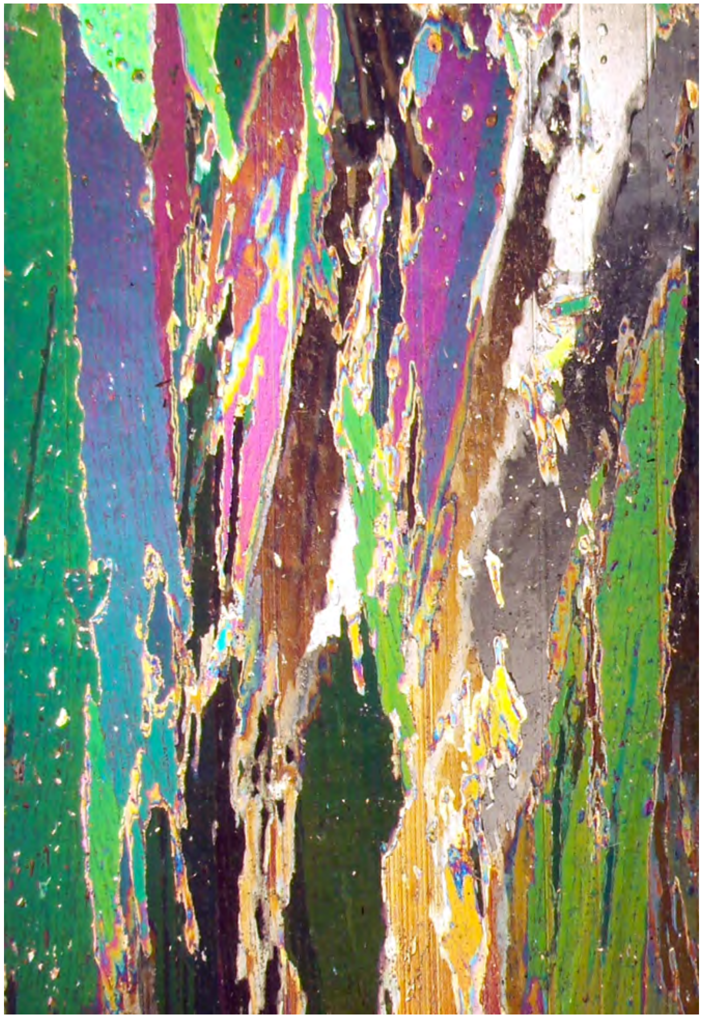


***measuring***
***fluid permeability***
***of Antarctic sea ice***

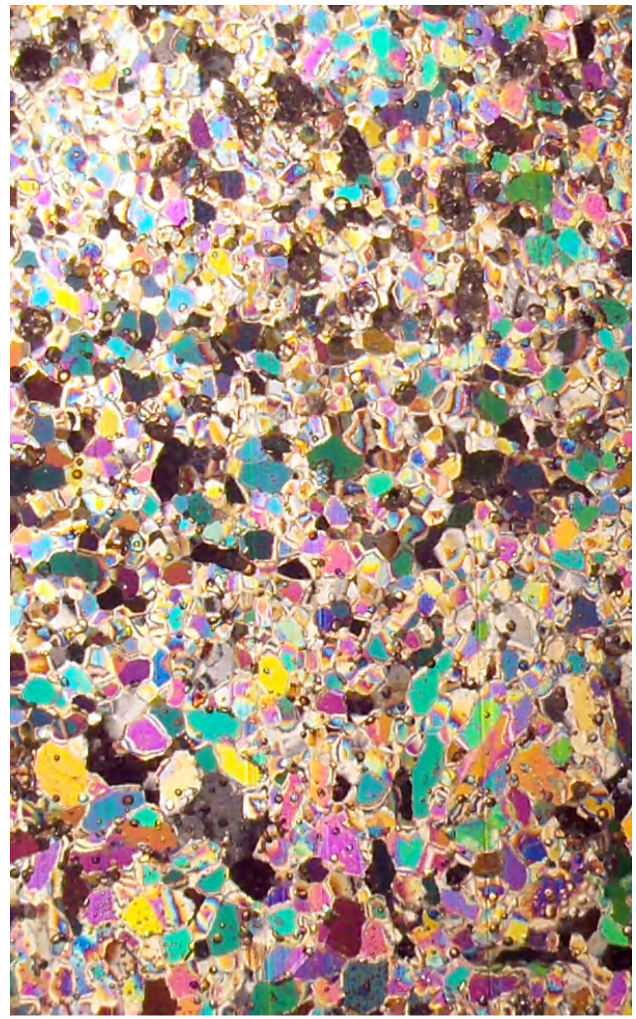
***SIPEX 2007***

## *higher threshold for fluid flow in Antarctic granular sea ice*

columnar



granular

