Sea Ice, Climate Change, and Polar Ecosystems

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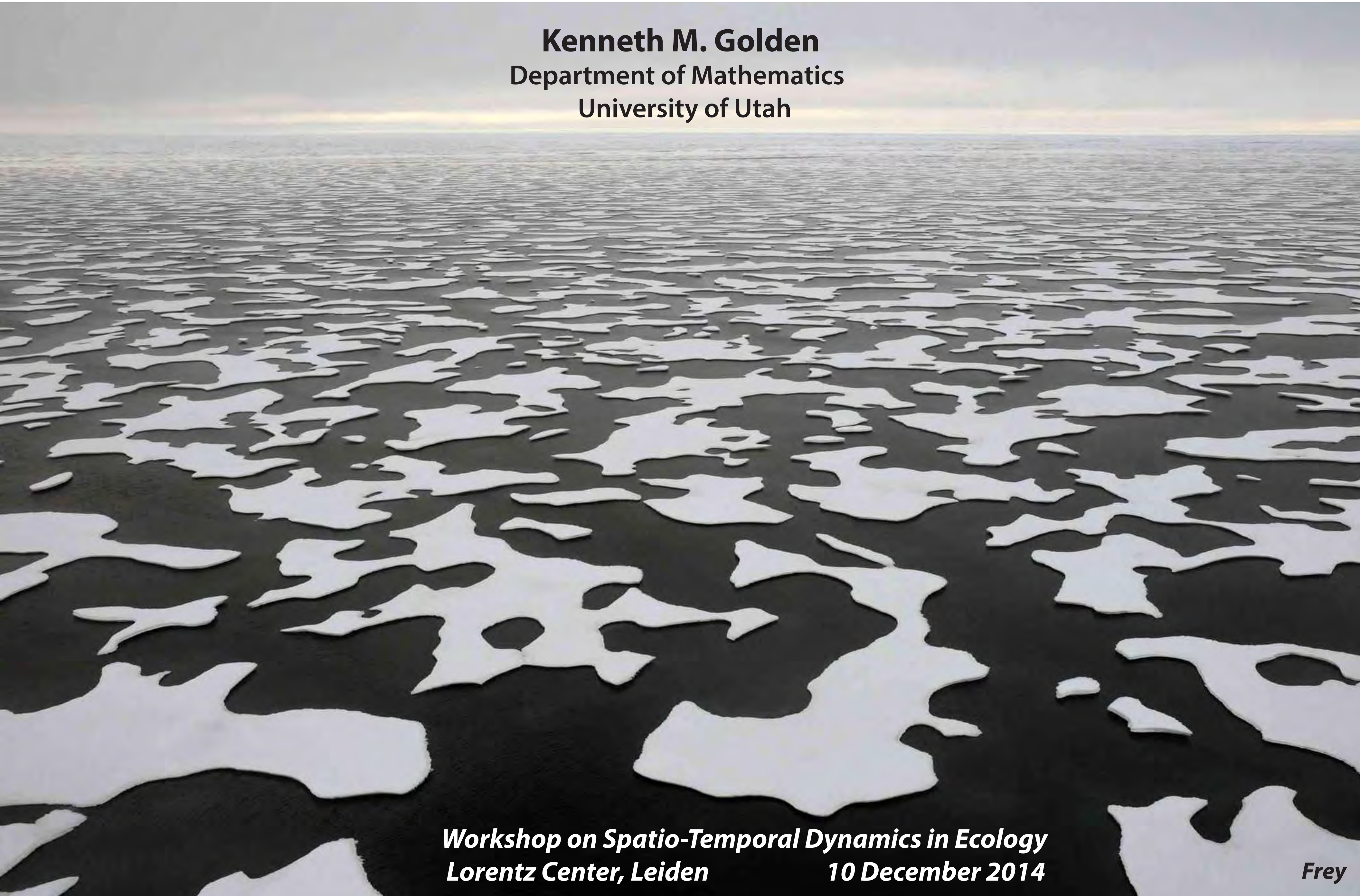
University of Utah



Workshop on Spatio-Temporal Dynamics in Ecology
Lorentz Center, Leiden *10 December 2014*

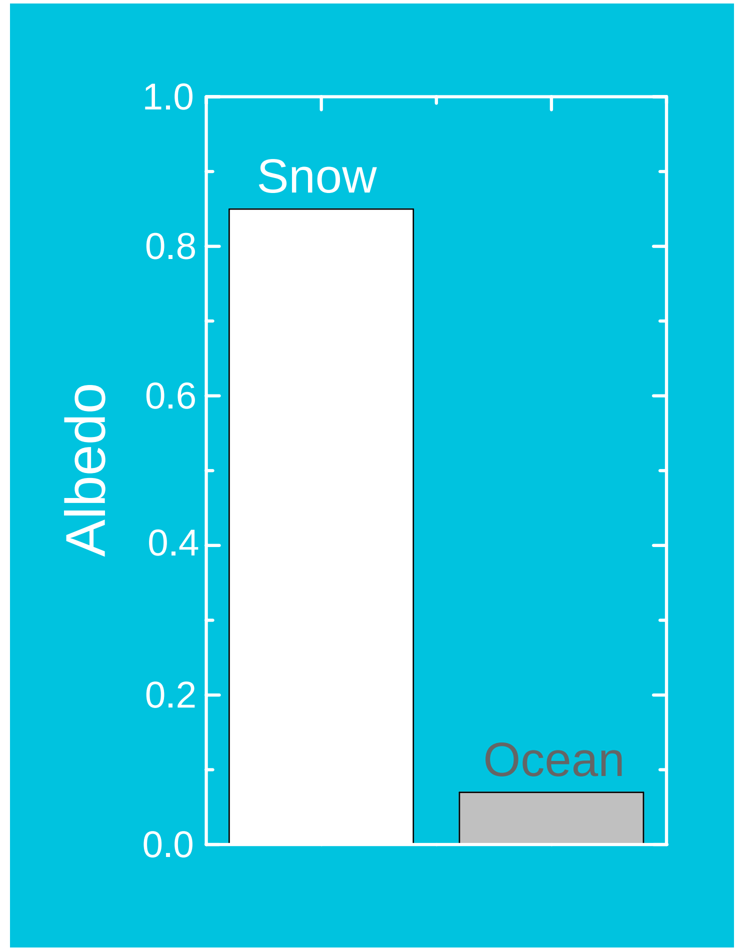
Frey

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

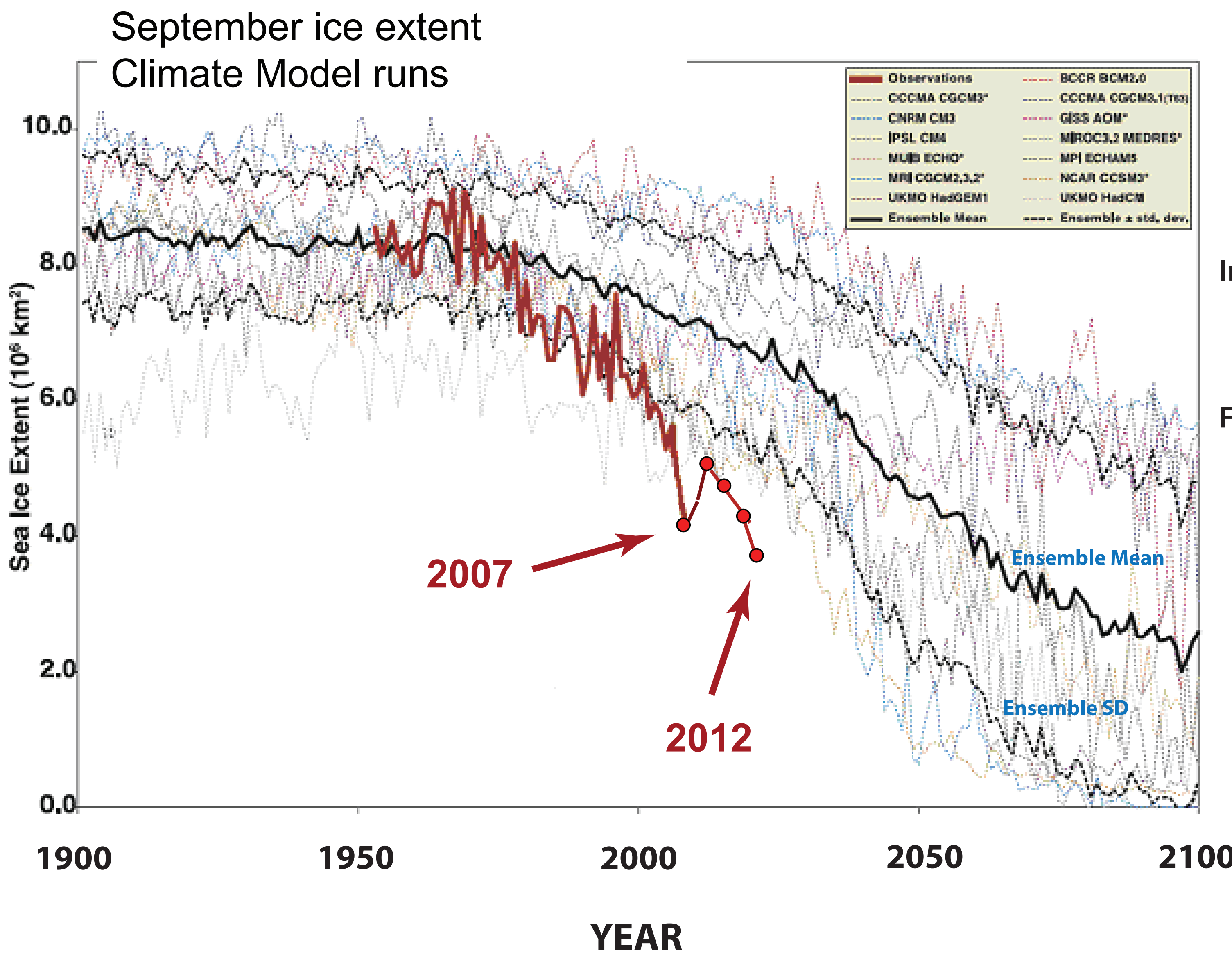


dark water and land absorb

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

Arctic sea ice decline - faster than predicted by climate models

Stroeve et al., GRL, 2007



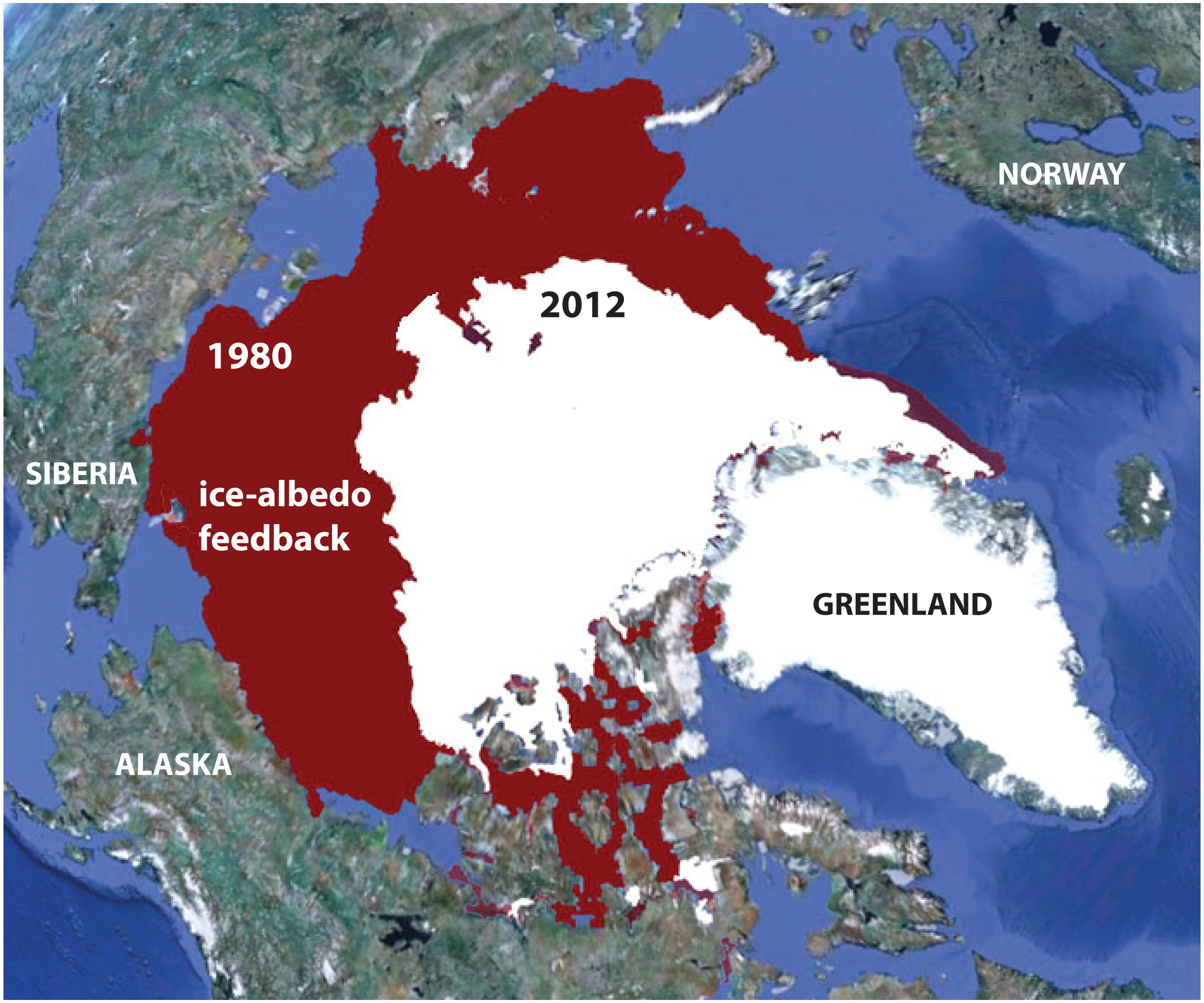
IPCC AR4 Models

Intergovernmental Panel on Climate Change (IPCC)

