Microbial Ecology and the Physics of Sea Ice

Kenneth M. Golden
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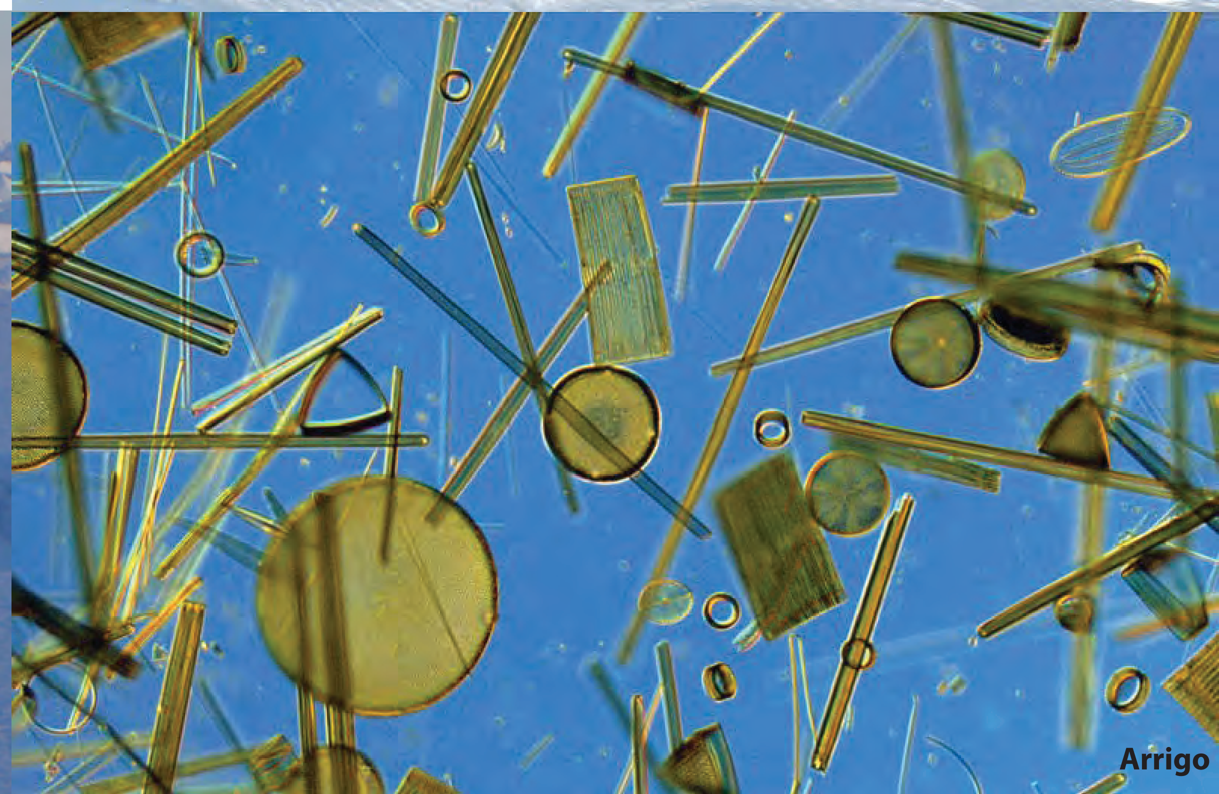
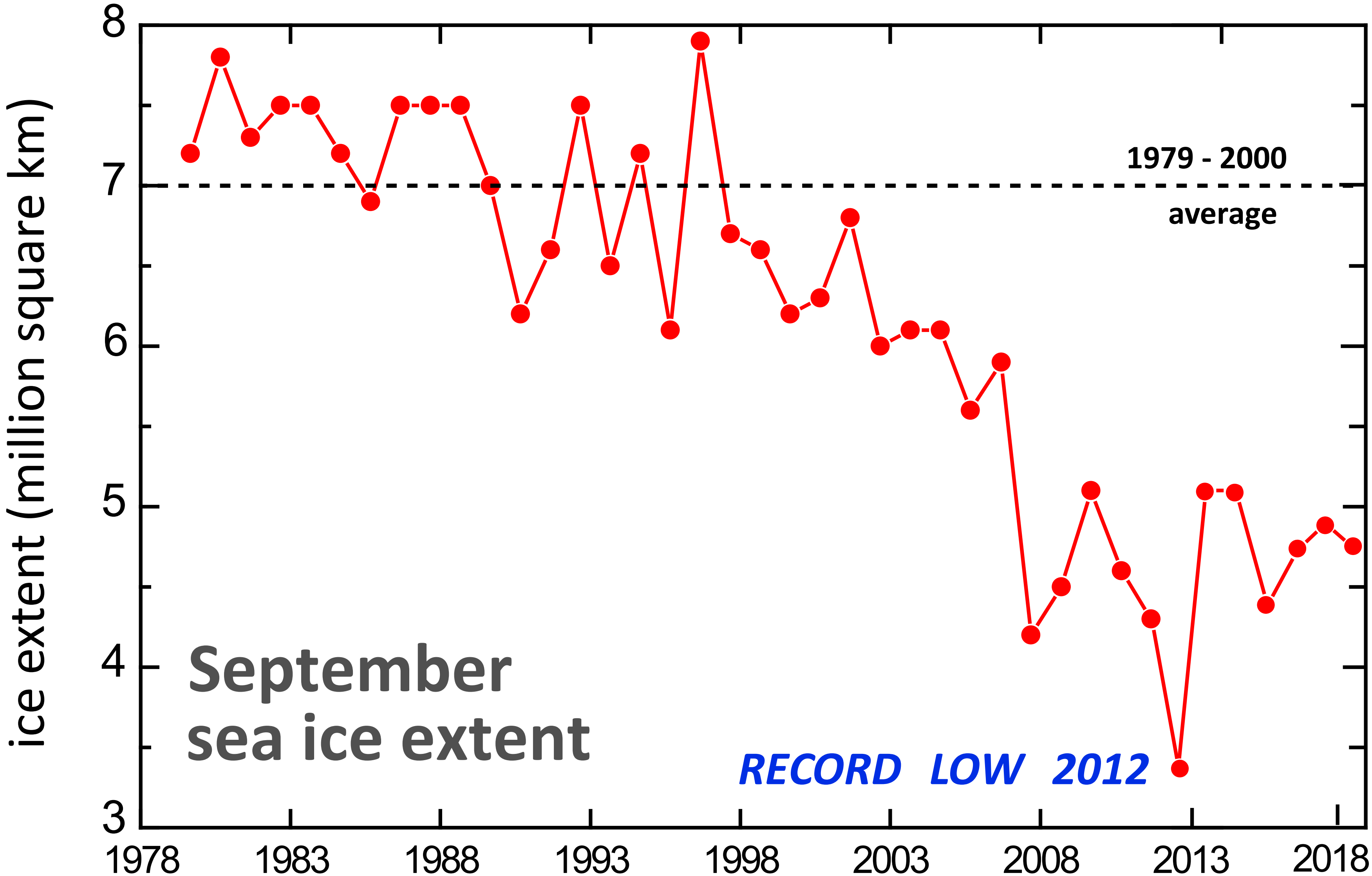