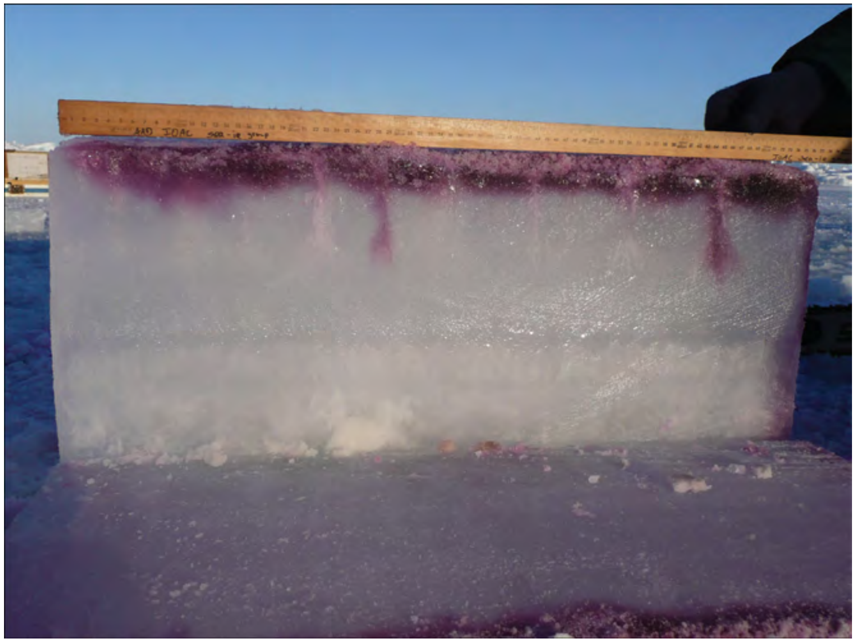


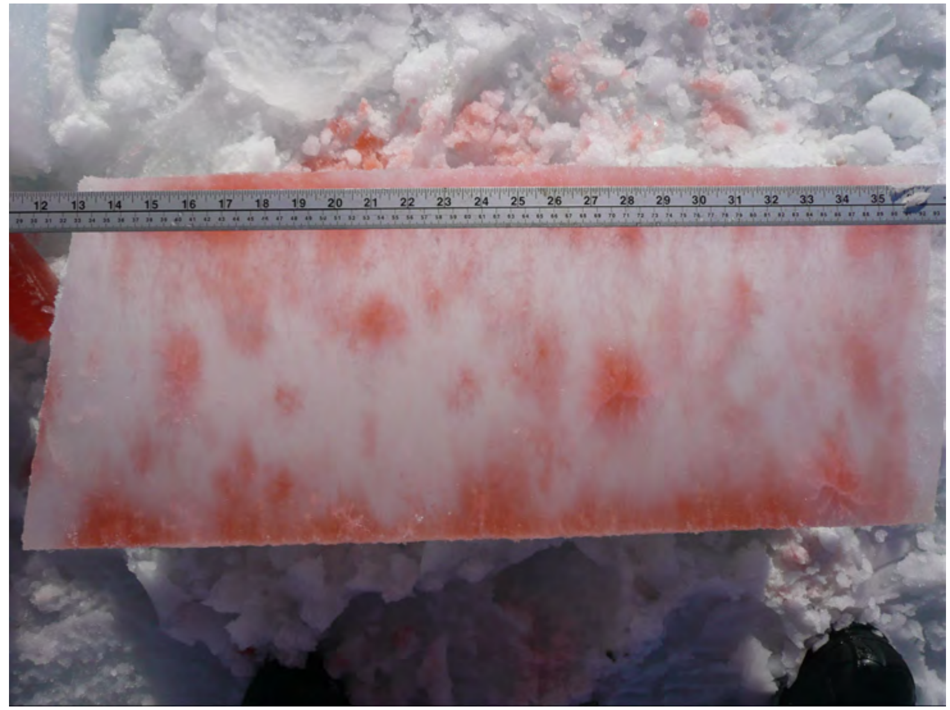
***5%***

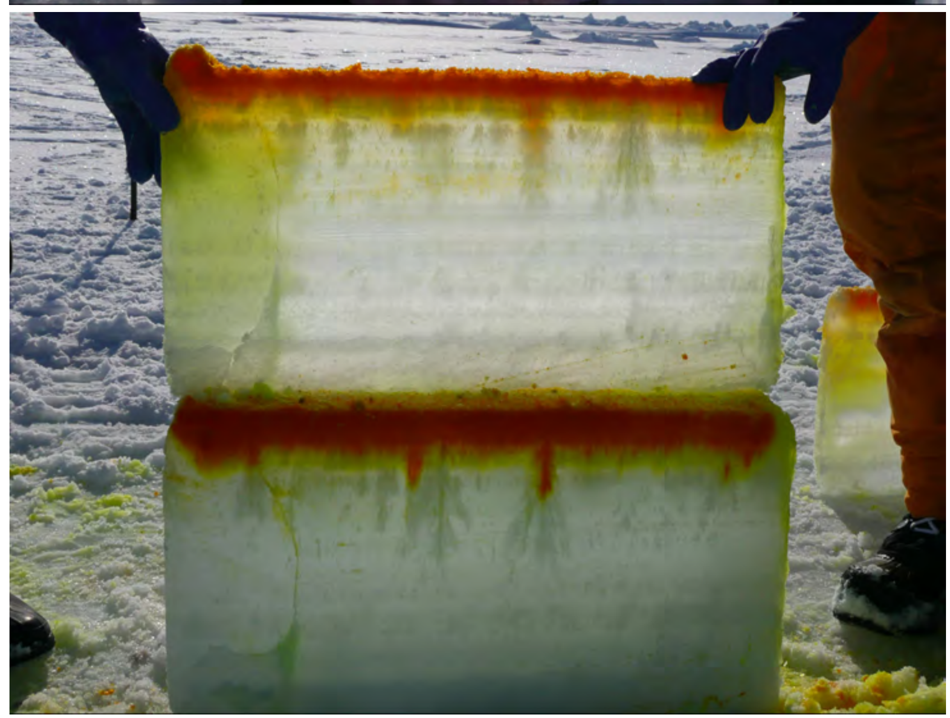
***10%***

***Golden, Sampson, Gully, Lubbers, Tison 2016***

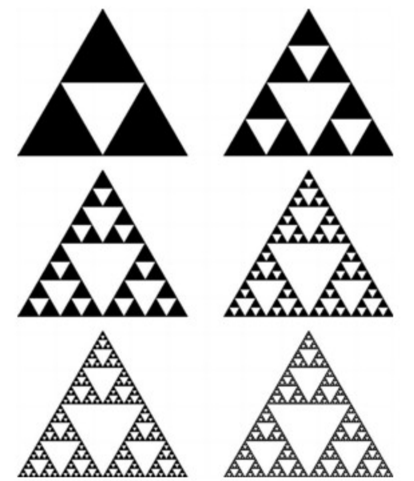
# tracers flowing through inverted sea ice blocks