Fourth Assessment AR4, 2007

Change in Arctic Sea Ice Extent

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



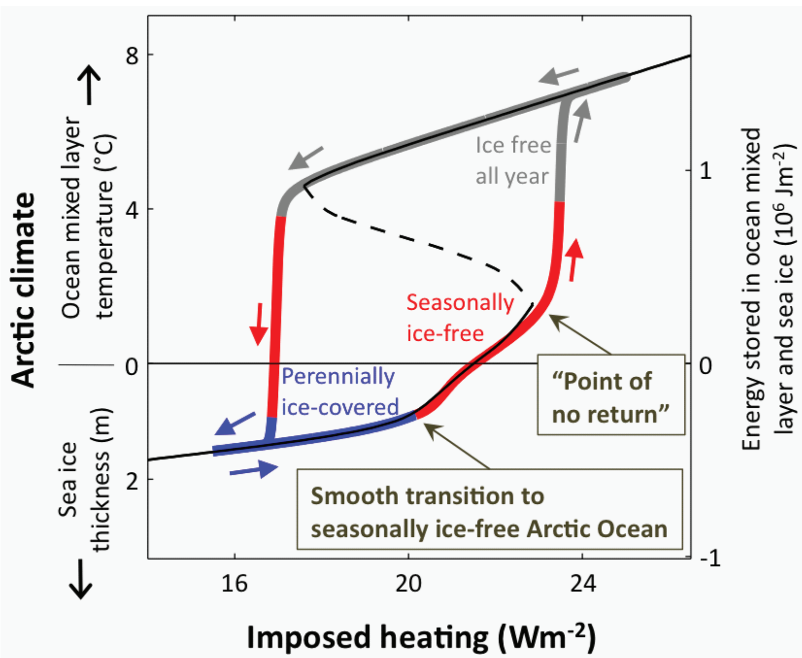
Perovich

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

an irreversible downward slide to ice-free Arctic summers (with hysteresis) driven by ice-albedo feedback

low order (toy) models of climate change

Eisenman, Wettlaufer, PNAS 2009: nonlinear ODE for energy in upper ocean



look for bifurcations in solutions

multiple equilibria: ice-free, ice covered, ...

- tipping point unlikely in loss of summer ice

Abbot, Silber, Pierrehumbert, JGR 2011

bifurcations when include clouds, ice loss

Sudakov, Vakulenko, Golden
Comm. Nonlinear Sci. & Num. Sim., 2014

impact of melt ponds

challenge

represent sea ice more rigorously in climate models

incorporate key processes

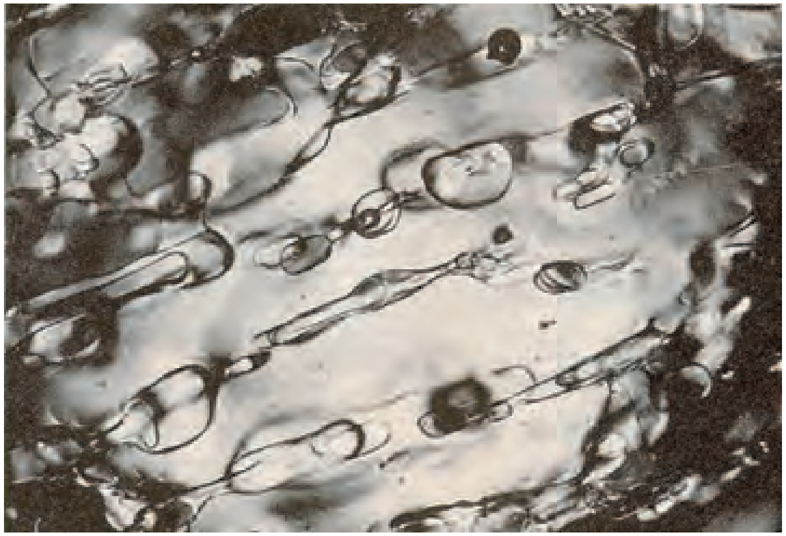
fundamental problem -- linkage of scales

sub-grid scale processes

sea ice is a multiscale composite

structured on many length scales

brine inclusions

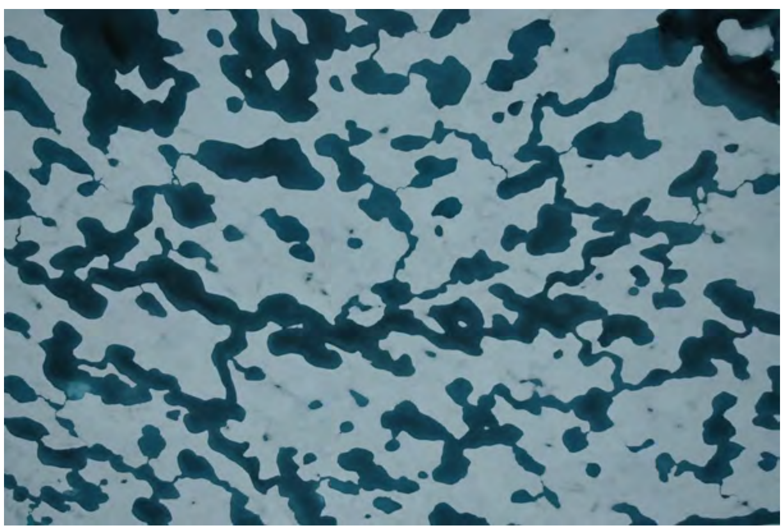


millimeters

pancakes

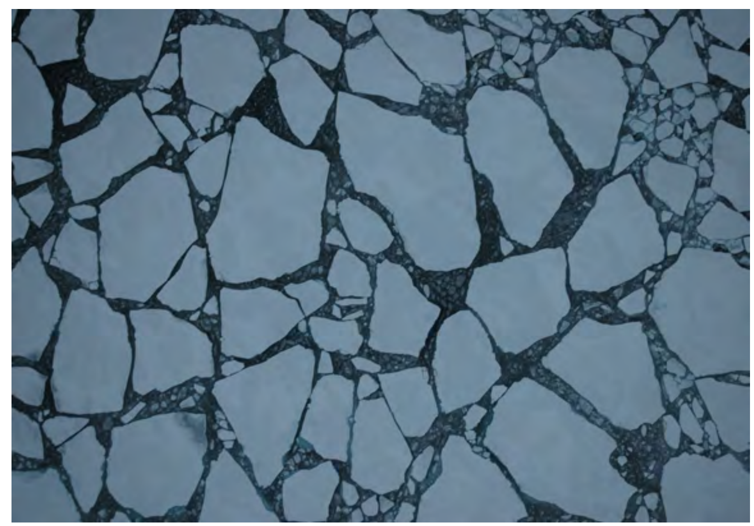
centimeters

melt ponds



meters

ice floes



kilometers

Who cares if Arctic sea ice disappears?

Use of sea ice as a platform

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

Photo: Marc Webber, US Fish & Wildlife Service

BMCM Tim Sullivan

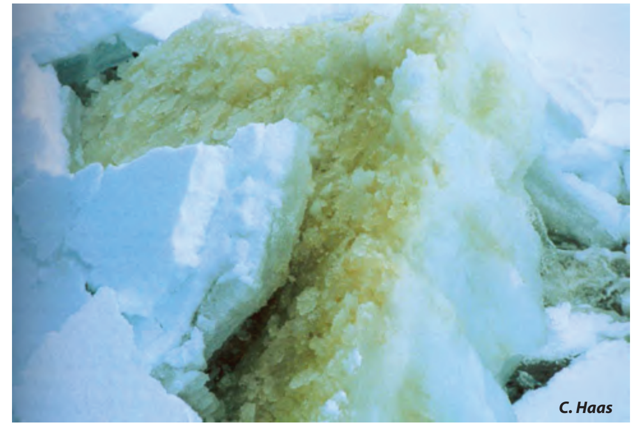
sea ice microphysics

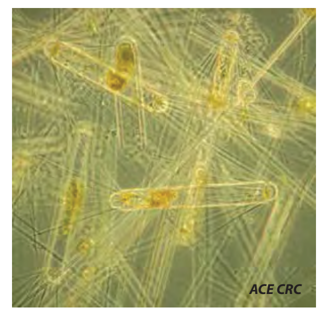
fluid transport

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

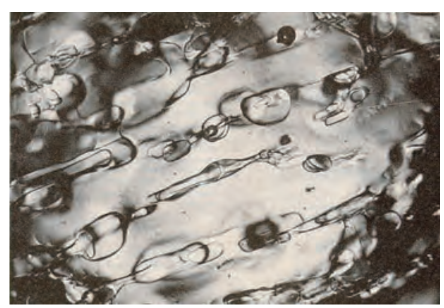
nutrient flux for algal communities





- *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

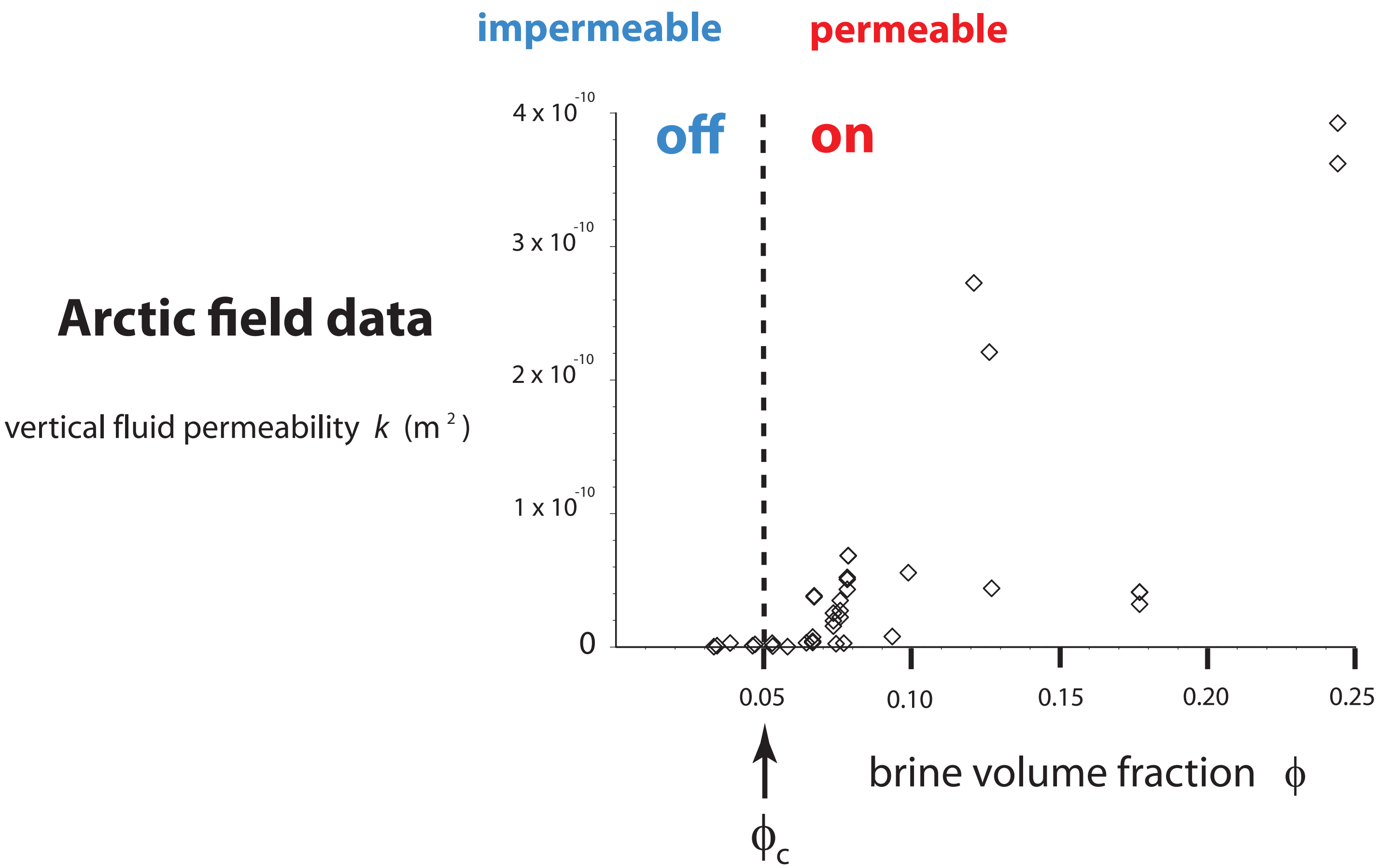
$\mathbf{k}$ = fluid permeability tensor

example of *homogenization*

mathematics for analyzing effective behavior of heterogeneous systems

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

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, *Geophys. Res. Lett.* 2007
Pringle, Miner, Eicken, Golden *J. Geophys. Res.* 2009