SEA ICE covers ~12% of Earth's ocean surface

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

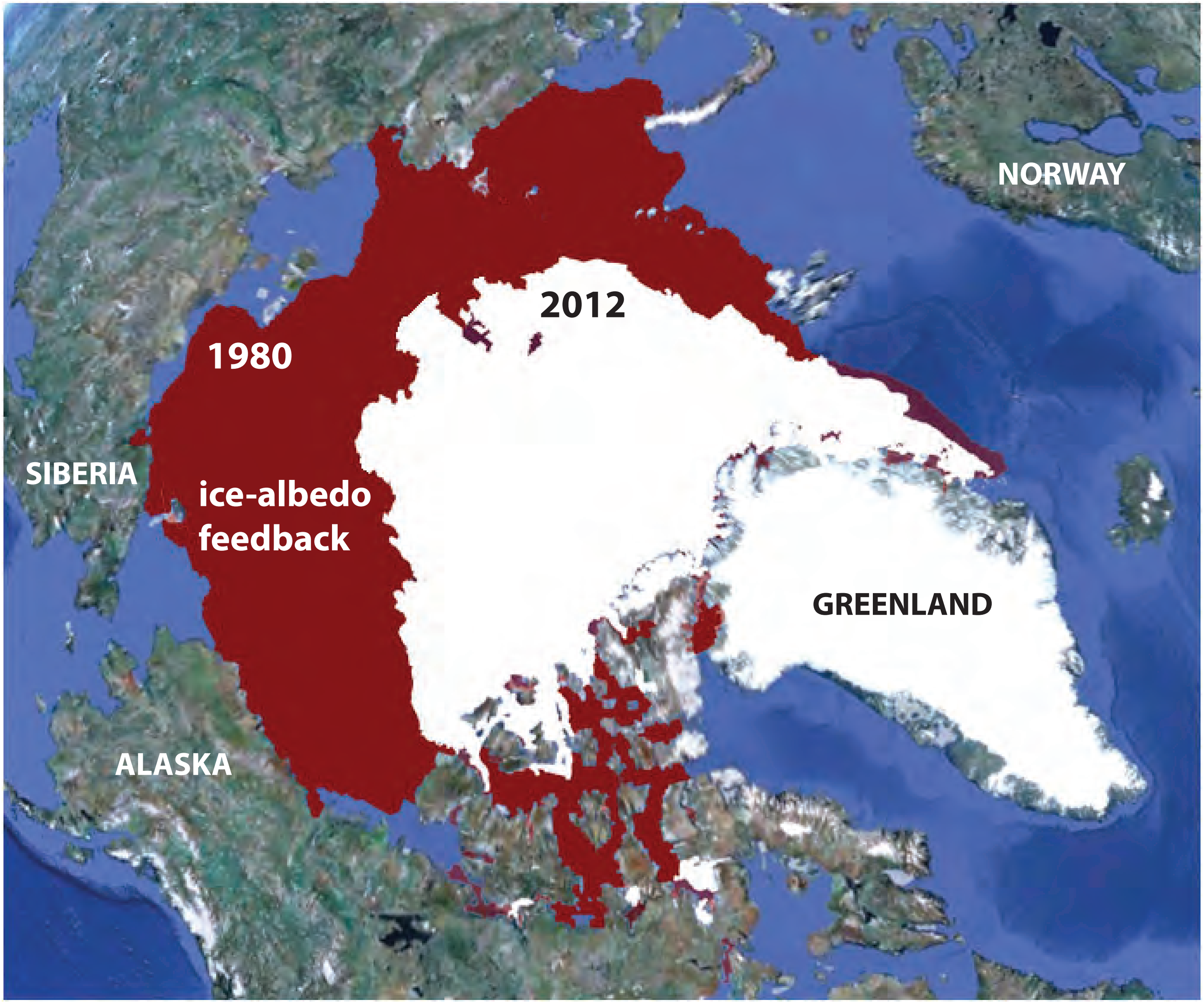
the summer Arctic sea ice pack is melting



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

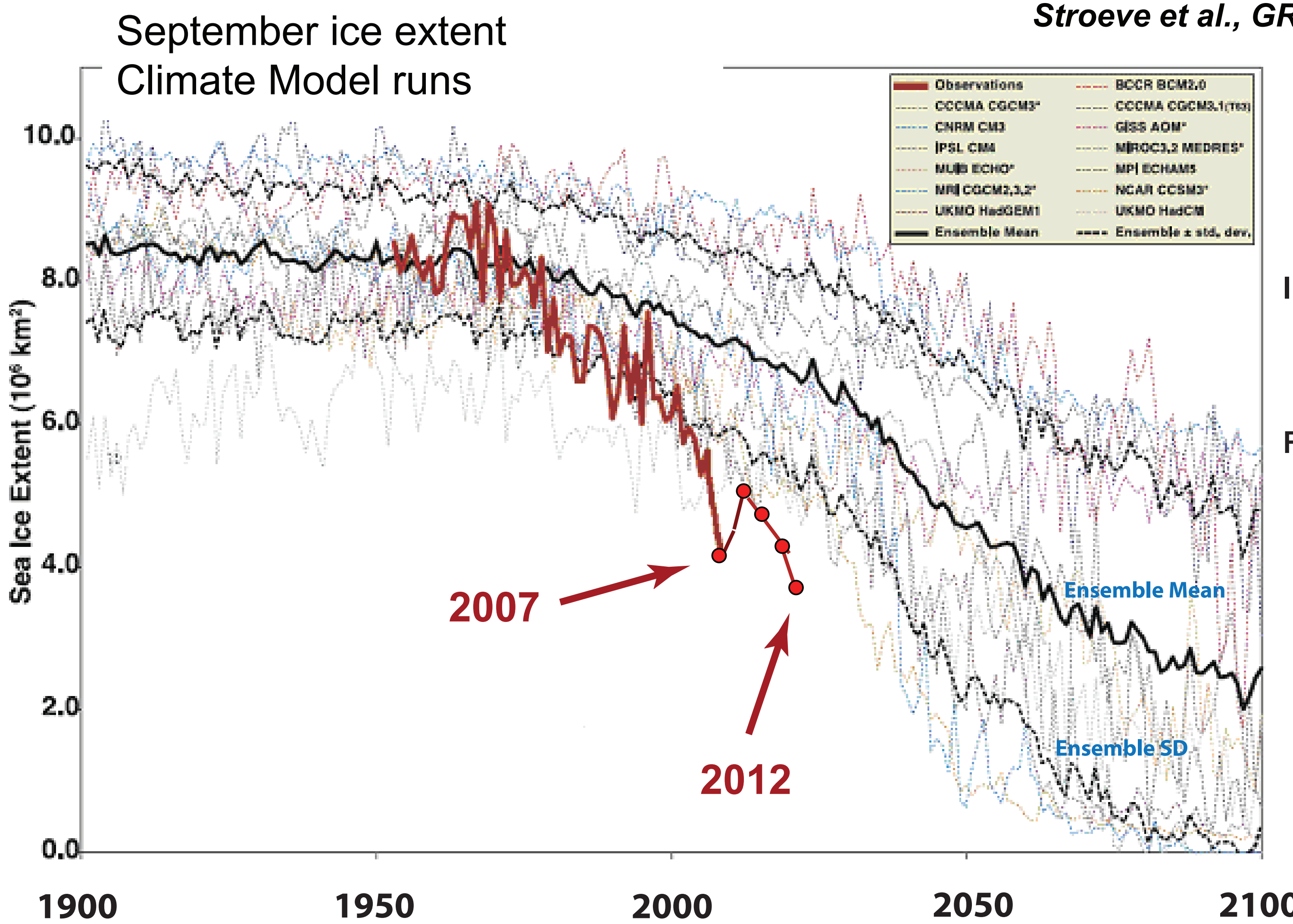


Perovich

Arctic sea ice decline: faster than predicted by climate models

Stroeve et al., GRL, 2007

Stroeve et al., GRL, 2012



IPCC AR4 Models

Intergovernmental Panel on Climate Change (IPCC)