# *fractals and multiscale structure*

## *melt pond formation and albedo evolution:*

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

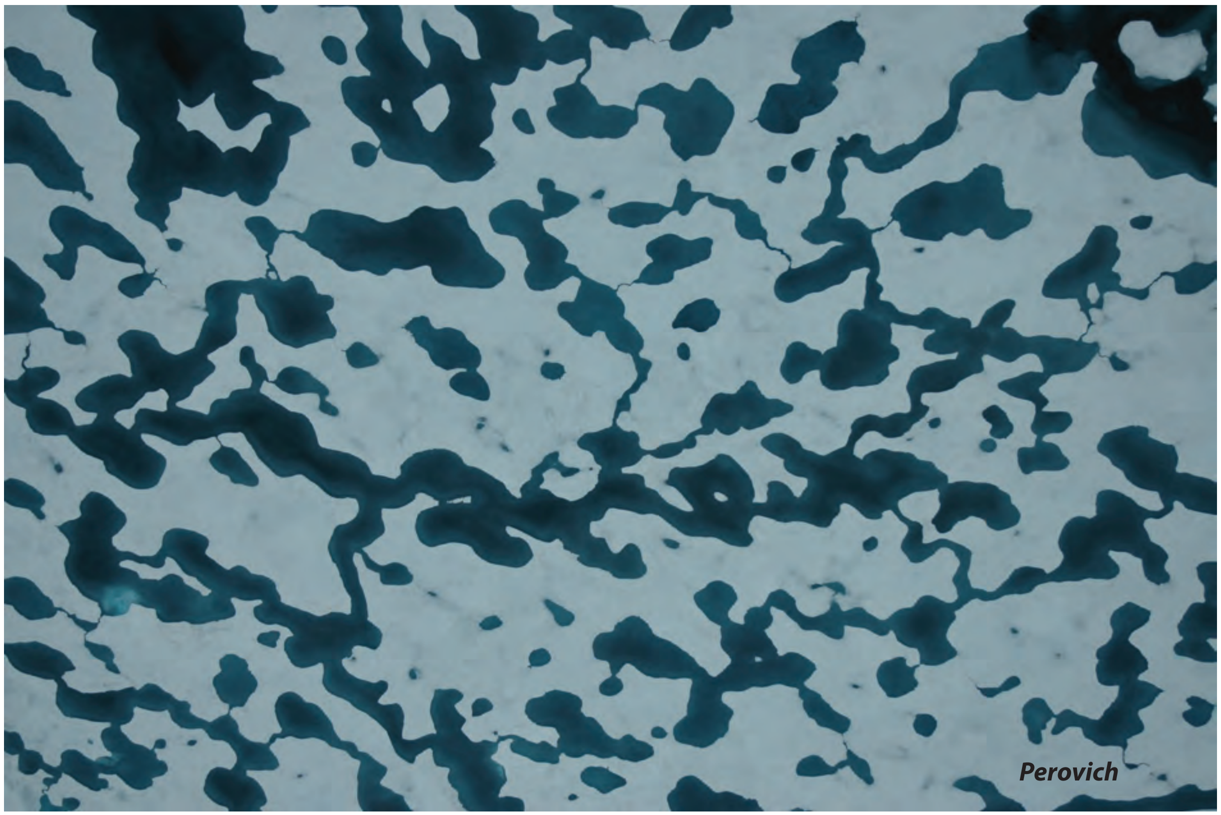
**numerical models of melt pond evolution, including topography, drainage (permeability), etc.**