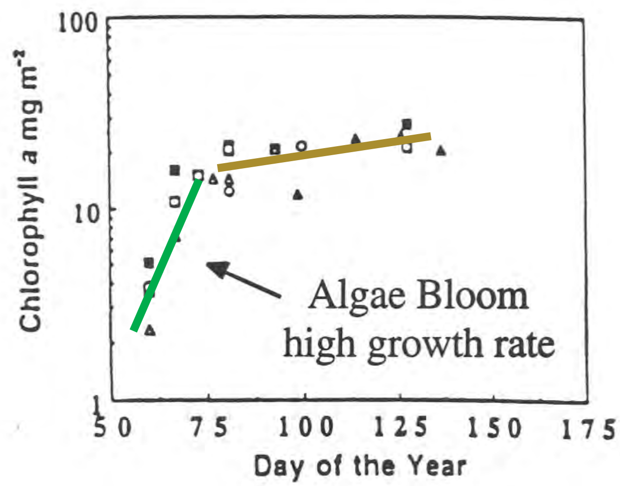
sea ice algal communities

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

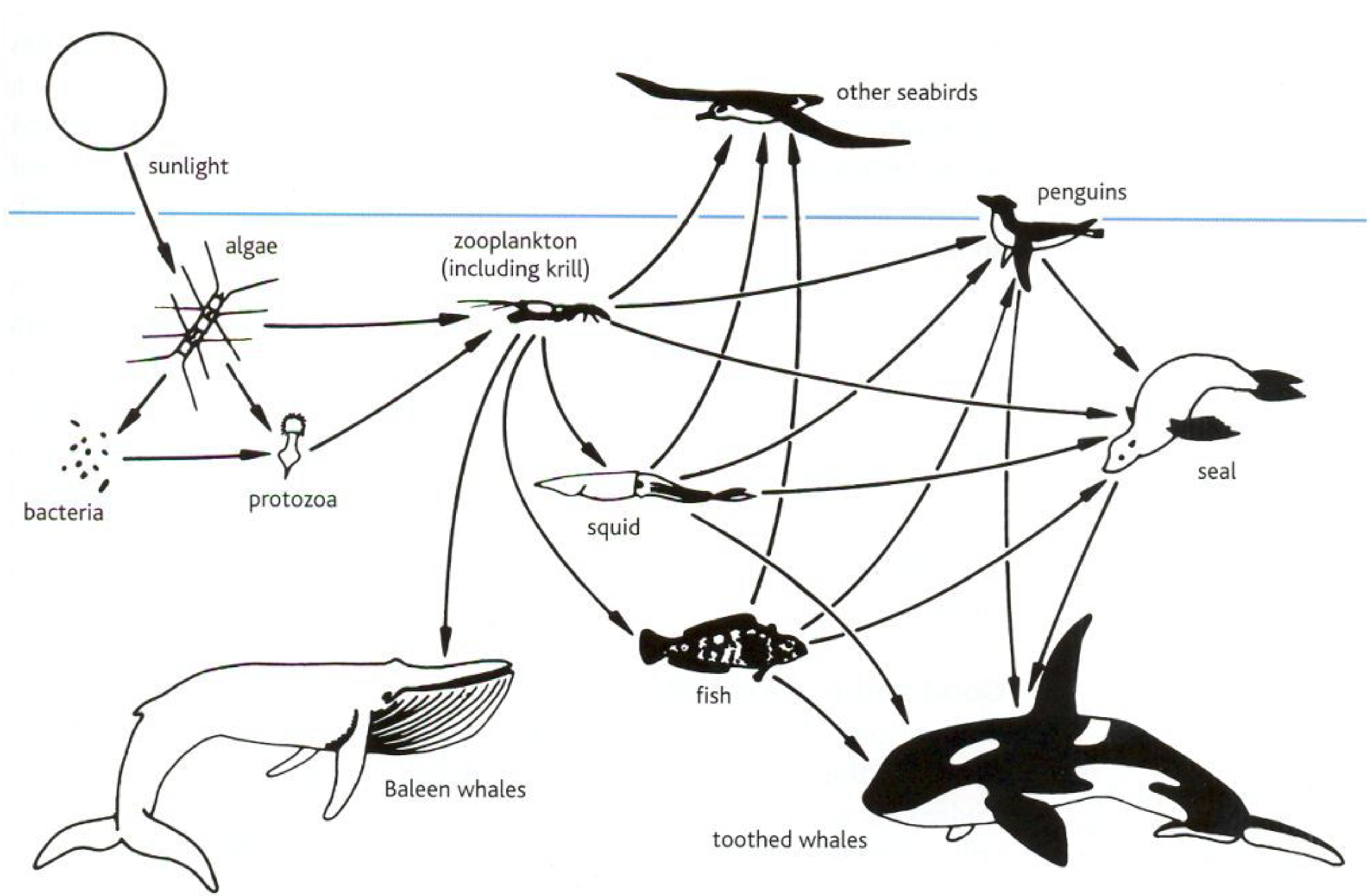
Golden, Ackley, Lytle ***Science 1998***

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

sea ice ecosystem

sea ice algae
support life in the polar oceans

Antarctic marine food web



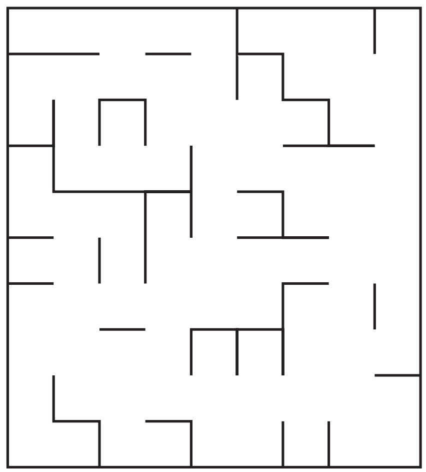
D. Thomas 2004

Why is the rule of fives true?

percolation theory

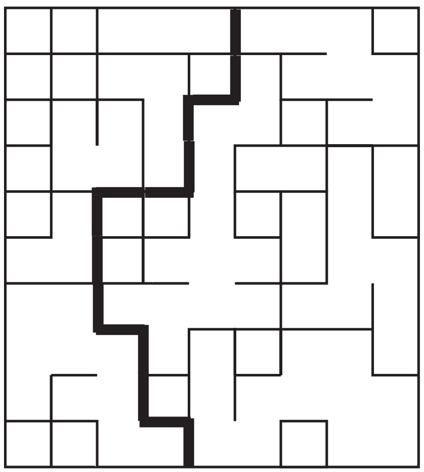
mathematical theory of connectedness

impermeable



$p = 1/3$

permeable



$p = 2/3$

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

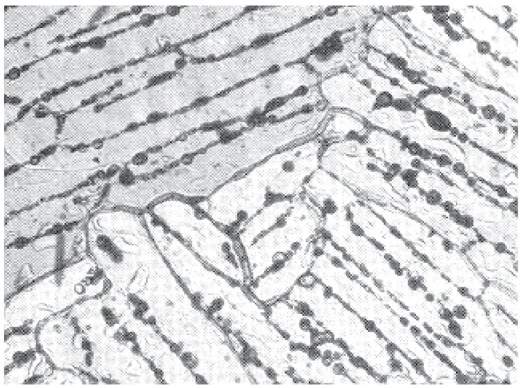
percolation threshold

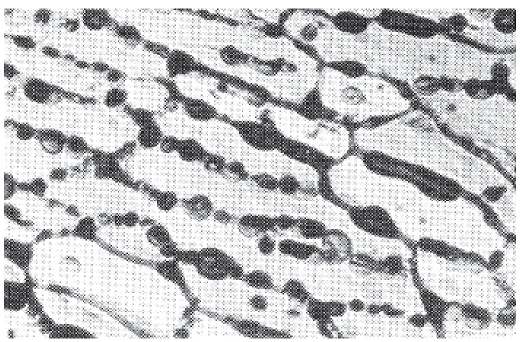
$p_c = 1/2$ for $d = 2$

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

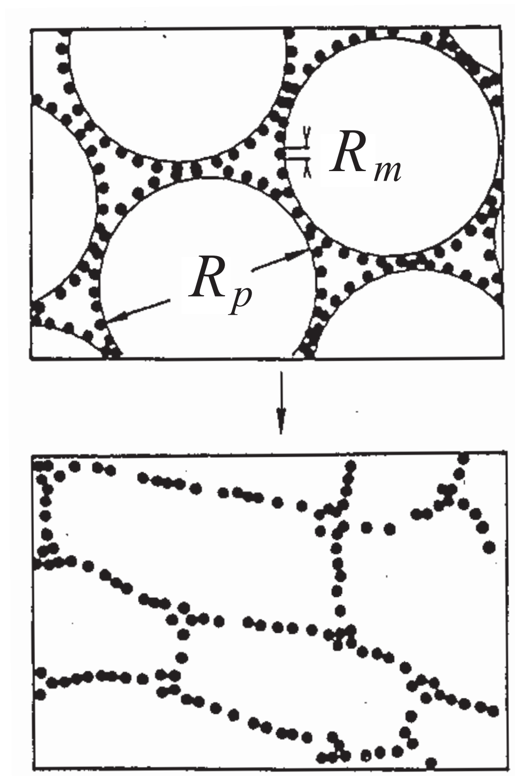
Continuum percolation model for ***stealthy*** materials applied to sea ice microstructure explains **Rule of Fives** and Antarctic data on ice production and algal growth