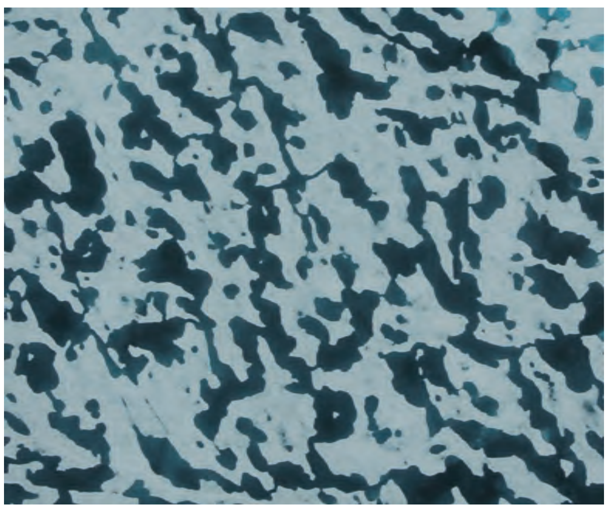
Fourth Assessment AR4, 2007

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

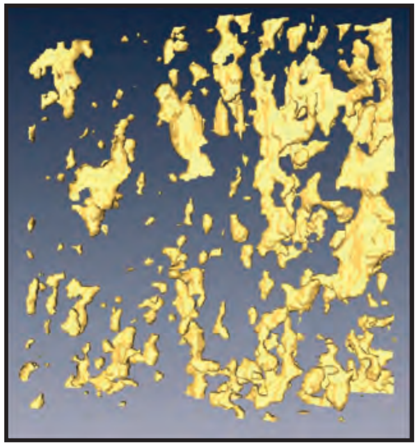
linkage of scales

Sea Ice is a Multiscale Composite Material

sea ice microstructure

brine inclusions

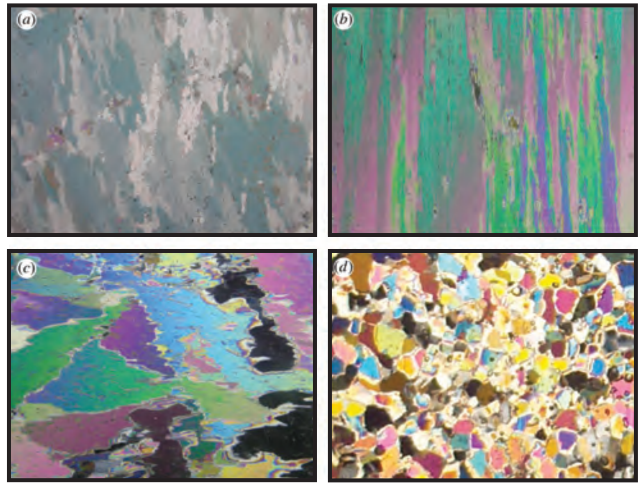
Weeks & Assur 1969



H. Eicken

Golden *et al.* *GRL* 2007

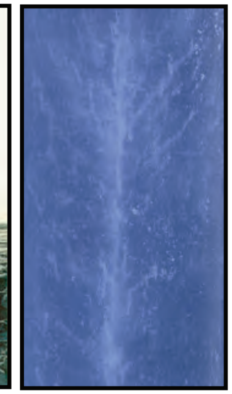
polycrystals



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

brine channels

D. Cole



K. Golden

millimeters

centimeters

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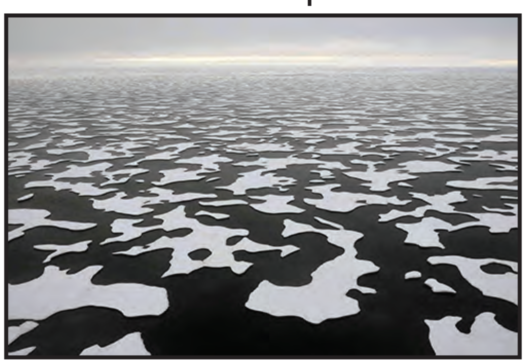
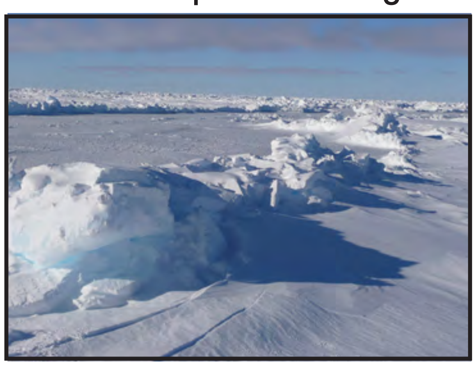
sea ice mesostructure

Arctic melt ponds



K. Frey

Antarctic pressure ridges



K. Golden

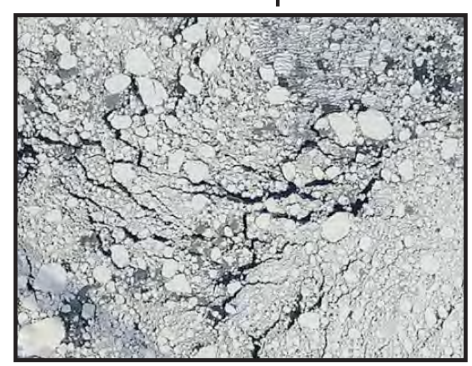
meters

sea ice macrostructure

sea ice floes

J. Weller

sea ice pack



NASA

kilometers

What is this talk about?

1. LIFE IN THE ICE

   sea ice microphysics and fluid transport

2. LIFE UNDER THE ICE

   melt ponds, under-ice light field, algal blooms

3. Species competition - resources depend on climate

Solving problems in physics and biology of sea ice drives advances in theory of composite materials and ecological systems.

Microbial life IN sea ice

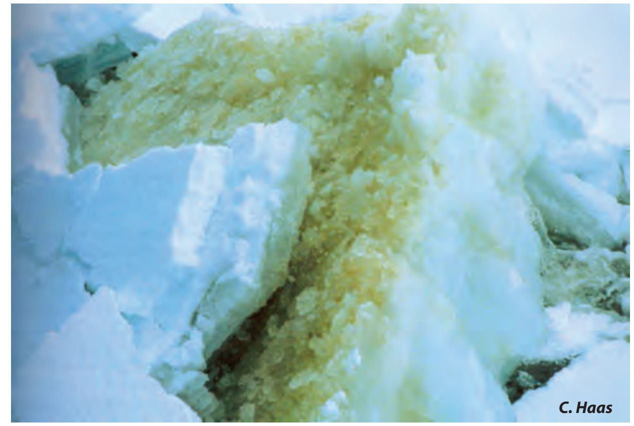
sea ice microphysics

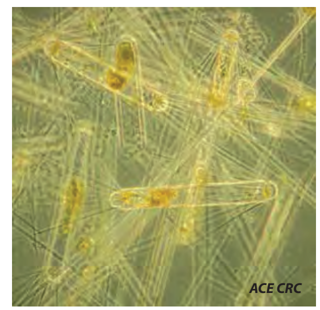
fluid transport

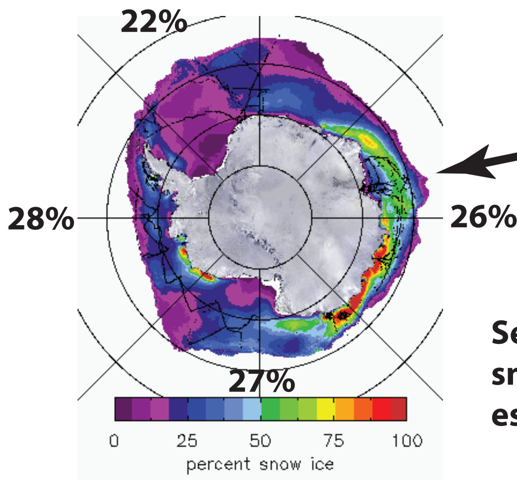
fluid flow through the porous microstructure of sea ice governs key processes in polar climate and ecosystems

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

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

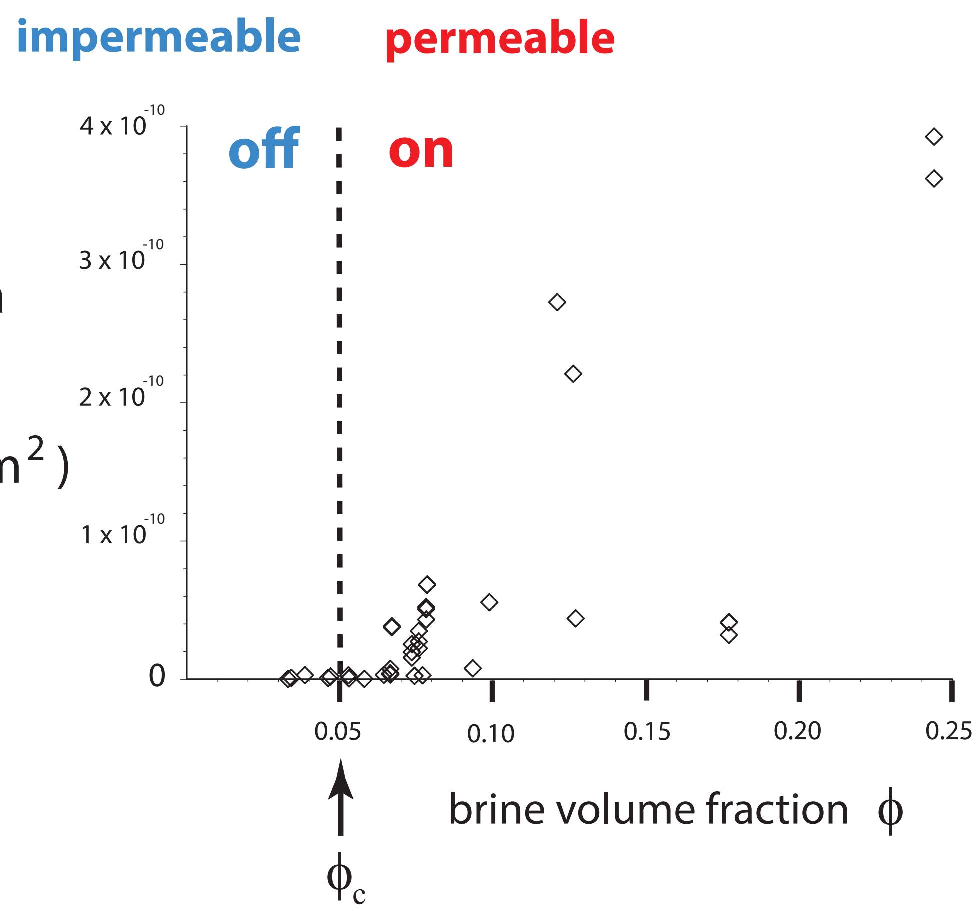
viscosity

$\mathbf{k}$ = 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 $\phi_c \approx 5\%$ $\longleftrightarrow$ $T_c \approx -5^\circ C$, $S \approx 5$ ppt

RULE OF FIVES

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

sea ice algal communities

D. Thomas 2004

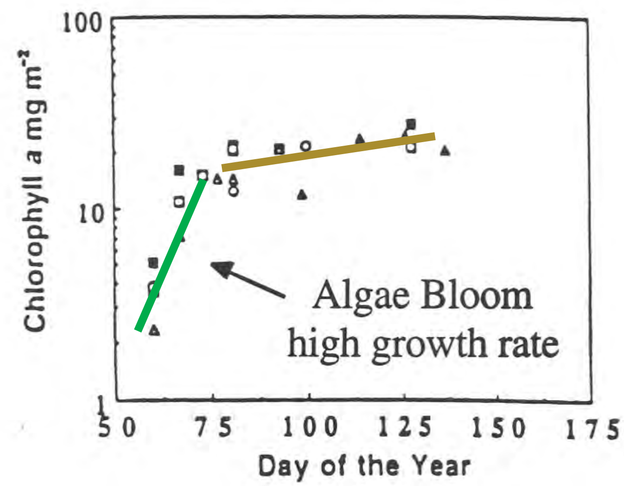
nutrient replenishment
controlled by ice permeability