Lüthje, Feltham, Taylor, Worster 2006

Flocco, Feltham 2007

Skyllingstad, Paulson, Perovich 2009

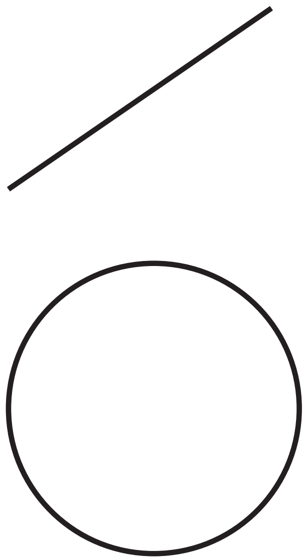
Flocco, Feltham, Hunke 2012




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

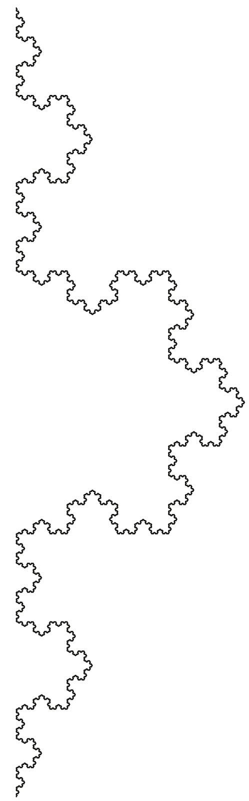
# fractal curves in the plane

## they wiggle so much that their dimension is >1



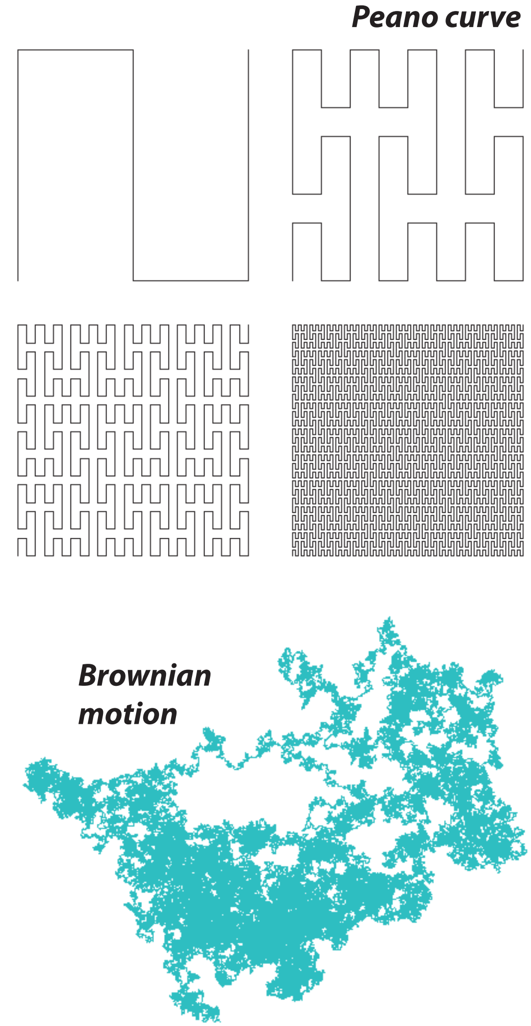
*simple curves*

$D = 1$



*Koch snowflake*

$D = 1.26$




*space filling curves*

$D = 2$

# *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*

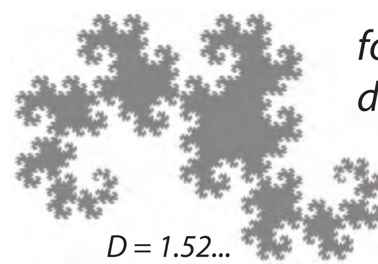
L

L

$A = L^2$

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

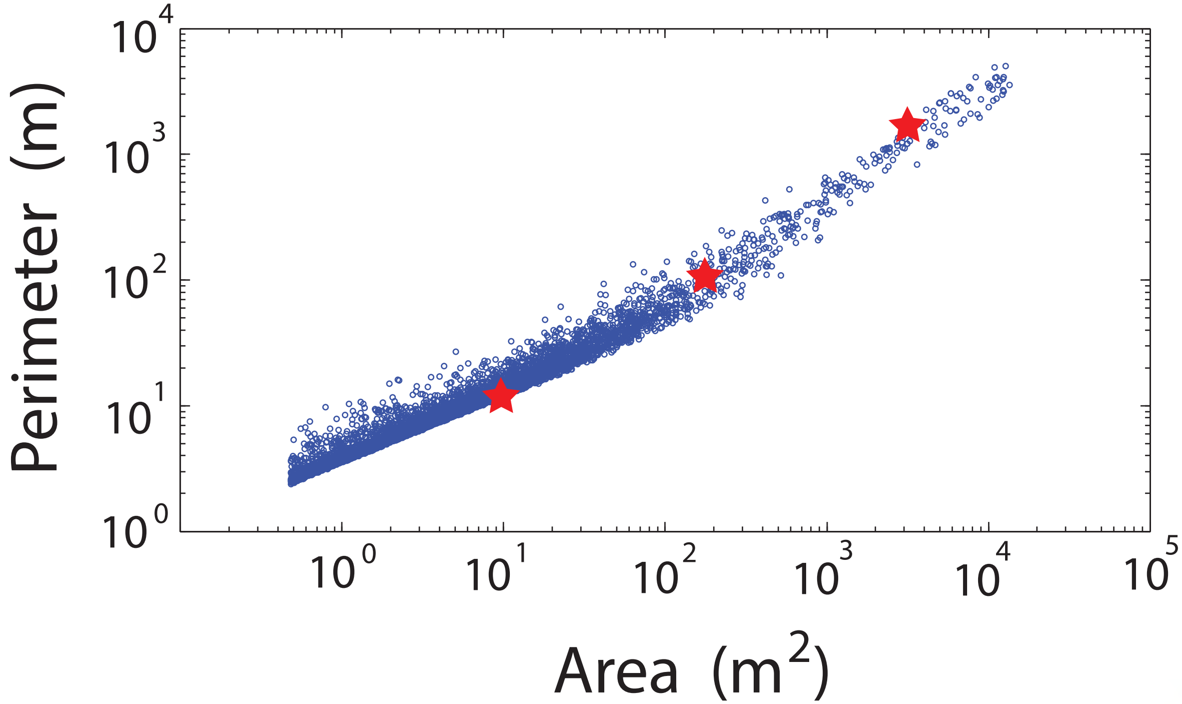
$$P \sim \sqrt{A}^{\,D}$$