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

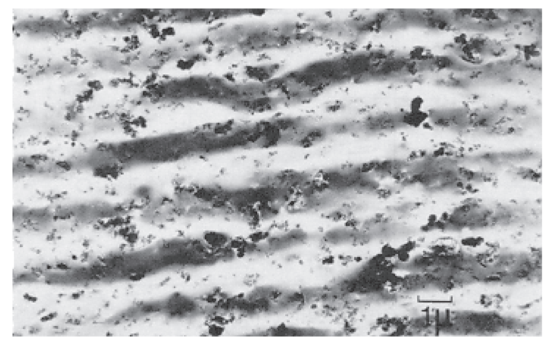




sea ice



compressed powder



radar absorbing composite

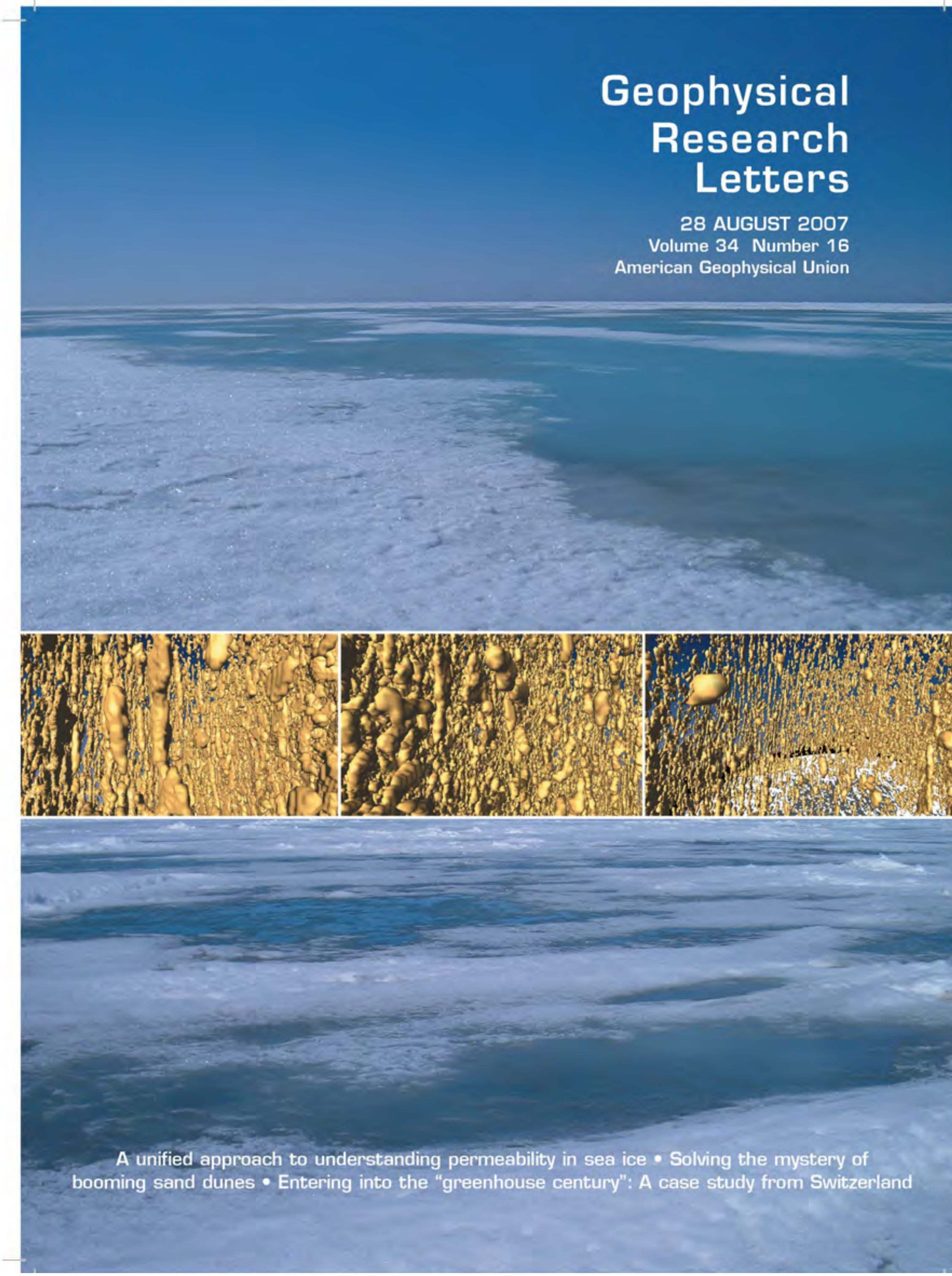
sea ice is radar absorbing

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

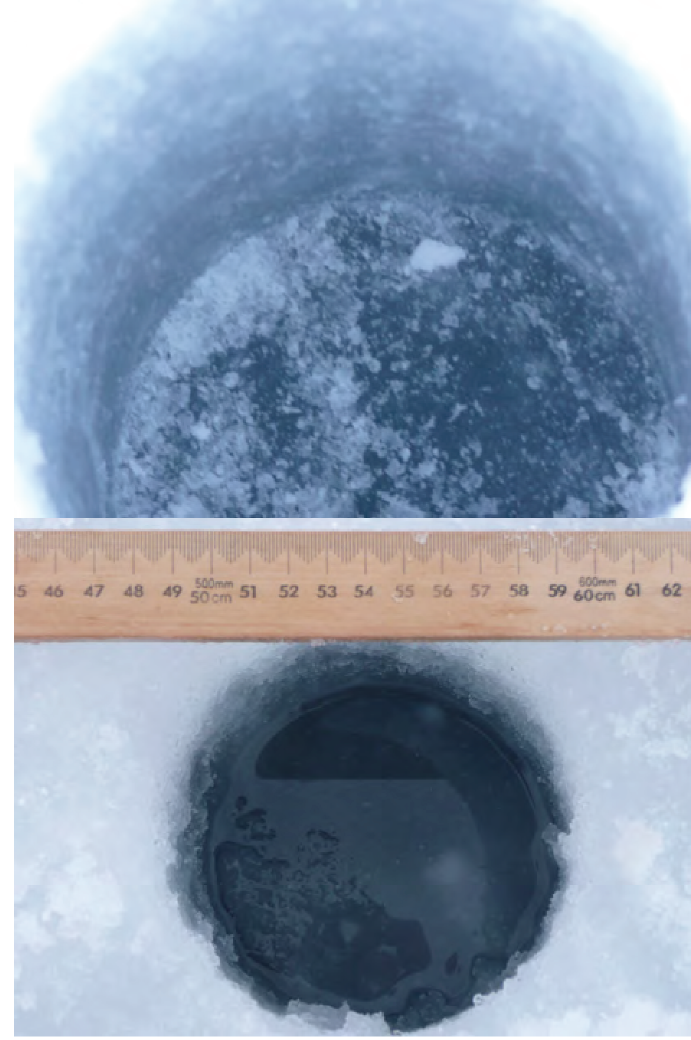
Arctic and Antarctic field experiments

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

Homogenization for diffusion processes

Anomalous diffusion and sea ice dynamics

sub- and super-diffusive behavior of motion of sea ice floes as tracked by buoy data

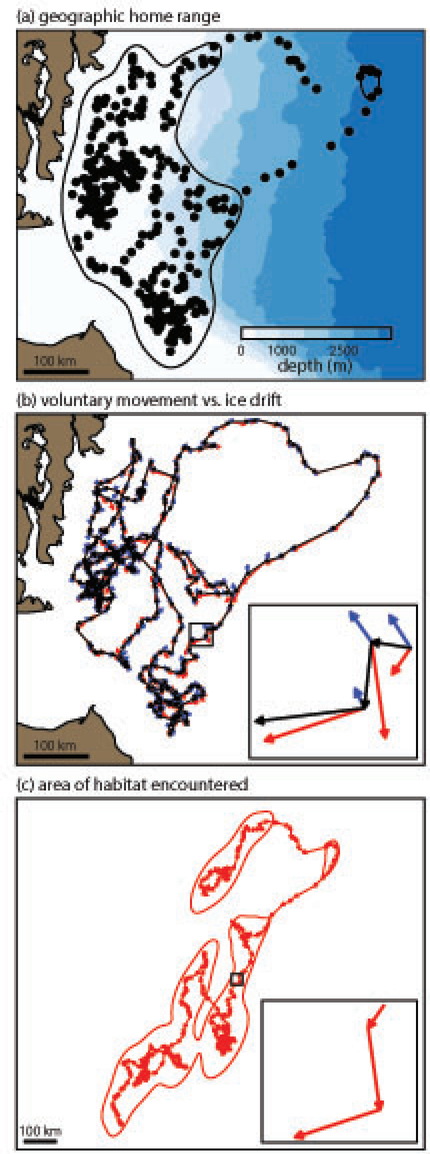
Jennifer Lukovich, Jennifer Hutchings, David Barber, 2014

Ben Murphy, Court Strong, Jack Xin (UC Irvine), Ken Golden

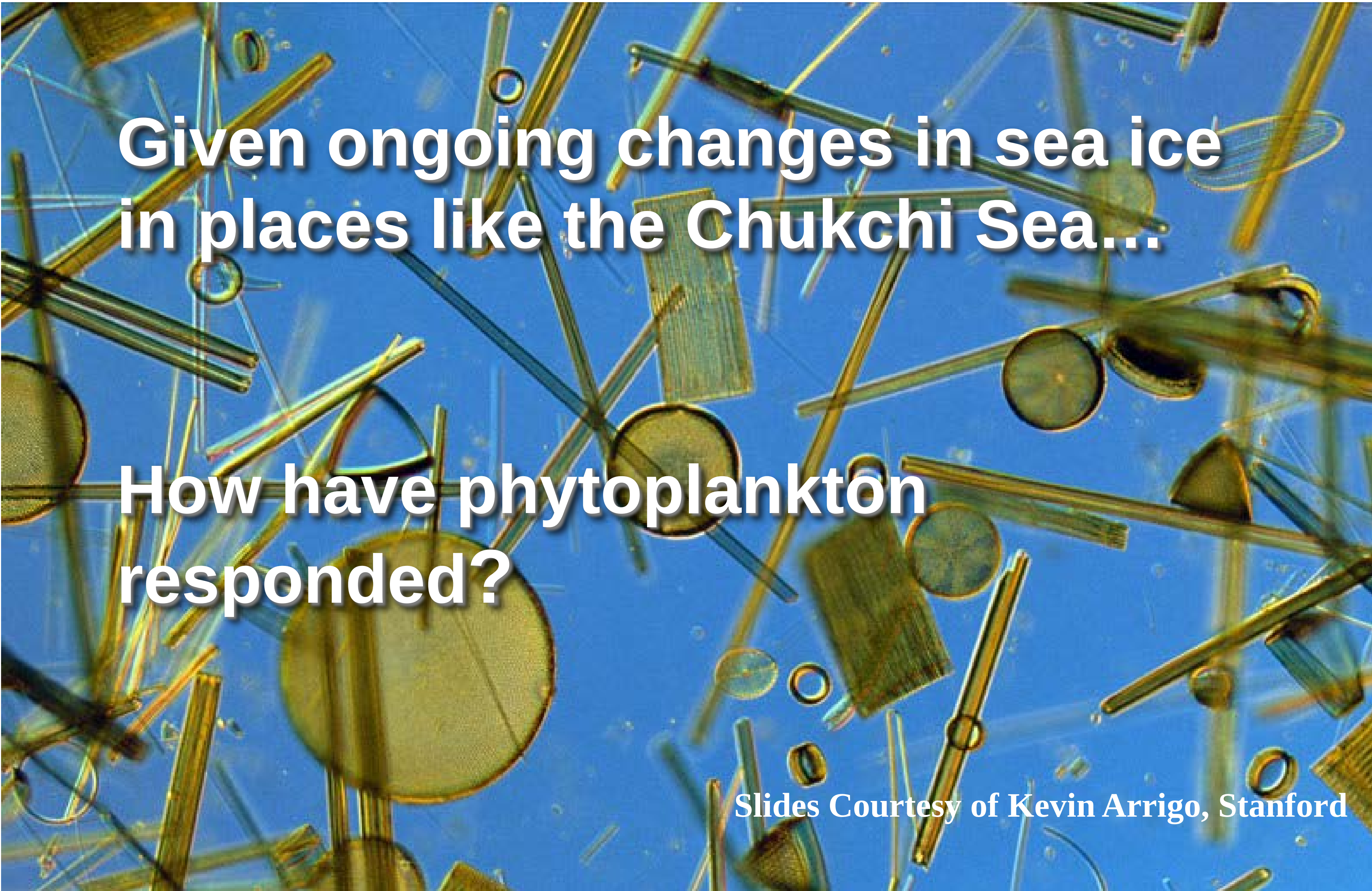
Home ranges in moving habitats: polar bears and sea ice

"diffusive" polar bear motion superimposed with drifting sea ice

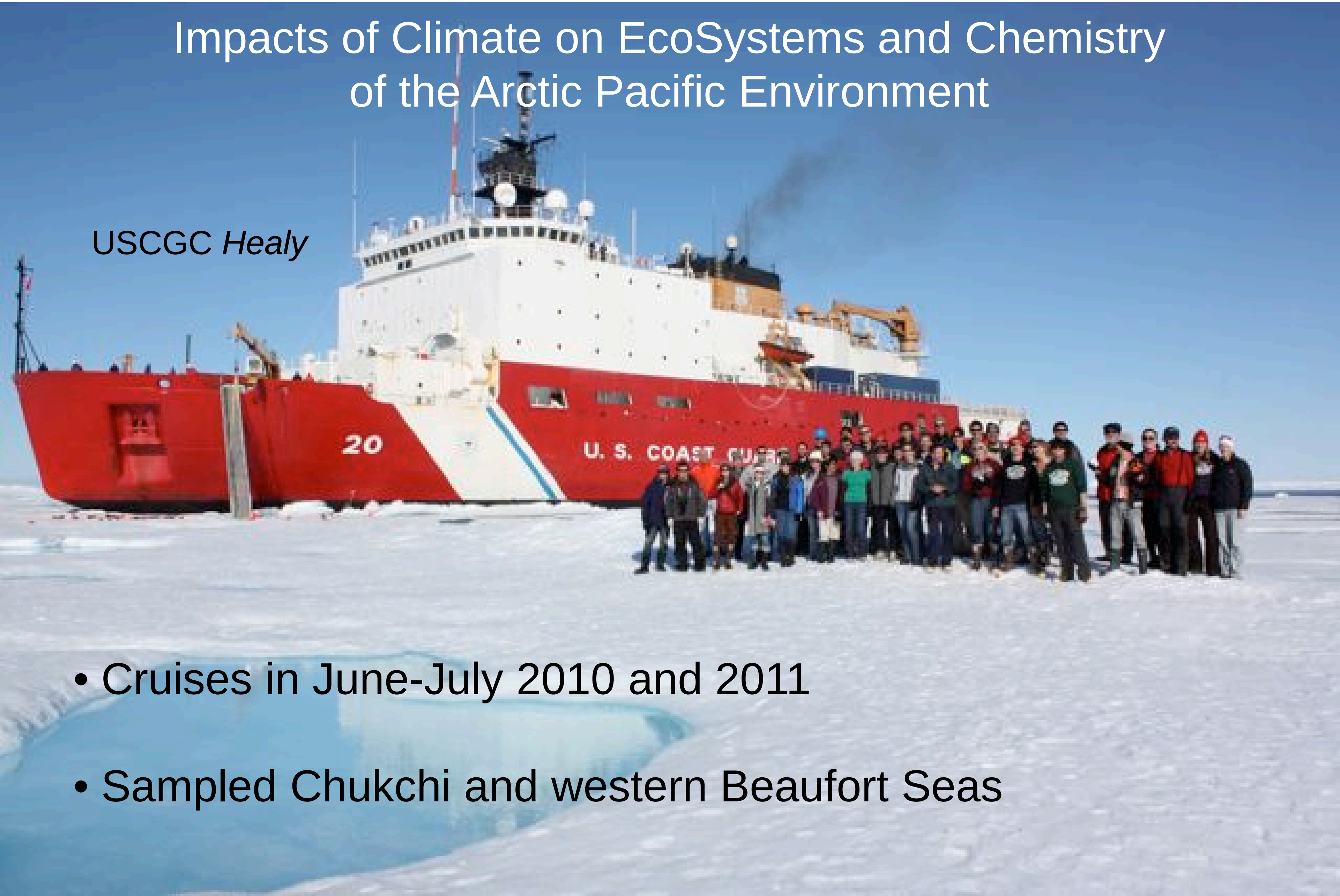
Marie Auger-Méthé, Mark Lewis, Andrew Derocher, 2014