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

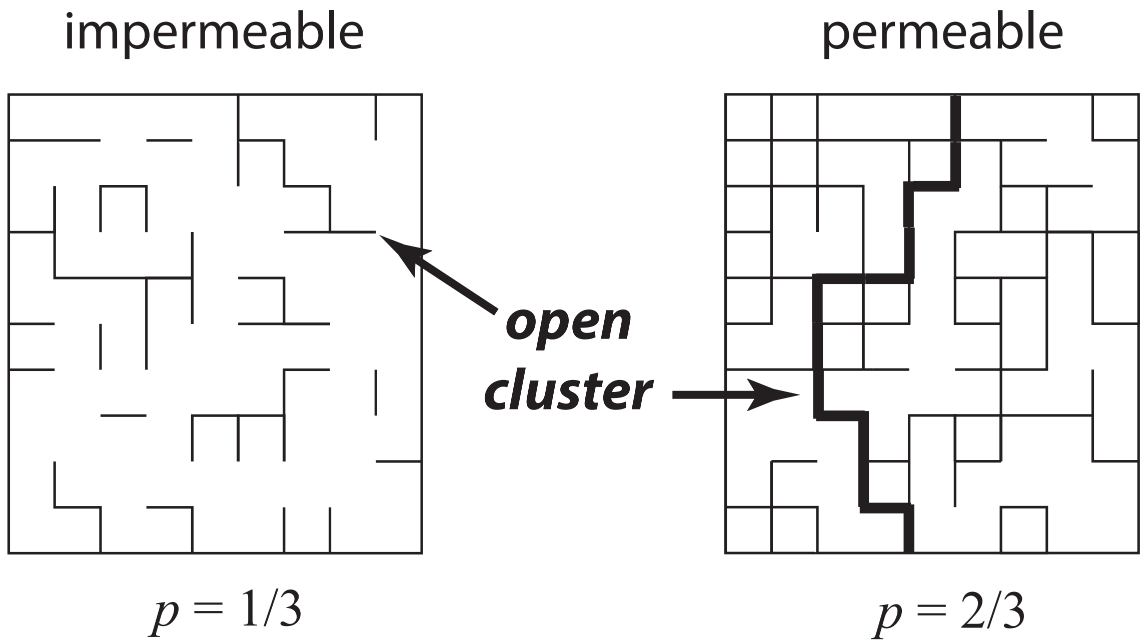


Convection-fueled algae bloom
Ice Station Weddell

Why is the rule of fives true?

percolation theory

probabilistic theory of connectedness



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

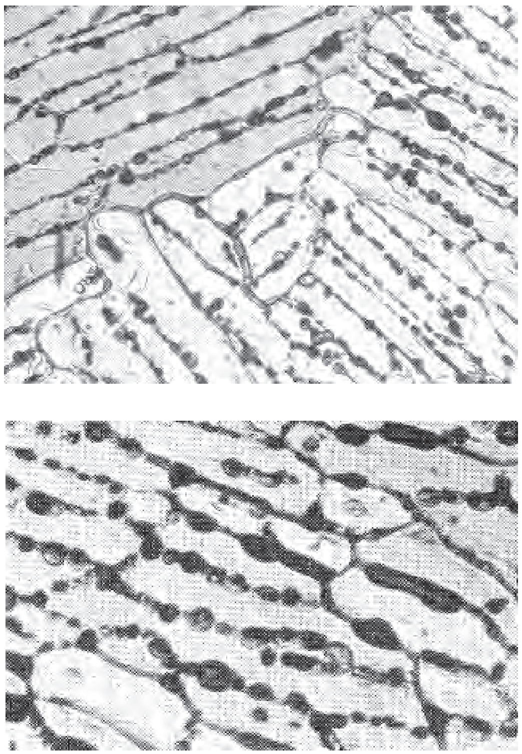
percolation threshold

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

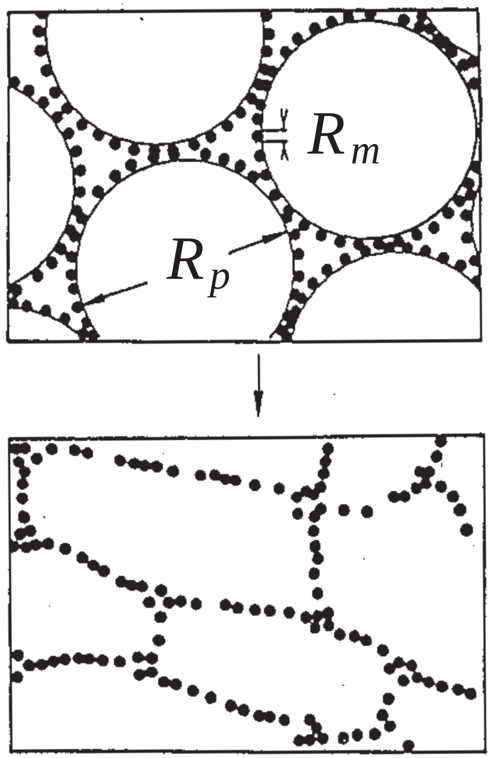
smallest *p* for which there is an infinite open cluster

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

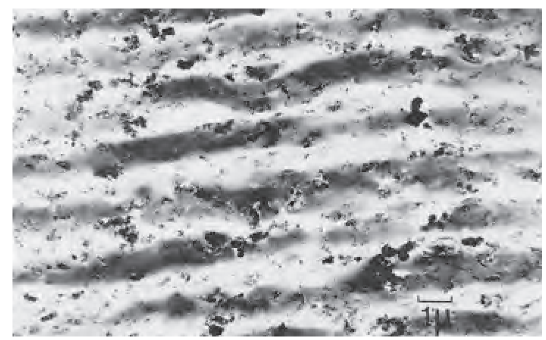
$\phi_c \approx 5\ \%$ Golden, Ackley, Lytle, *Science*, 1998



sea ice



compressed powder



radar absorbing composite

sea ice is radar absorbing

Thermal evolution of permeability and microstructure in sea ice

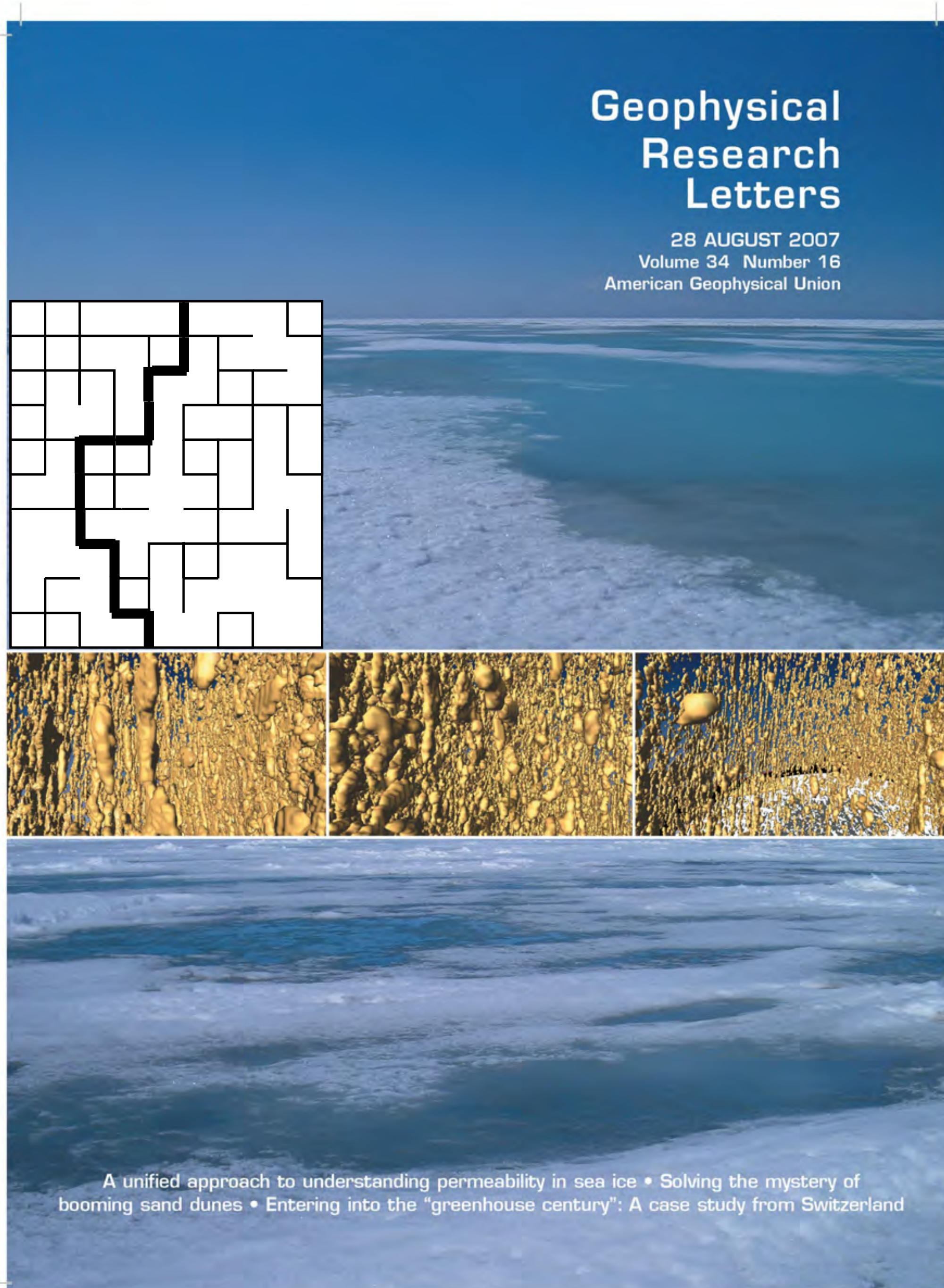
Golden, Eicken, Heaton, Miner, Pringle, Zhu, Geophysical Research Letters 2007