*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

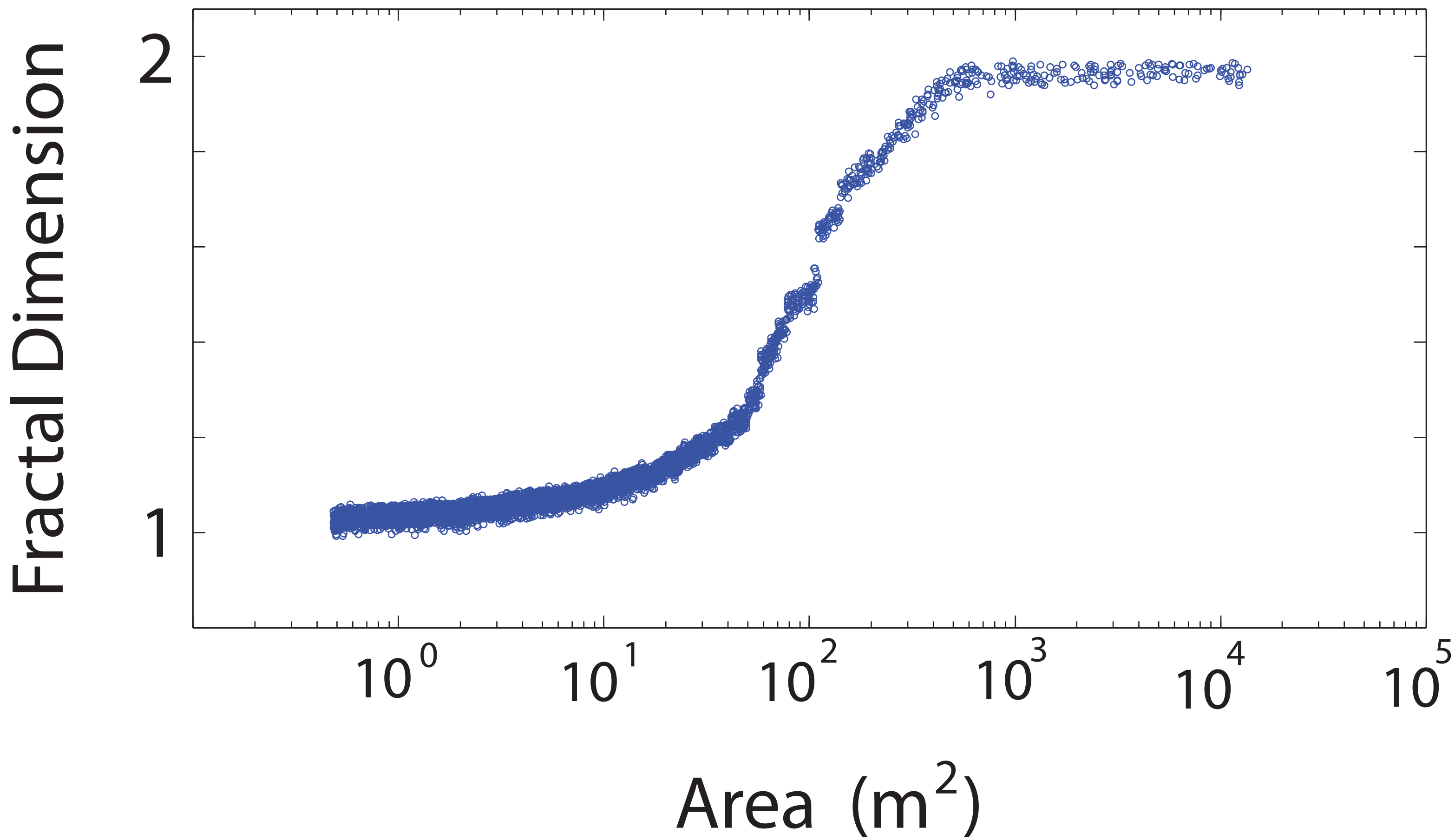



data from 5269 Arctic melt ponds


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

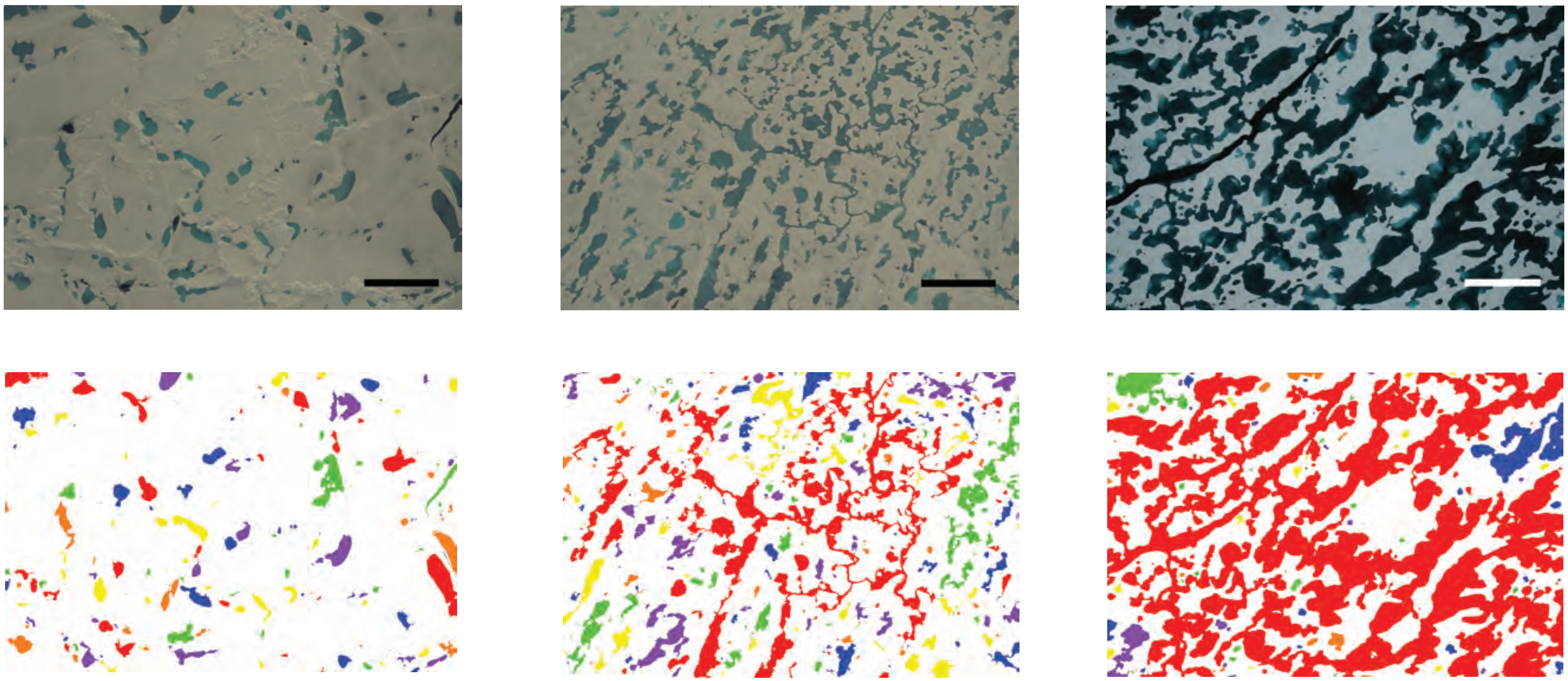
## *transition in the fractal dimension*

**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

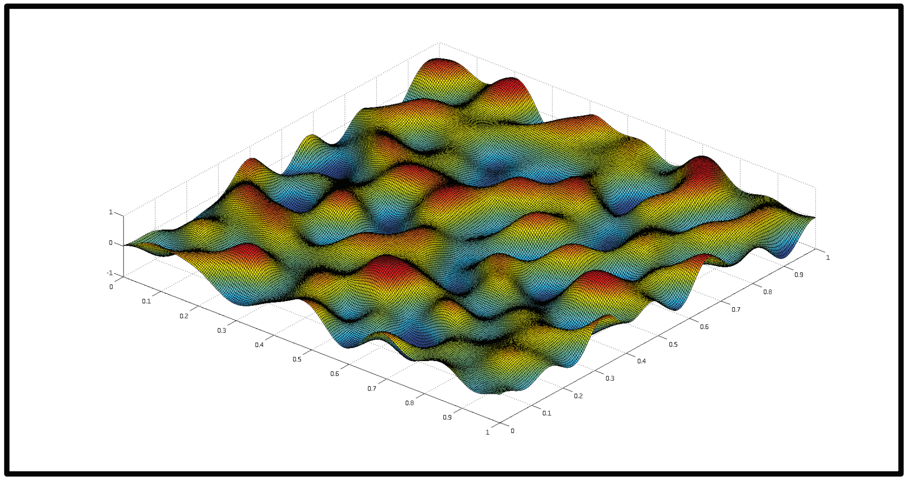
**results on percolation threshold, correlation length, cluster behavior**

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

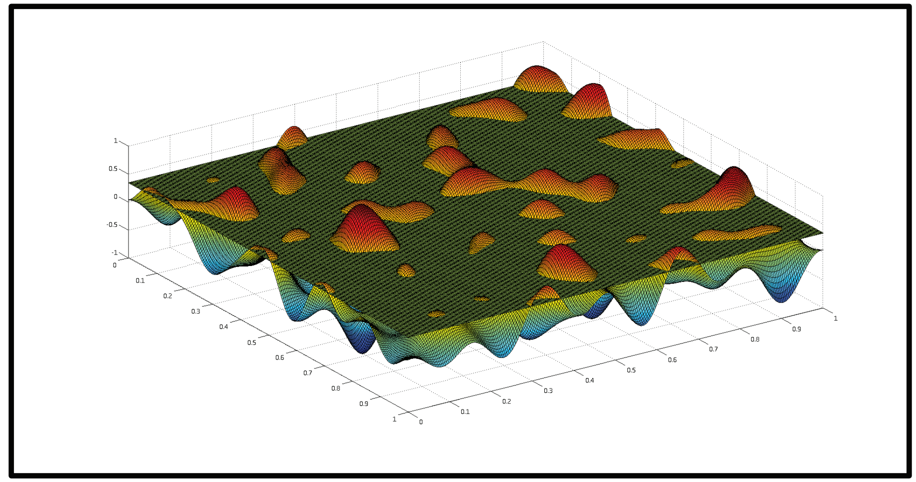
# Continuum percolation model for melt pond evolution

## *level sets of random surfaces*

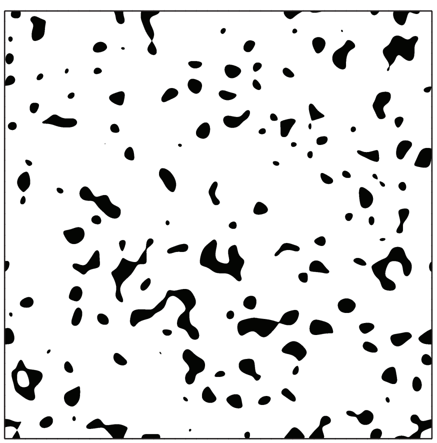
*Brady Bowen, Court Strong, Ken Golden, J. Fractal Geometry 2017*