Question:


Given ongoing changes in sea ice in places like the Chukchi Sea…
How have phytoplankton responded?
Slides Courtesy of Kevin Arrigo, Stanford

ICESCAPE



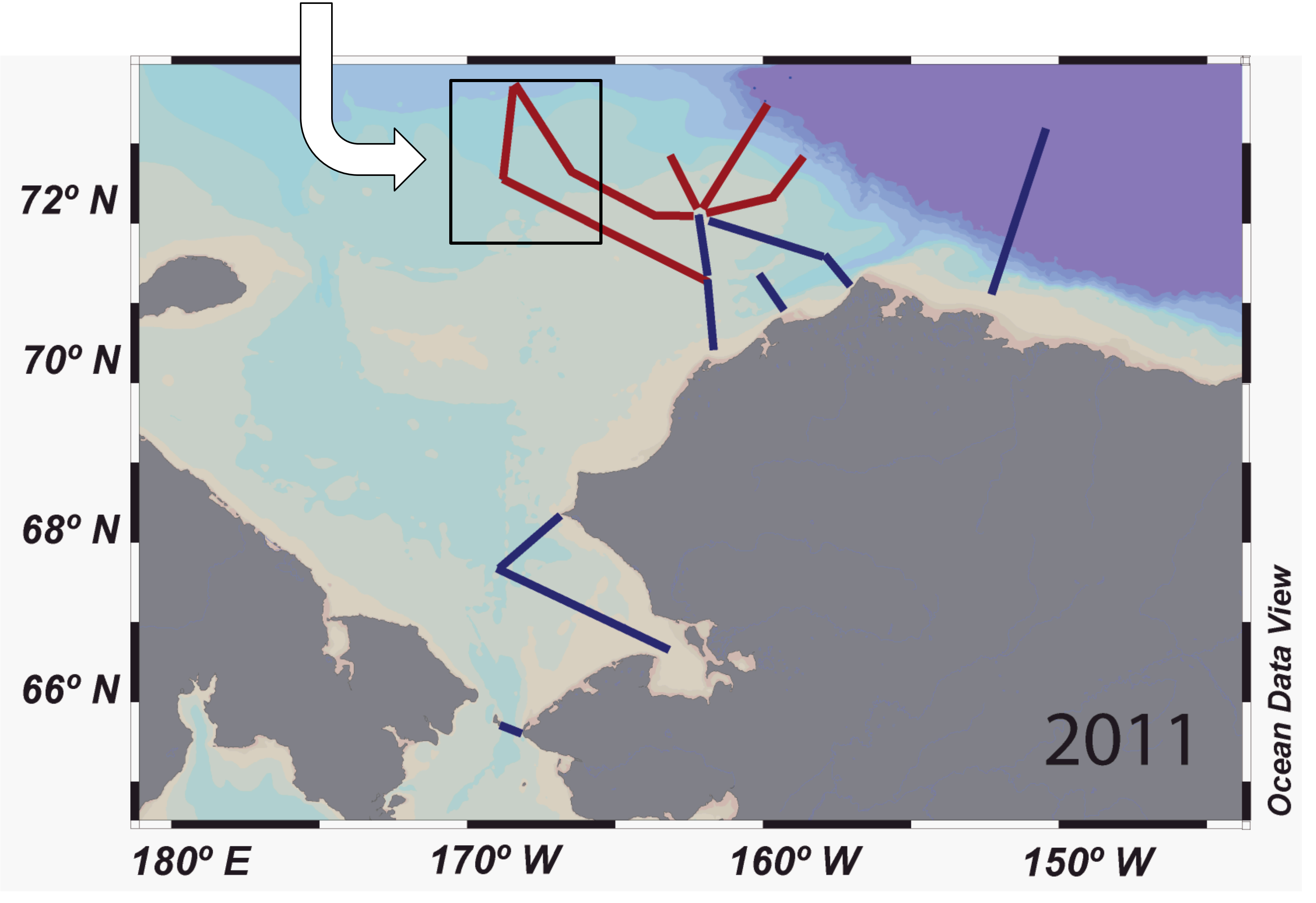
Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment

USCGC *Healy*

- Cruises in June-July 2010 and 2011
- Sampled Chukchi and western Beaufort Seas

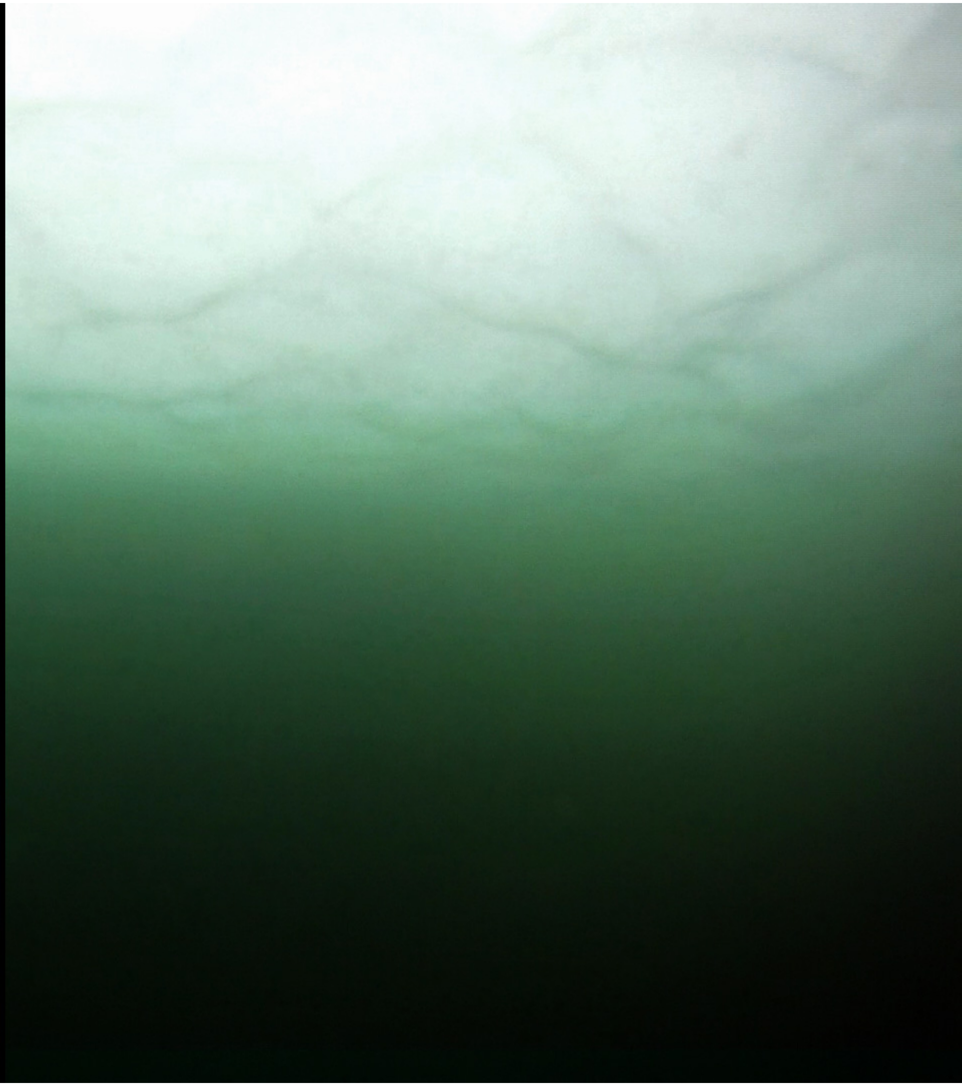
ICESCAPE 2011

Site of under-ice phytoplankton bloom



Extremely high biomass

No bloom under ice

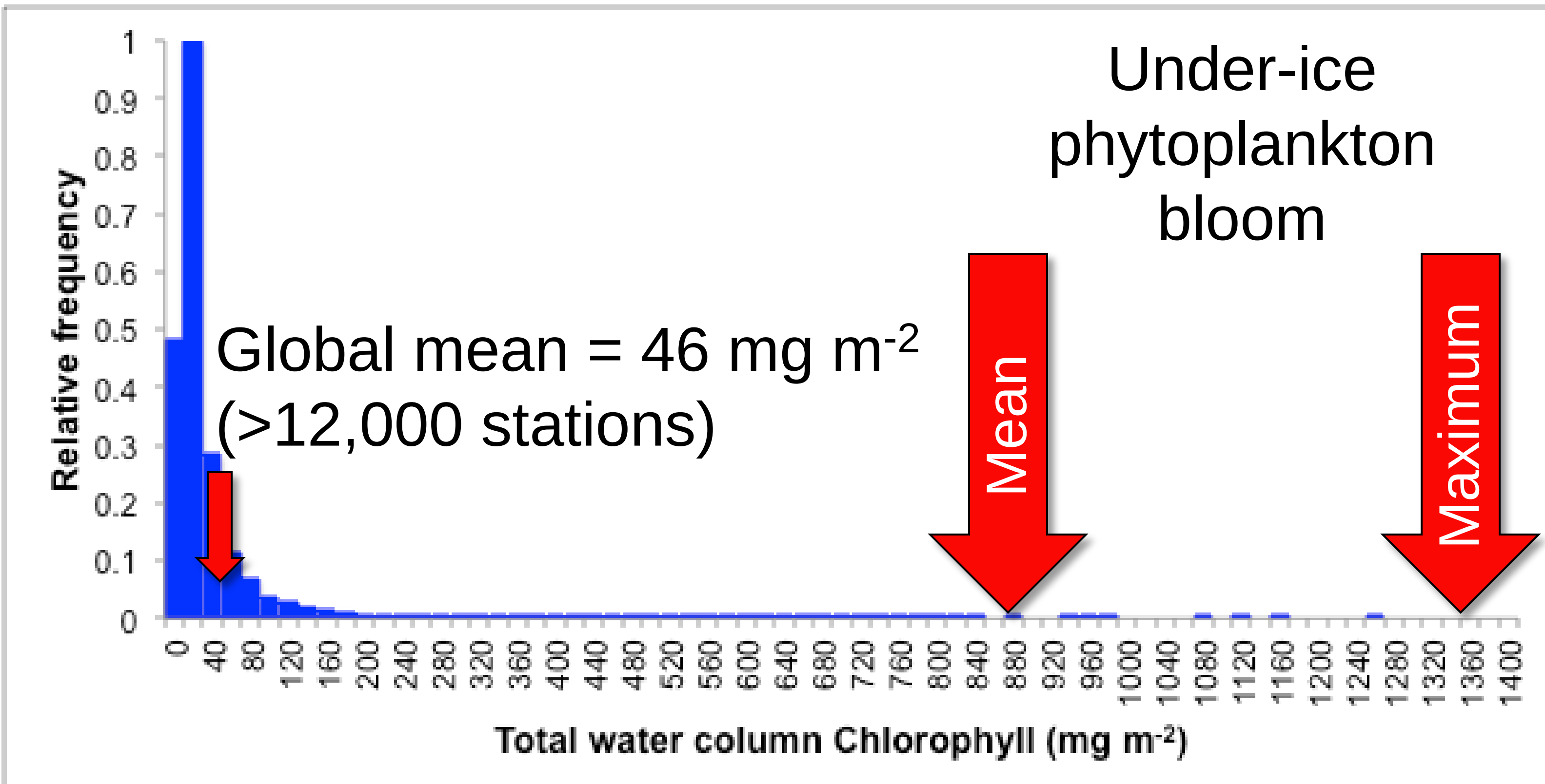


Bloom under ice

Extremely high biomass

Phytoplankton standing crops associated with **under-ice blooms** were some of the highest measured anywhere in the world