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

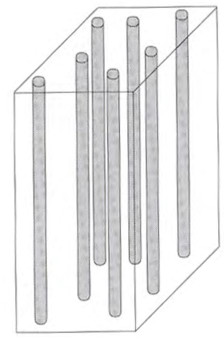
confirms rule of fives

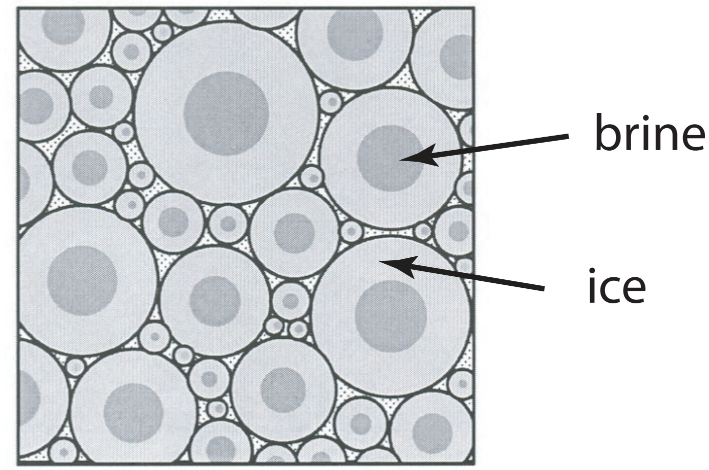
Pringle, Miner, Eicken, Golden
J. Geophys. Res. 2009

PIPE BOUNDS on vertical fluid permeability k

Golden, Heaton, Eicken, Lytle, Mech. Materials 2006
Golden, Eicken, Heaton, Miner, Pringle, Zhu, Geophys. Res. Lett. 2007

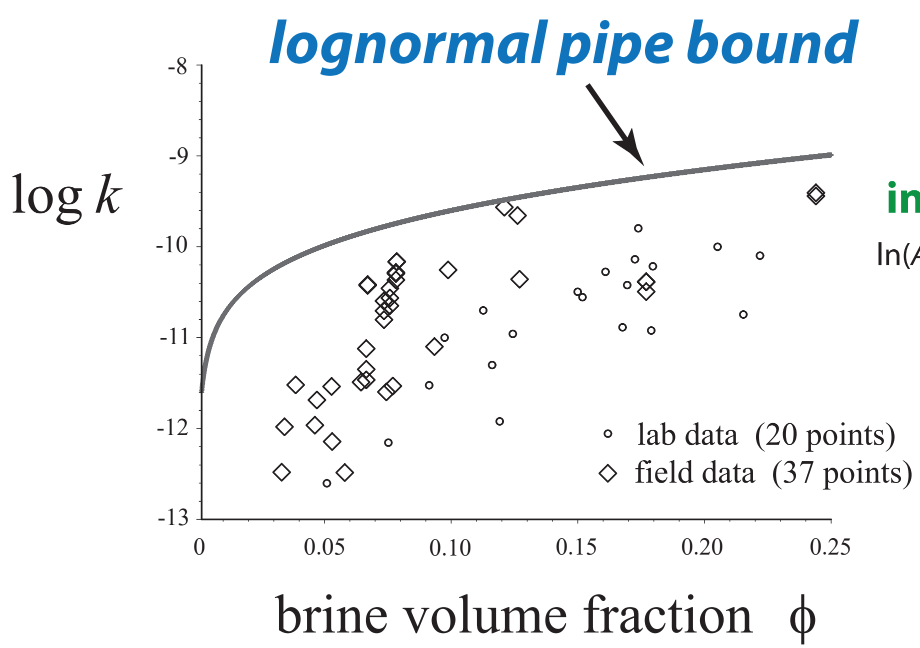
vertical pipes
with appropriate radii
maximize k





optimal coated cylinder geometry

fluid analog of arithmetic mean upper bound for effective conductivity of composites (Wiener 1912)



Golden et al., Geophys. Res. Lett. 2007

$$k \;\leq\; \frac{\phi\langle R^4\rangle}{8\langle R^2\rangle} \;=\; \frac{\phi}{8}\langle R^2\rangle e^{\sigma^2}$$

inclusion cross sectional areas A lognormally distributed

ln(A) normally distributed, mean μ (increases with T) variance σ^2 (Gow and Perovich 96)

get bounds through variational analyis of ***trapping constant*** γ for diffusion process in pore space with absorbing BC

Torquato and Pham, *PRL* 2004

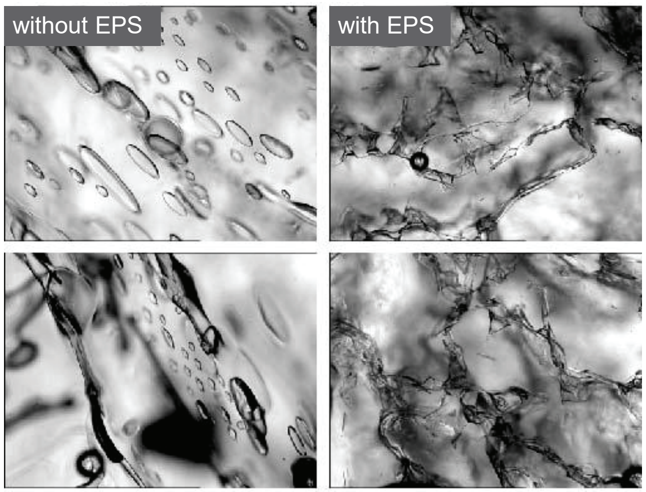
$$\mathbf{k} \;\leq\; \gamma^{-1}\mathbf{I}$$

for any ergodic porous medium (Torquato 2002, 2004)

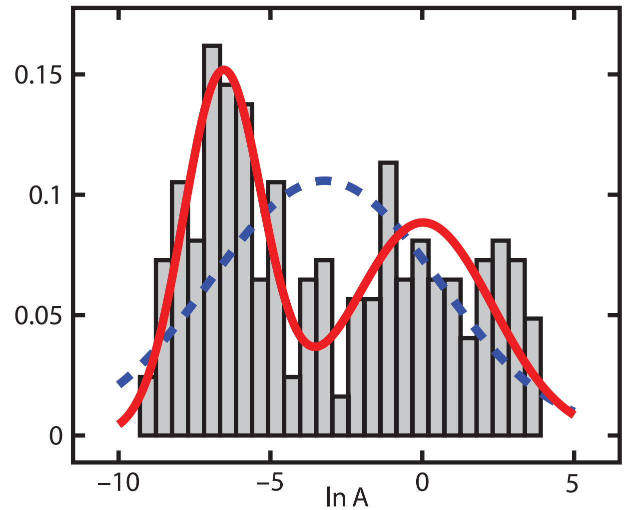
BACTERIAL FORAGING

Sea ice algae secrete extracellular polymeric substances (EPS) affecting evolution of brine microstructure.

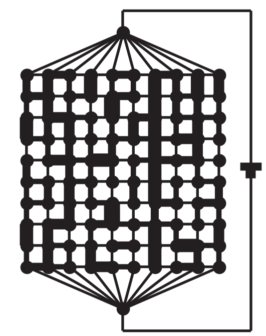
How does EPS affect fluid transport?