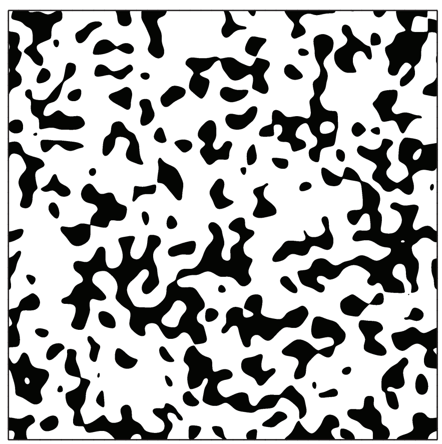


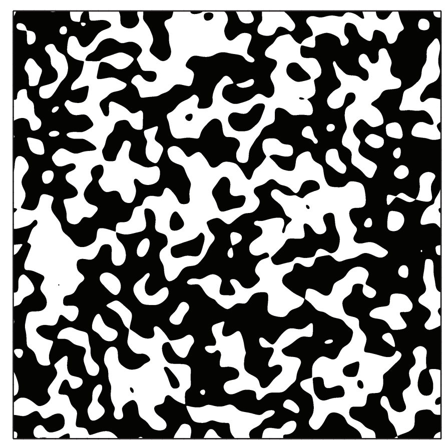
random Fourier series representation of surface topography



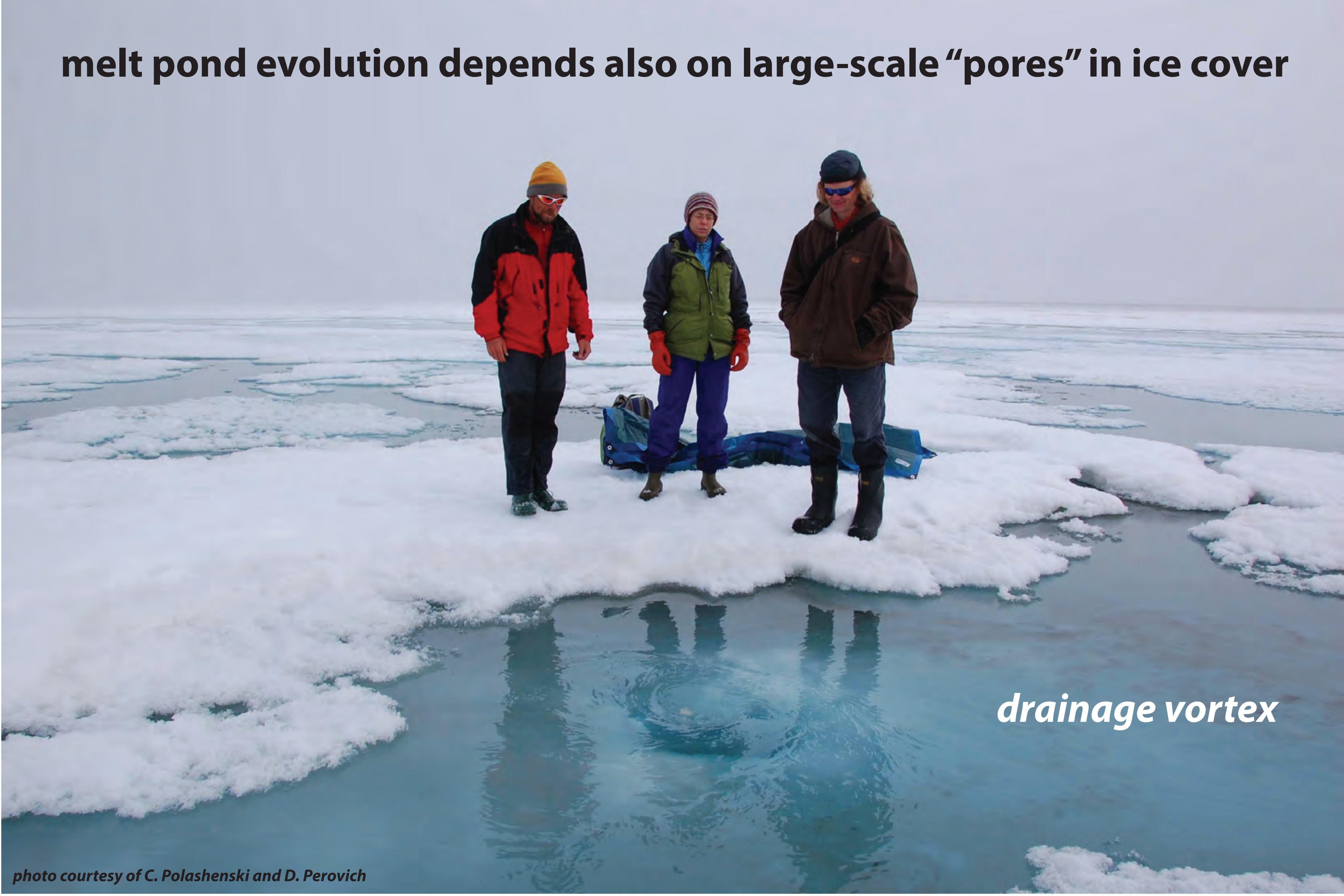
## intersections of a plane with the surface define melt ponds







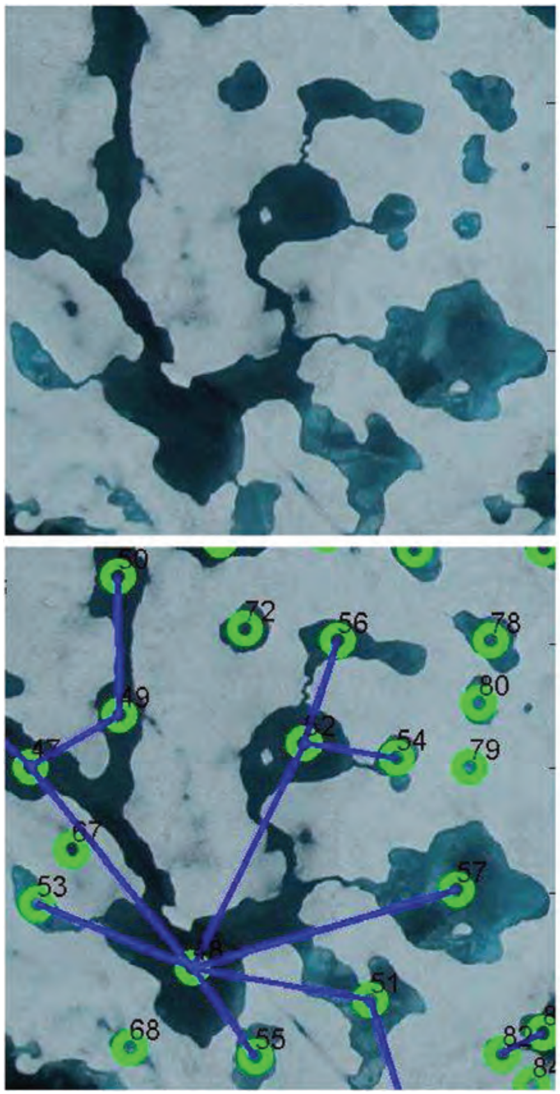
*electronic transport in disordered media* *diffusion in turbulent plasmas* *Isichenko, Rev. Mod. Phys., 1992* melt pond evolution depends also on large-scale "pores" in ice cover




Melt pond connectivity enables vast expanses of melt water to drain down seal holes, thaw holes, and leads in the ice.