PHYTOPLANKTON STANDING CROPS WORLDWIDE

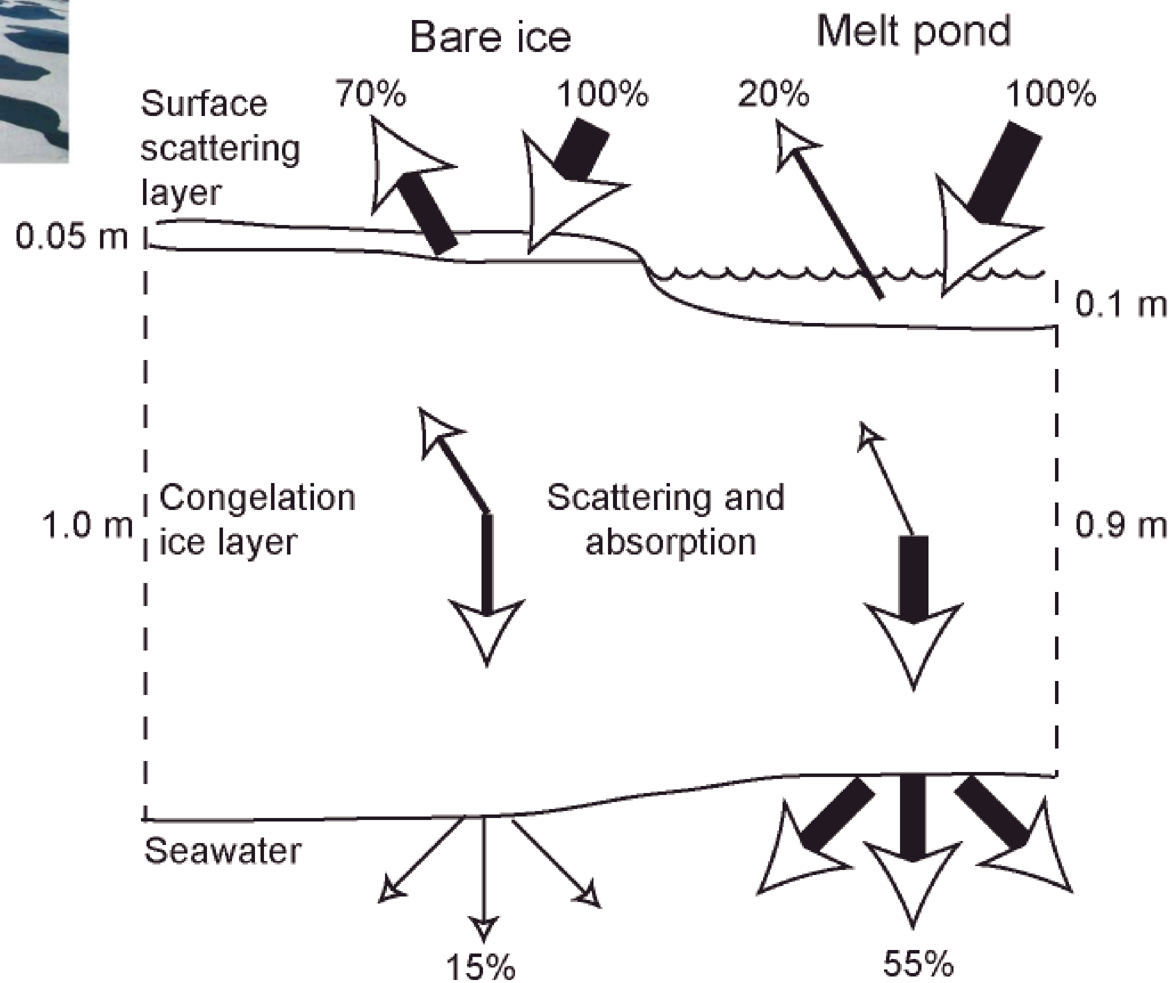


How is such an intense bloom possible?

How is such an intense bloom possible?

Enough light under the ice?

Ice was thick but melt pond fraction was high (30-50%)



Melt ponds transmit >50% of incident surface irradiance

~4 times more than bare ice

melt pond formation and albedo evolution:

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

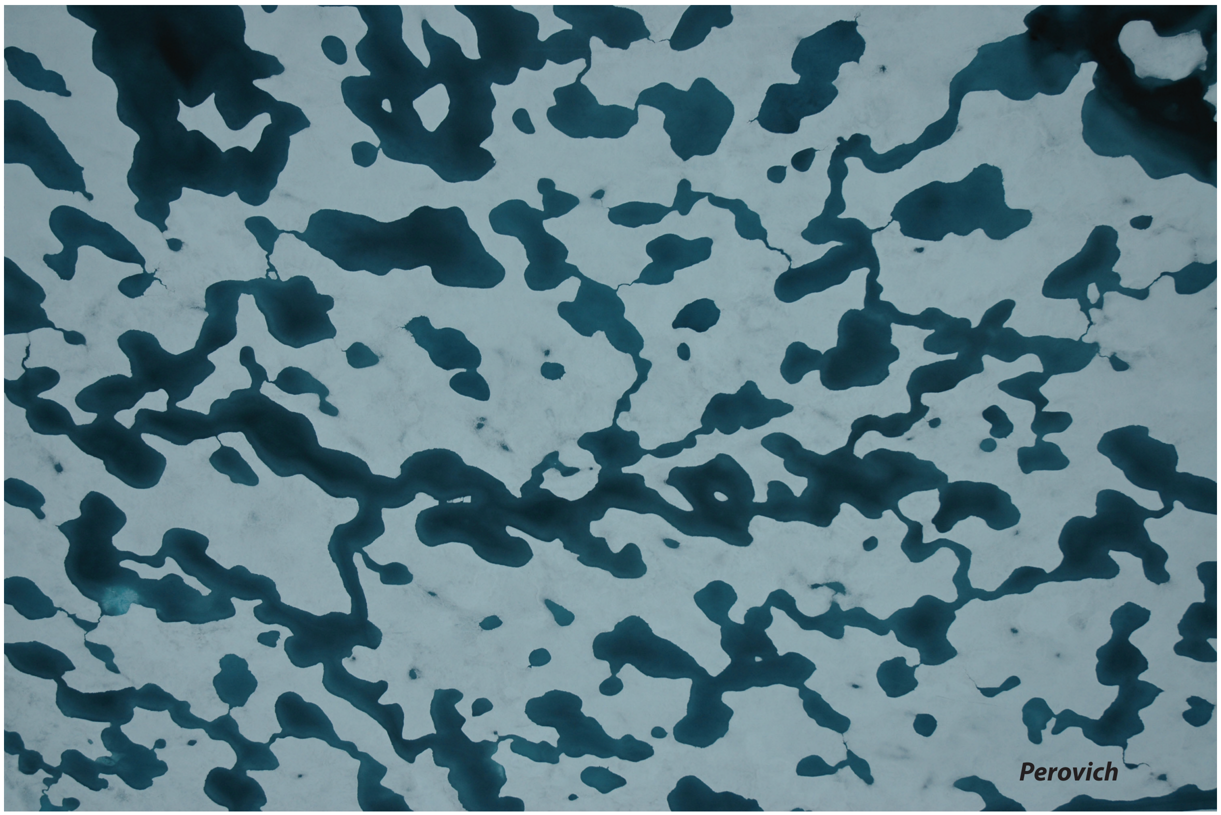
numerical models of melt pond evolution, including topography, drainage (permeability), etc.