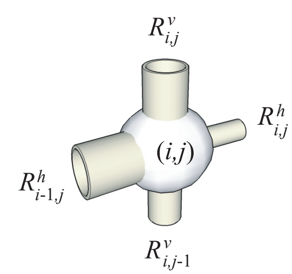


Krembs, Eicken, Deming, PNAS 2011



RANDOM PIPE MODEL





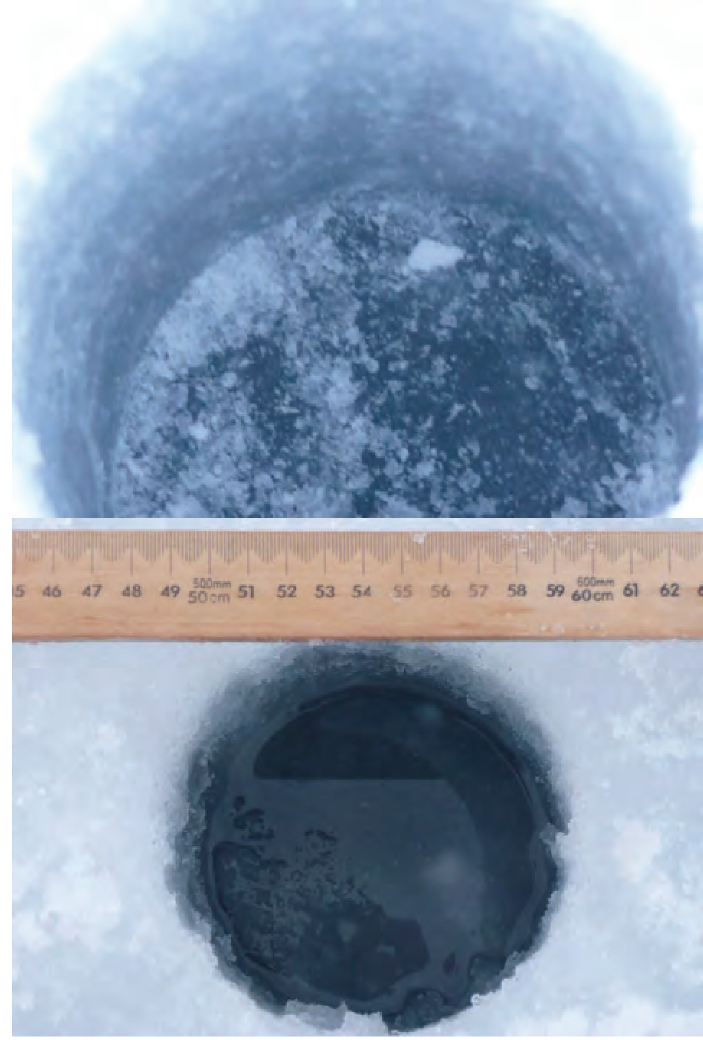
- **Bimodal** lognormal distribution for brine inclusions
- Develop random pipe network model with bimodal distribution;
  Use numerical methods that can handle larger variances in sizes.
- Results predict observed drop in fluid permeability *k*.
- **Rigorous bound on *k* for bimodal distribution of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

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

Zhu, Jabini, Golden, Eicken, Morris
Ann. Glac. 2006

How does the biology affect the physics?

photo by Jan Lieser



measuring fluid permeability of Antarctic sea ice

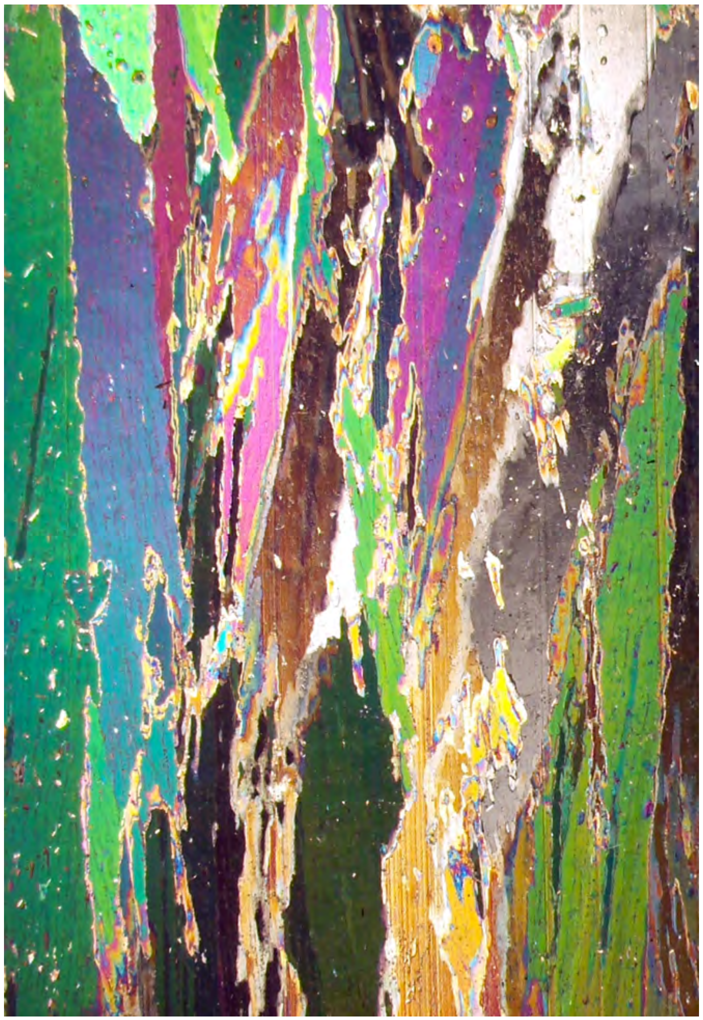
SIPEX 2007

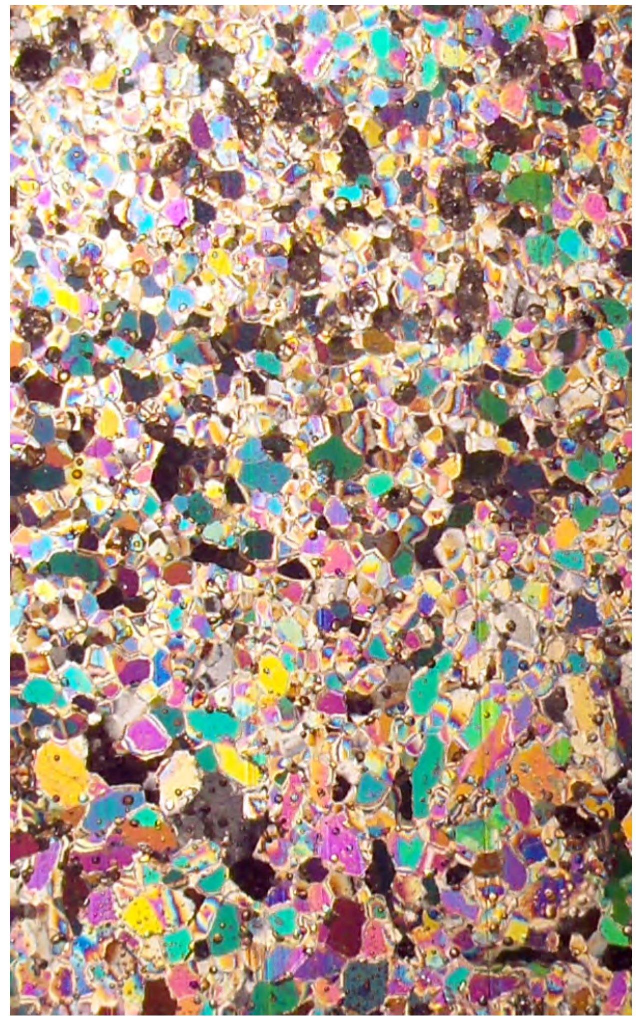
higher threshold for fluid flow in Antarctic granular sea ice