# Network modeling of Arctic melt ponds

Barjatia, Tasdizen, Song, Sampson, Golden
*Cold Regions Science and Tecnology*, 2016




**develop algorithms to map images of melt ponds onto**

**random resistor networks**

**graphs of nodes and edges with edge conductances**

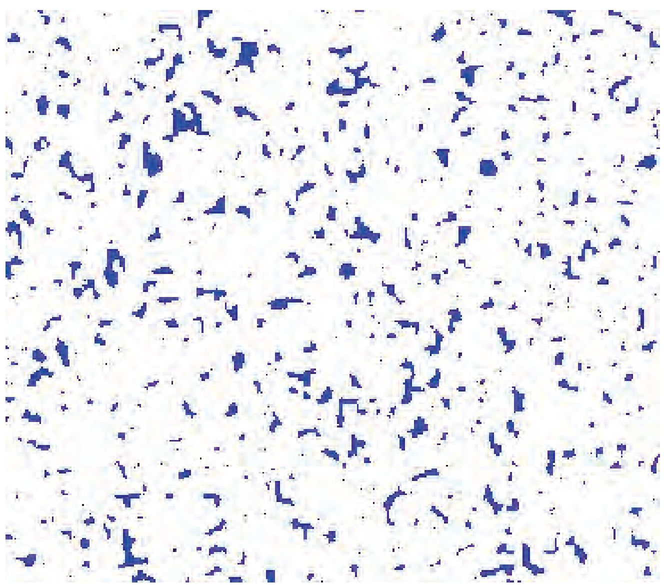
edge conductance ~ neck width

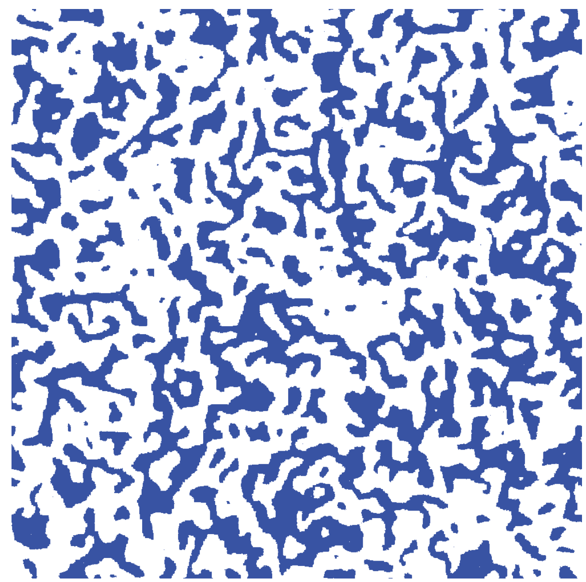
***compute effective horizontal fluid conductivity***

**Ising model for ferromagnets** $\longrightarrow$ **Ising model for melt ponds**

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

**magnetization** $M = \lim_{N\to\infty} \frac{1}{N} \left\langle \sum_j s_j \right\rangle$ **pond coverage** $\frac{(M+1)}{2}$





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

predictions of fractal transition, pond size exponent **Ma, Sudakov, Strong, Golden 2017**

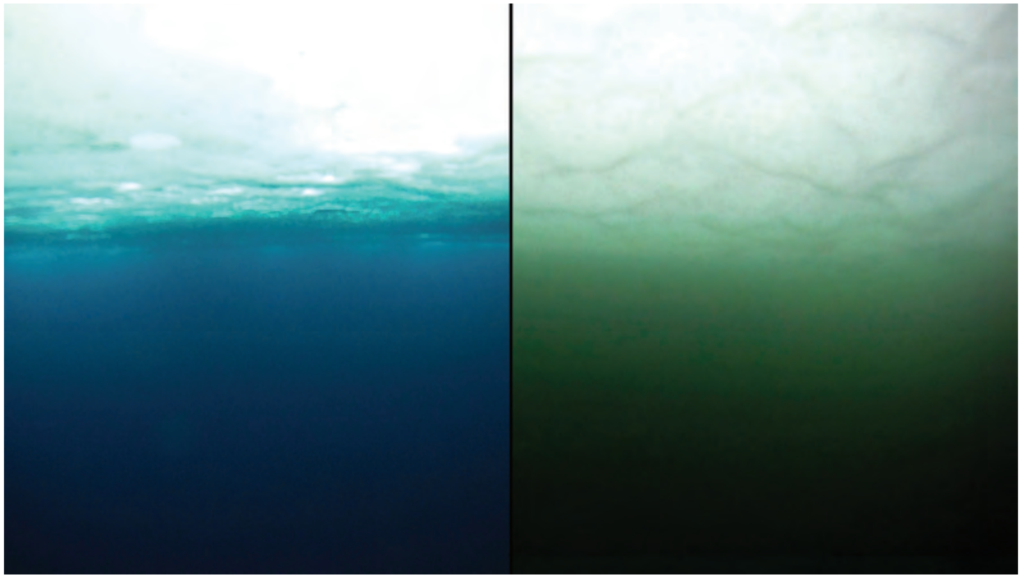
2011 massive
under-ice algal bloom

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 Melt Pond Conundrum:

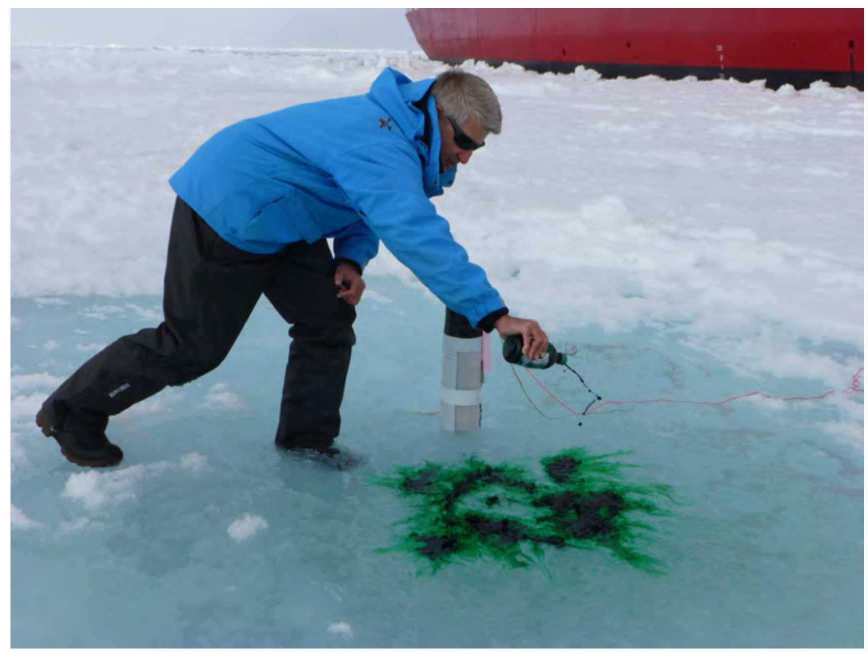
## *How can ponds form on top of sea ice that is highly permeable?*