Lüthje, Feltham, Taylor, Worster 2006

Flocco, Feltham 2007

Skyllingstad, Paulson, Perovich 2009

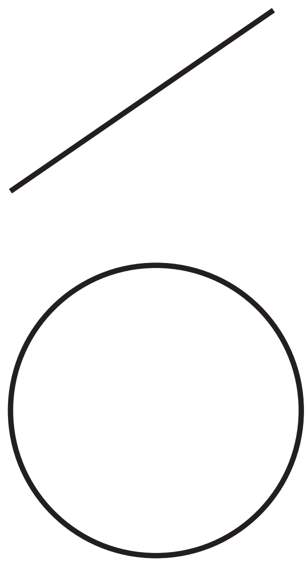
Flocco, Feltham, Hunke 2012



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

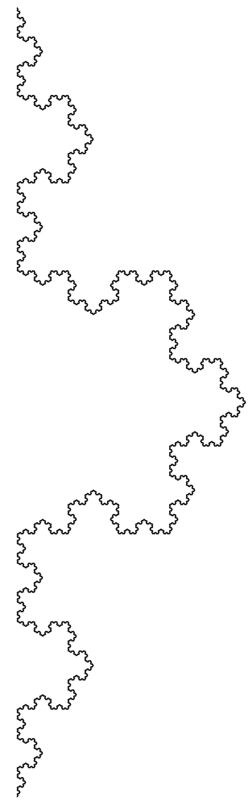
fractal curves in the plane

they wiggle so much that their dimension is >1



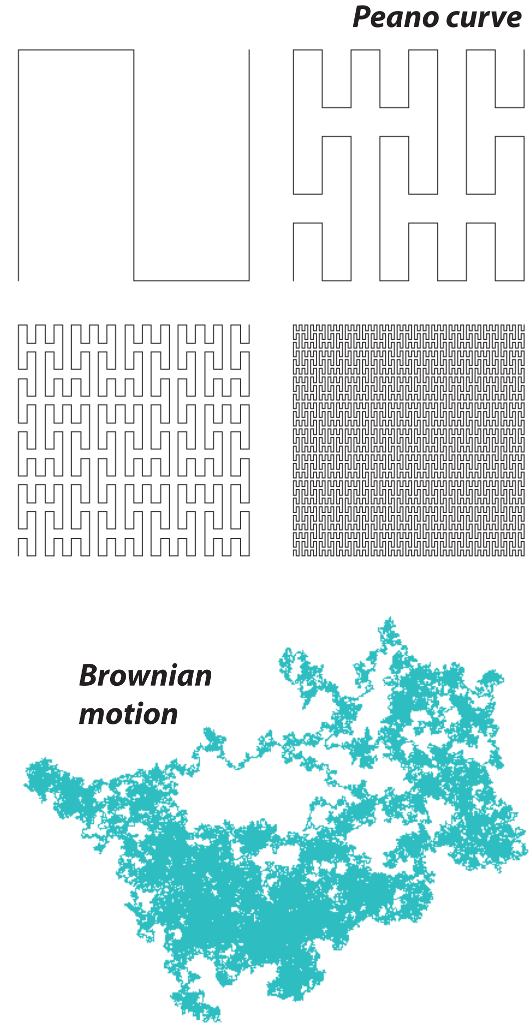
simple curves

$D = 1$



Koch snowflake

$D = 1.26$

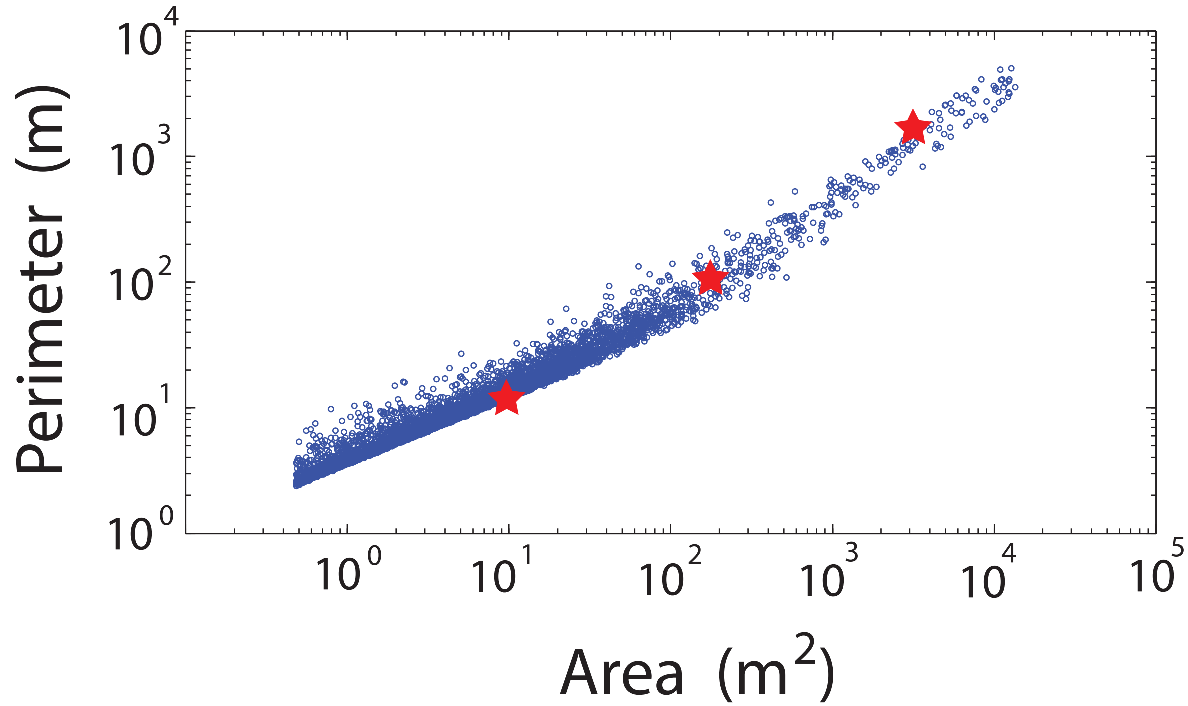


space filling curves

$D = 2$

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

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

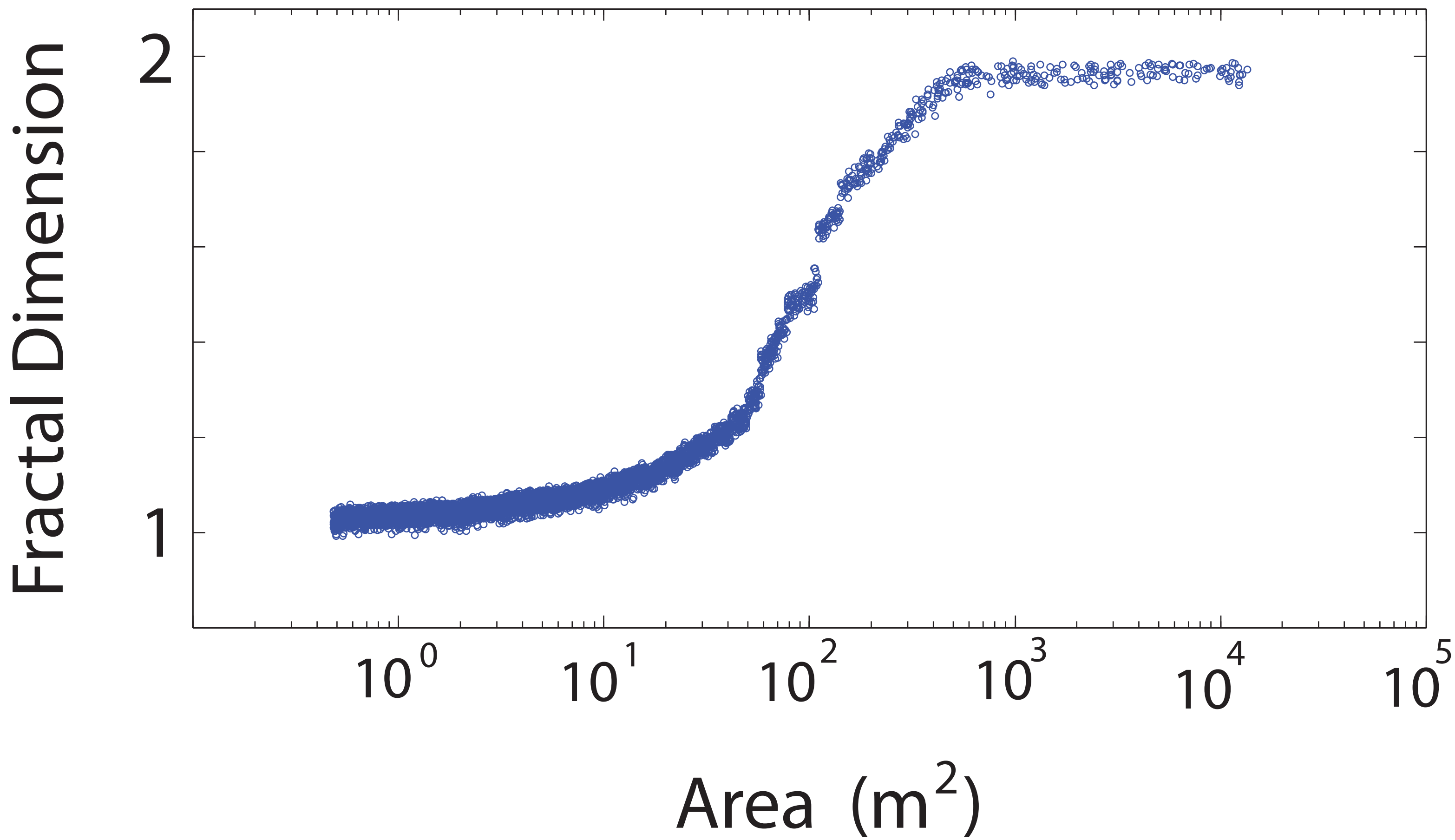


data from 5269 Arctic melt ponds

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

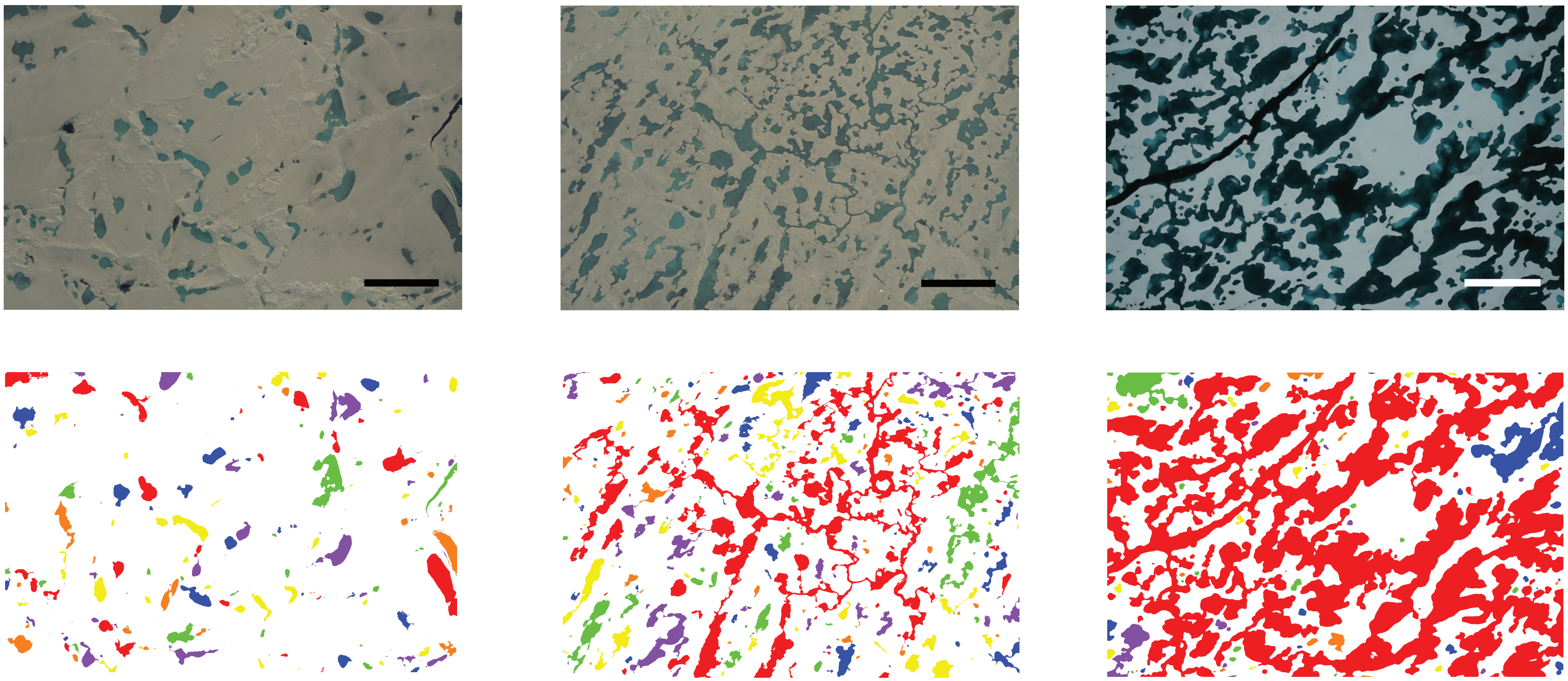
transition in the fractal dimension

complexity grows with length scale



compute "derivative" of area - perimeter data

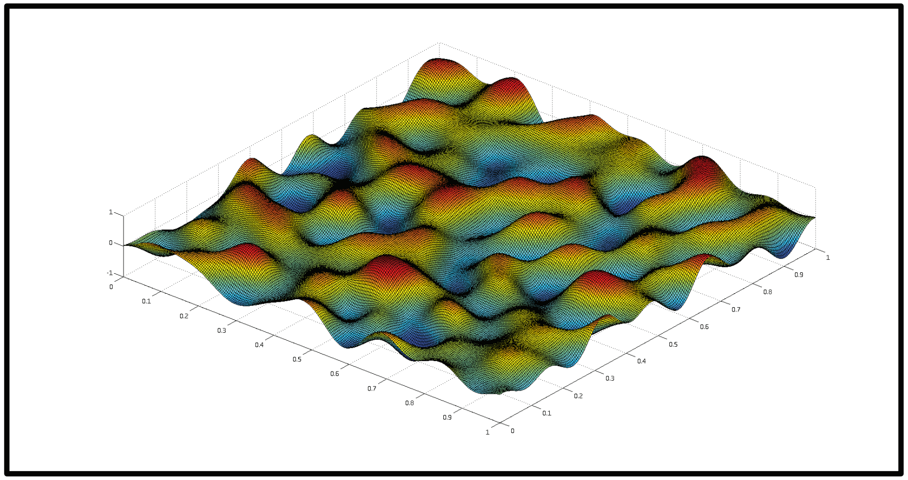
small simple ponds coalesce to form large connected structures with complex boundaries

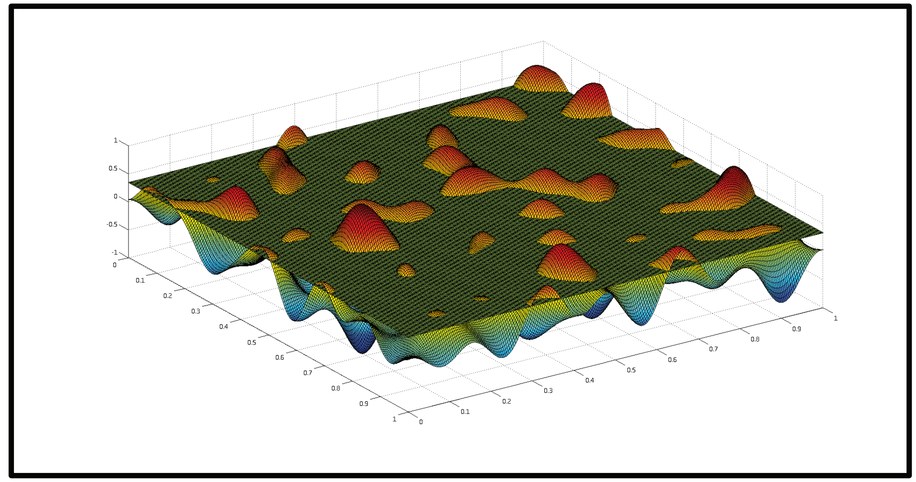


melt pond percolation

Continuum percolation model for melt pond evolution

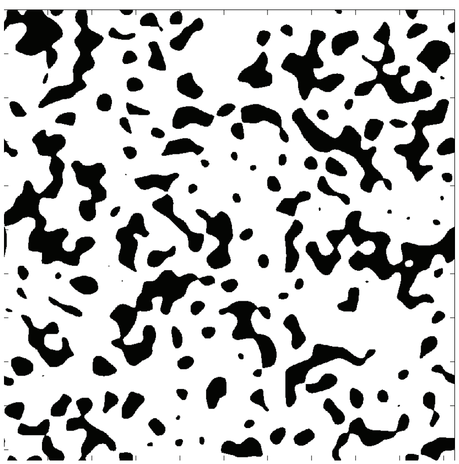
Brady Bowen, Court Strong, Ken Golden, 2014