columnar

granular

5%

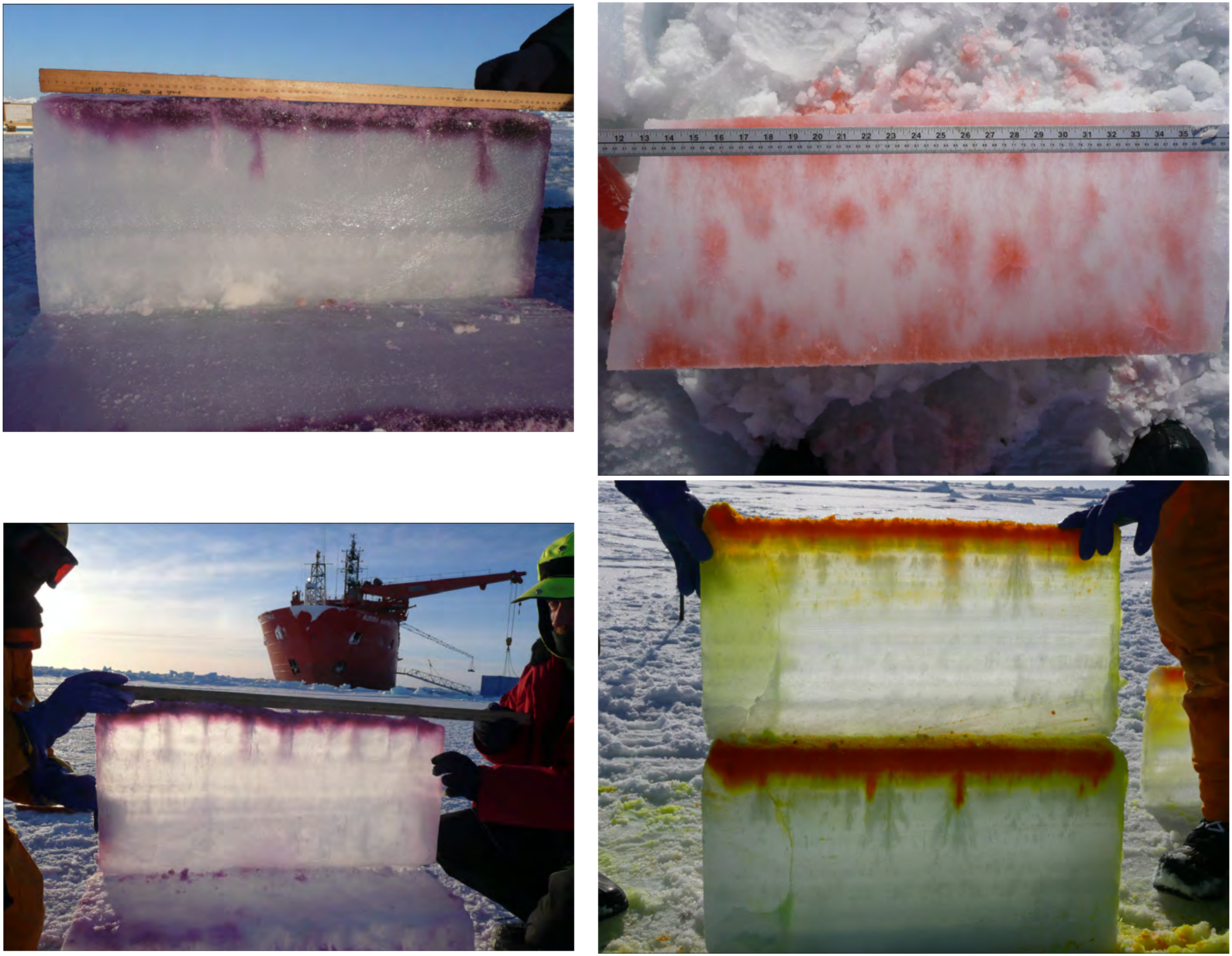




10%

Golden, Sampson, Gully, Lubbers, Tison 2020

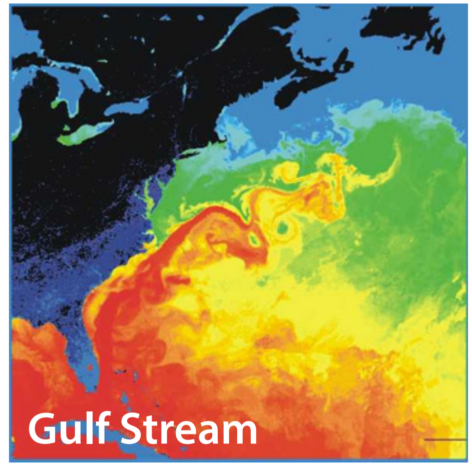
tracers flowing through inverted sea ice blocks

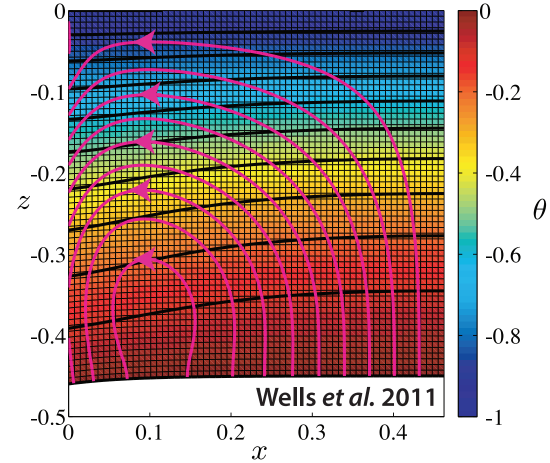


advection enhanced diffusion

effective diffusivity

nutrient and salt transport in sea ice
heat transport in sea ice with convection
sea ice floes in winds and ocean currents
tracers, buoys diffusing in ocean eddies
diffusion of pollutants in atmosphere





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

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

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

homogenize

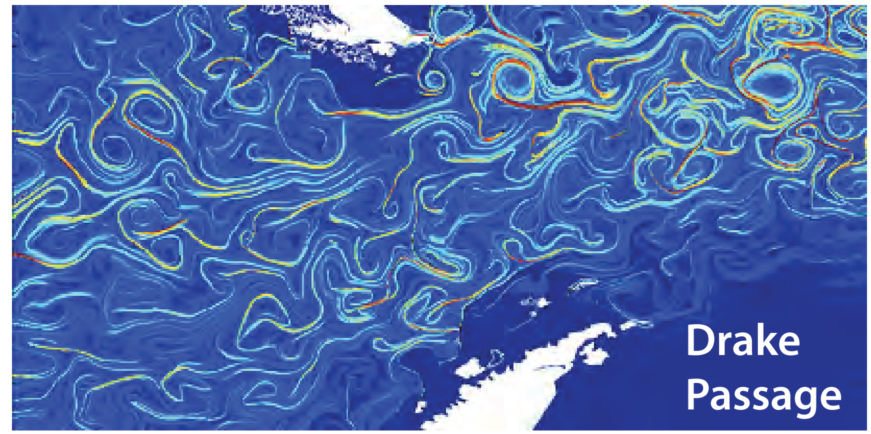
$$\frac{\partial \overline{T}}{\partial t} = \kappa^* \Delta \overline{T}$$

κ^* ***effective diffusivity***

Stieltjes integral for κ^* with spectral measure

Avellaneda and Majda, PRL 89, CMP 91

Murphy, Cherkaev, Xin, Zhu, Golden, *Ann. Math. Sci. Appl.* 2017
Murphy, Cherkaev, Zhu, Xin, Golden, *J. Math. Phys.* 2020



Stieltjes Integral Representation for Advection Diffusion

Murphy, Cherkaev, Zhu, Xin, Golden, *J. Math. Phys.* 2020

$$\kappa^* = \kappa \left(1 + \int_{-\infty}^{\infty} \frac{d\mu(\tau)}{\kappa^2 + \tau^2} \right), \quad F(\kappa) = \int_{-\infty}^{\infty} \frac{d\mu(\tau)}{\kappa^2 + \tau^2}$$

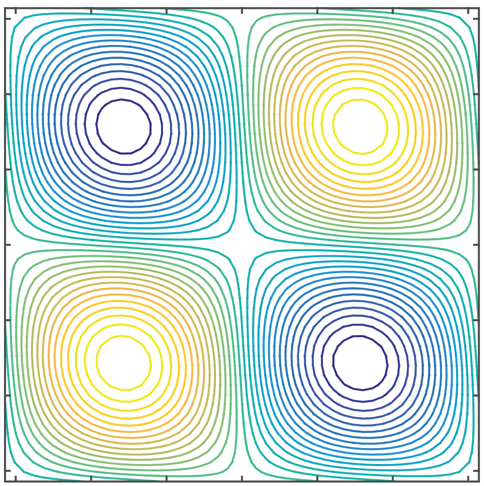
- μ is a positive definite measure corresponding to the spectral resolution of the self-adjoint operator $i\Gamma H\Gamma$
- $H =$ stream matrix , $\kappa =$ local diffusivity
- $\Gamma := -\nabla(-\Delta)^{-1}\nabla\cdot$, Δ is the Laplace operator
- $i\Gamma H\Gamma$ is bounded for time independent flows
- $F(\kappa)$ is analytic off the spectral interval in the κ-plane