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. Summer Arctic sea ice is melting rapidly, and melt ponds and other processes must be accounted for in order to predict melting rates.

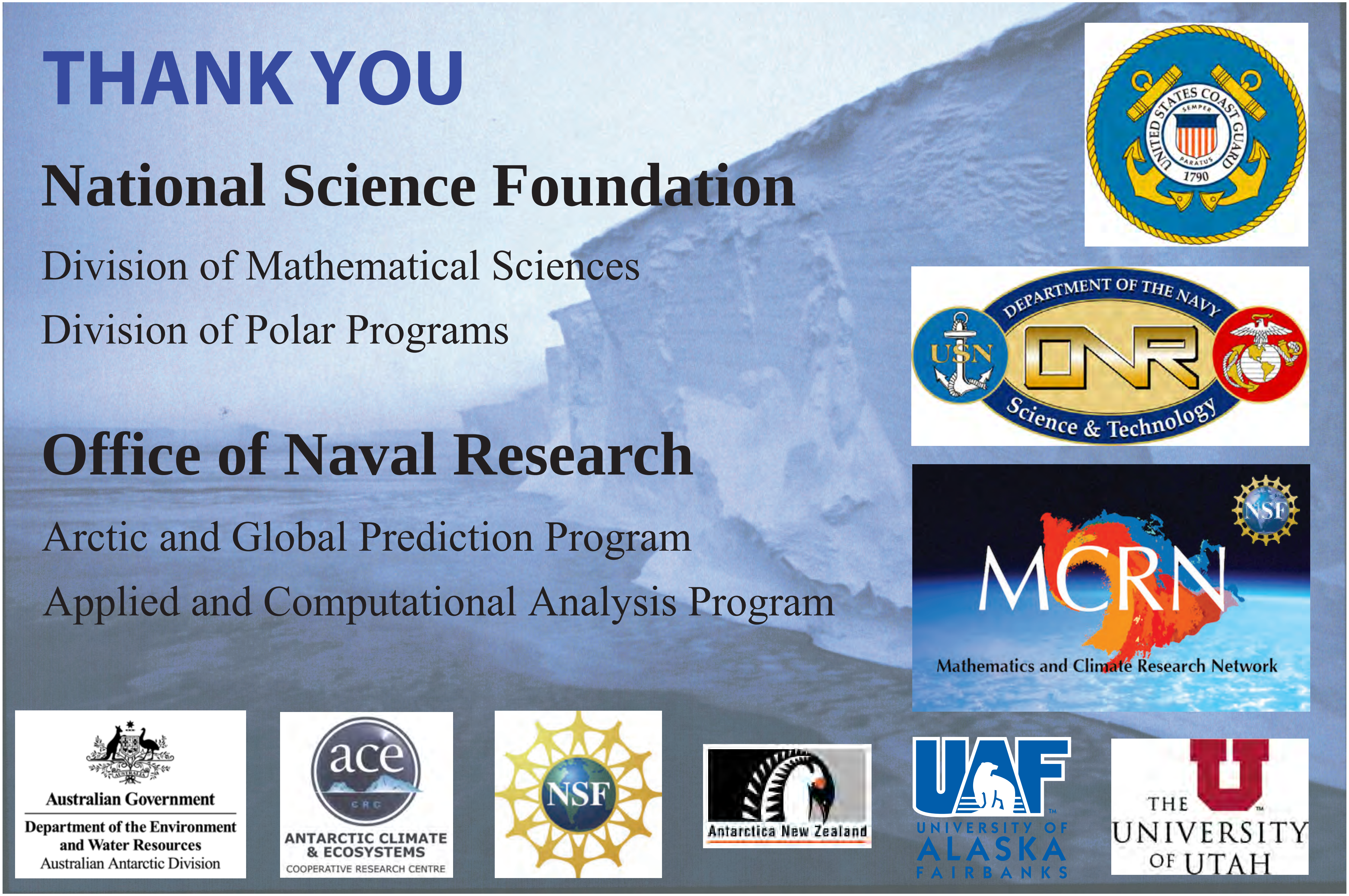
2. Fluid flow through sea ice mediates melt pond evolution and many processes important to climate change and polar ecosystems.

3. Statistical physics and homogenization help *link scales*, provide rigorous methods for finding effective behavior, and advance how sea ice is represented in climate models.

4. Critical behavior (in many forms) is inherent in the climate system.

5. Field experiments are essential to developing relevant mathematics.

6. Our research will help to improve projections of climate change, the fate of Earth's sea ice packs, and the ecosystems they support.




***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.

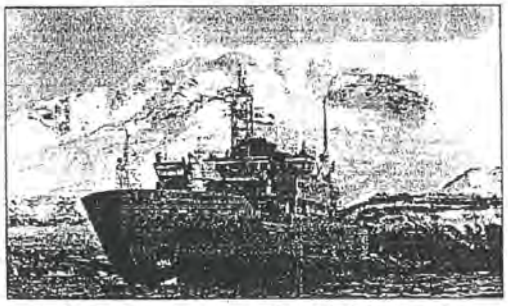
The gas had to be cleared before crew wearing breathing apparatus could enter and assess the situation.

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.



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."

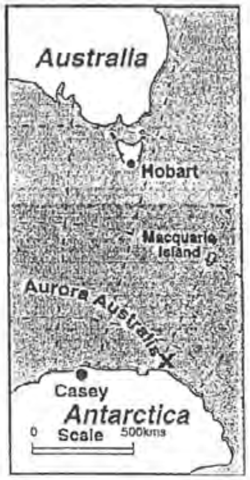
The Aurora Australis is owned by P&O Australia and charted by the Antarctic Division for about $11 million a year.

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.

2:45 am July 22, 1998

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

*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

about 10 minutes later ...

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