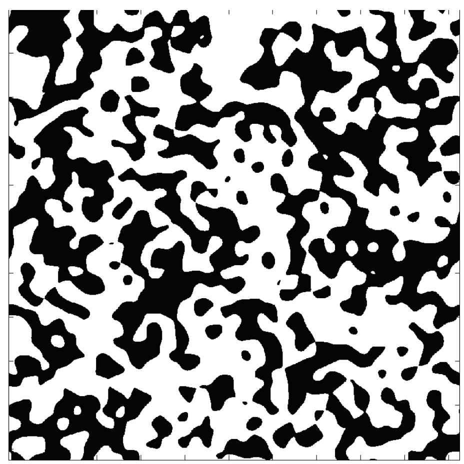


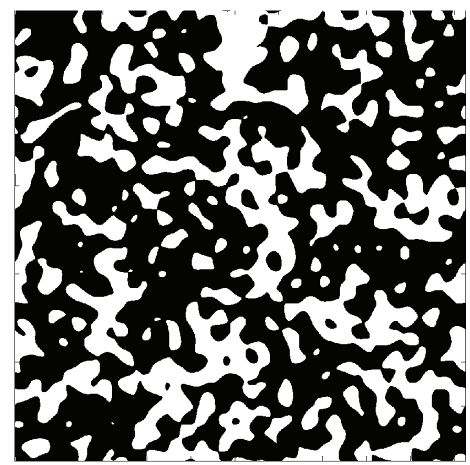


random Fourier series representation of surface topography

intersections of a plane with the surface define melt ponds

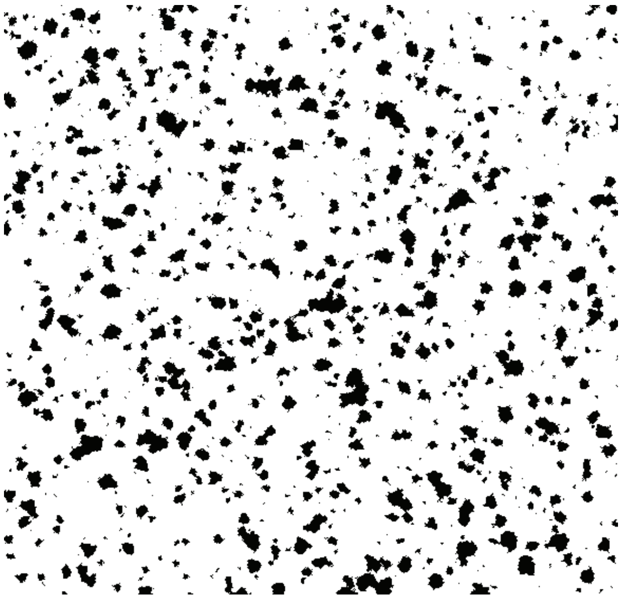


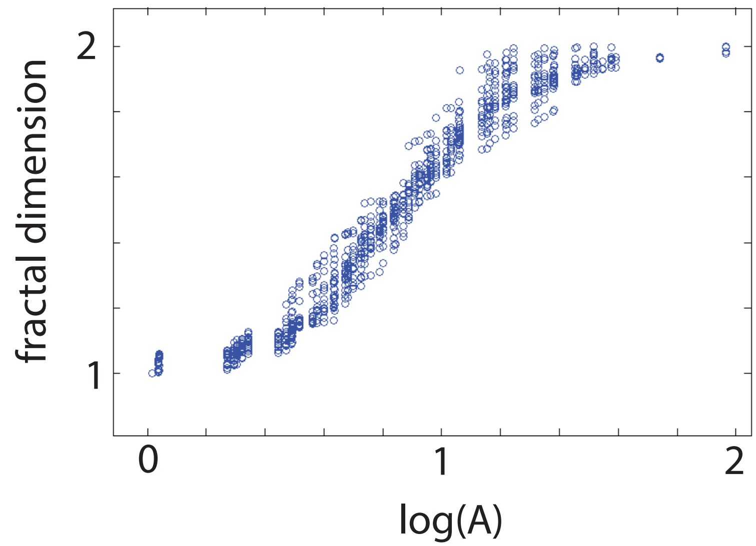


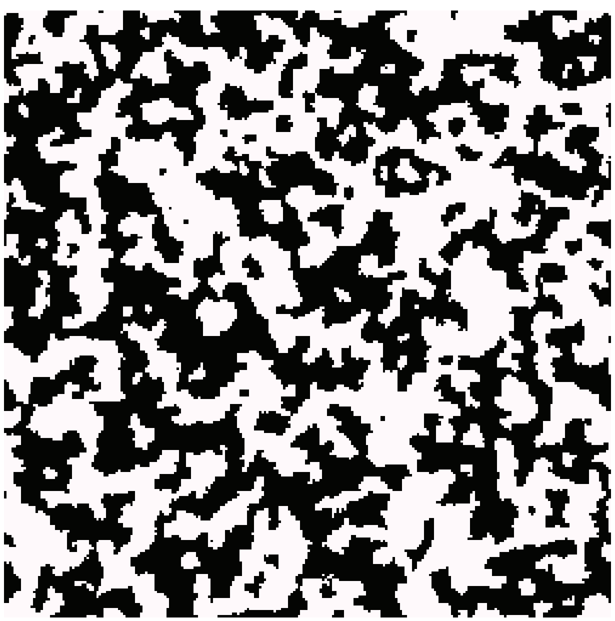


electronic transport in disordered media *diffusion in turbulent plasmas* *(Isichenko, Rev. Mod. Phys., 1992)*

simple stochastic growth model of melt pond evolution







voter model

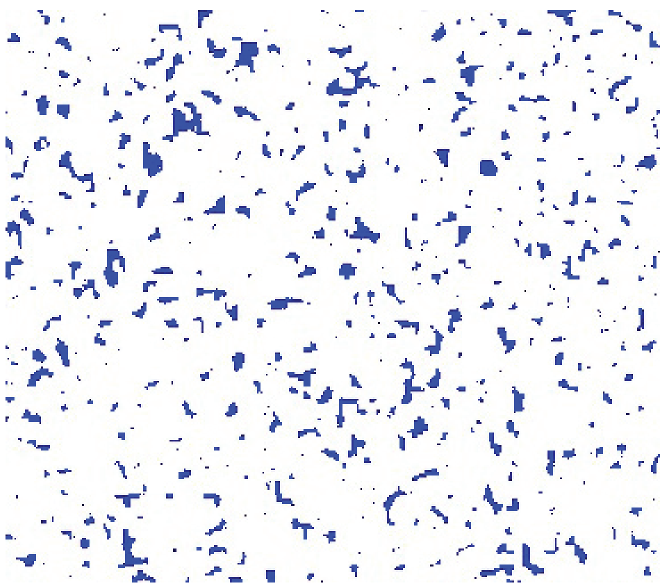
a square is more likely to melt if its neighbors have melted

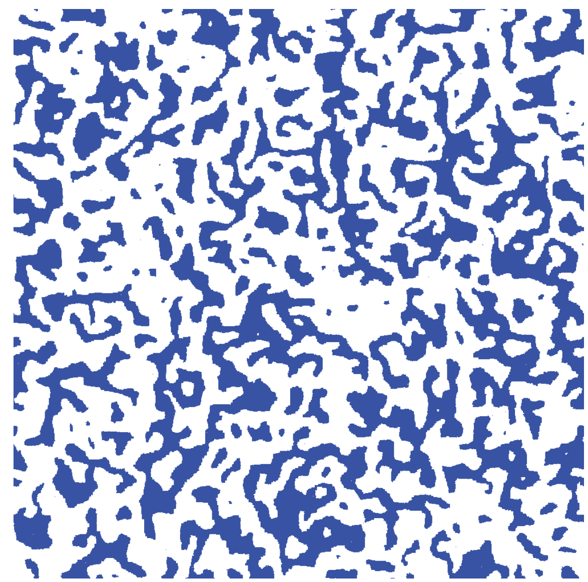
Rebecca Nickerson (West HS, Salt Lake City) and Ken Golden

Ising model for ferromagnets → Ising model for melt ponds

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

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



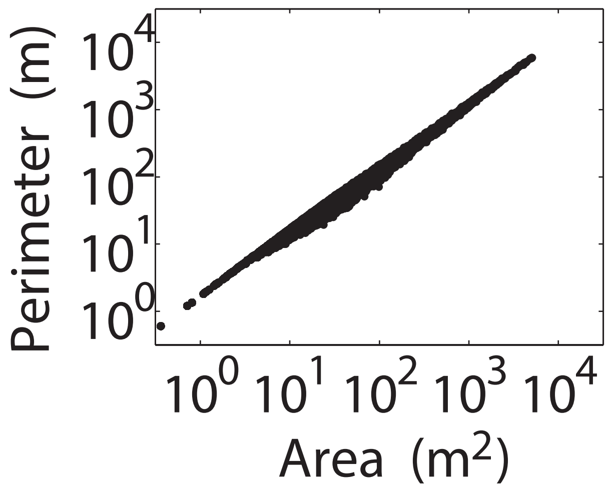


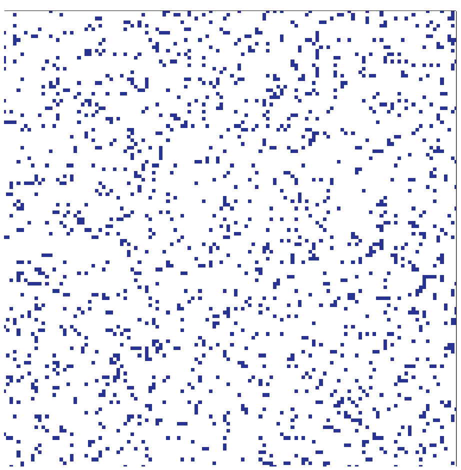
"melt ponds" are clusters of magnetic spins that align with the applied field

Ma, Sudakov, Golden 2014
(Thekkedath, Alali, Strong, Golden)

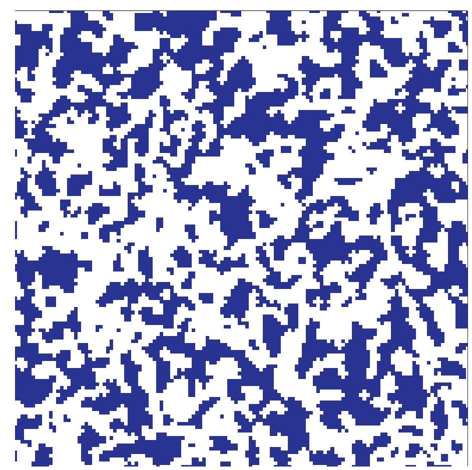
Melt Pond Ising Model

- Minimize an Ising Hamiltonian
  random magnetic field represents the initial ice topography
  interaction term represents horizontal heat transfer
- Ice-albedo feedback incorporated by taking coupling constant in interaction term to be proportional to the pond coverage





predicted length scale of fractal transition agrees well with data



The Conundrum of Melt Pond Formation:

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

C. Polashenski, K. M. Golden, E. Skyllingstad, D. K. Perovich

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

aboard USCGC Healy

Hypothesis – Freshwater re-seals ice

Borehole test with varying salinity

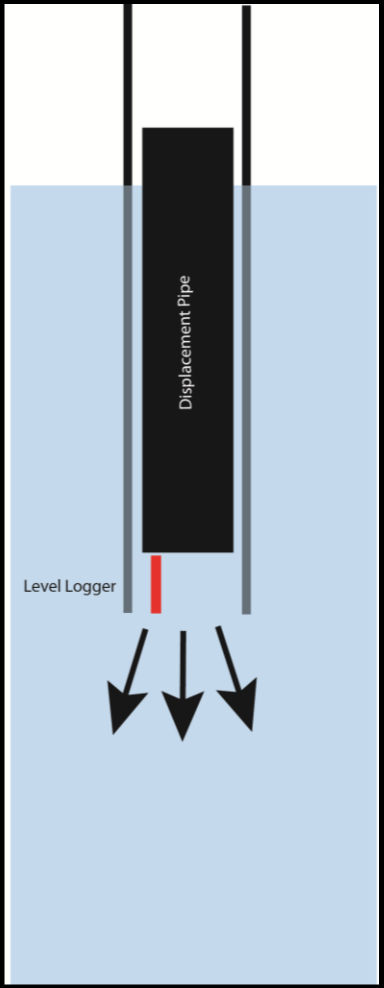
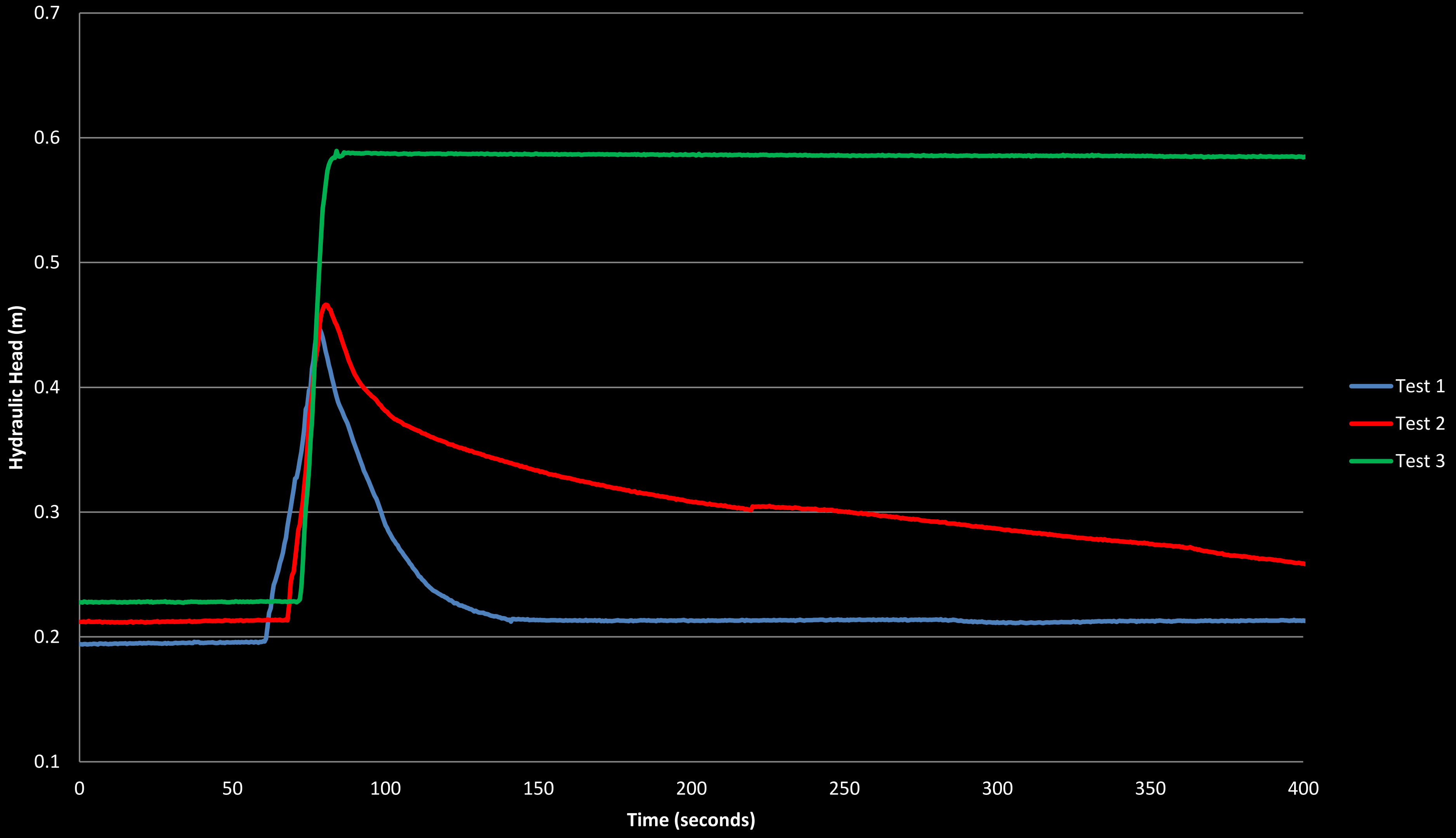


Figure 3a - Hydraulic Head vs. Time, Freshwater Percolation Seals Ice



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. Mathematics of composite materials, statistical physics and dynamical systems help us understand sea ice, and suggest rigorous frameworks for representing sea ice in climate models .

4. Sea ice ecology is rich in interesting mathematics and bio-physics.

5. This research will help to improve projections of climate change and the fate of Earth's sea ice packs and their ecosystems.

THANK YOU

National Science Foundation

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