separation of material properties and flow field

spectral measure calculations

Rigorous bounds on convection enhanced thermal conductivity of sea ice

Kraitzman, Hardenbrook, Murphy, Zhu, Cherkaev, Strong, Golden 2020

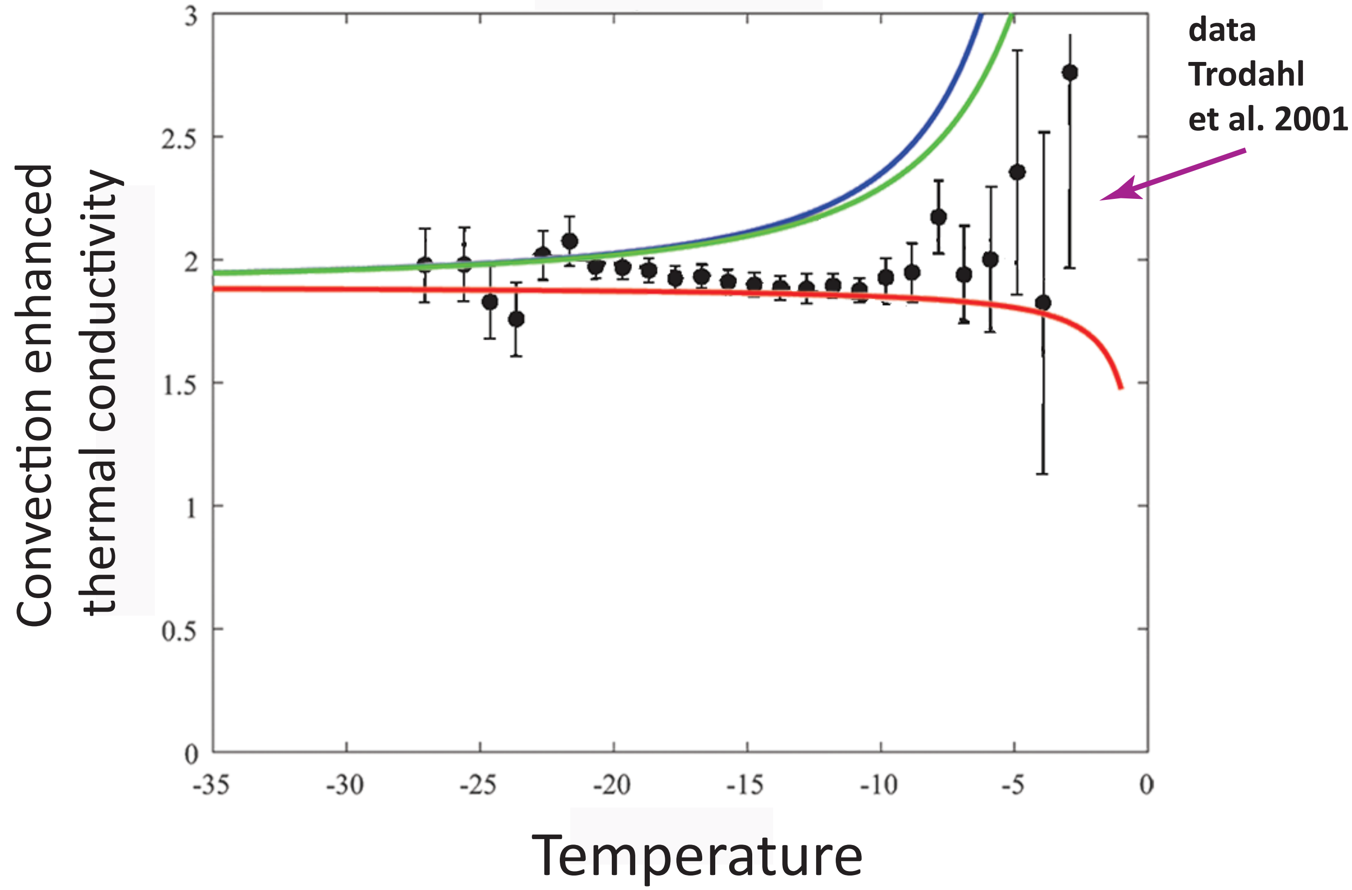


cat's eye flow model for
brine convection cells

similar bounds
for shear flows

rigorous bounds assuming information on flow field INSIDE inclusions

Kraitzman, Cherkaev, Golden
SIAM J. Appl. Math (in revision), 2020



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

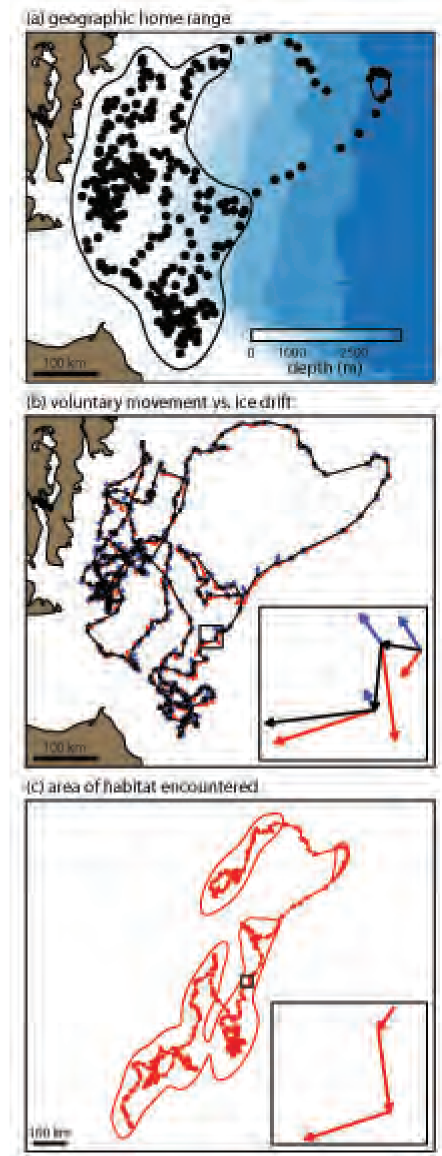
Ice floe diffusion in winds and currents

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, *Ann. Glac.* 2015

Huy Dinh, Elena Cherkaev, Ken Golden, 2019



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, *Ecography*, 2016

Microbial life UNDER sea ice

melt ponds, algal blooms

melt pond formation and albedo evolution:

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

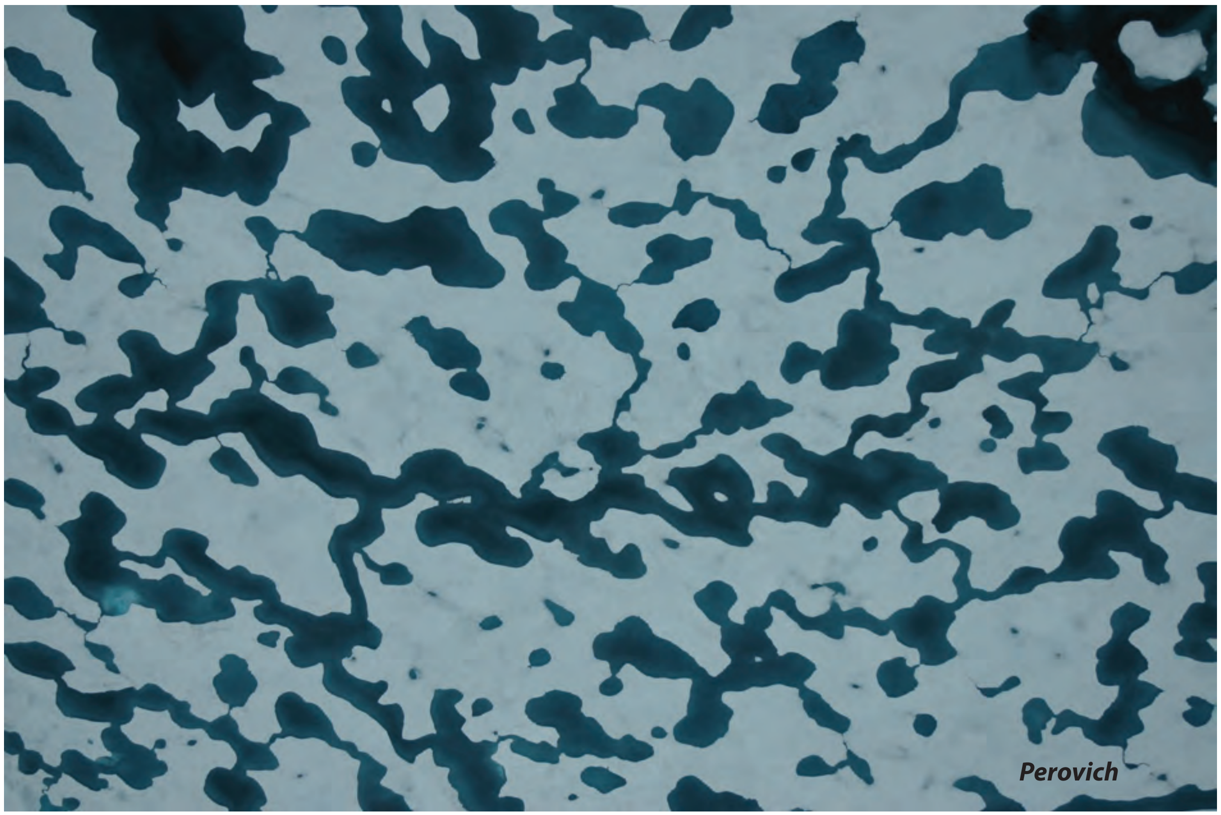
numerical models of melt pond evolution, including topography, drainage (permeability), etc.

Lüthje, Feltham, Taylor, Worster 2006

Flocco, Feltham 2007

Skyllingstad, Paulson, Perovich 2009

Flocco, Feltham, Hunke 2012

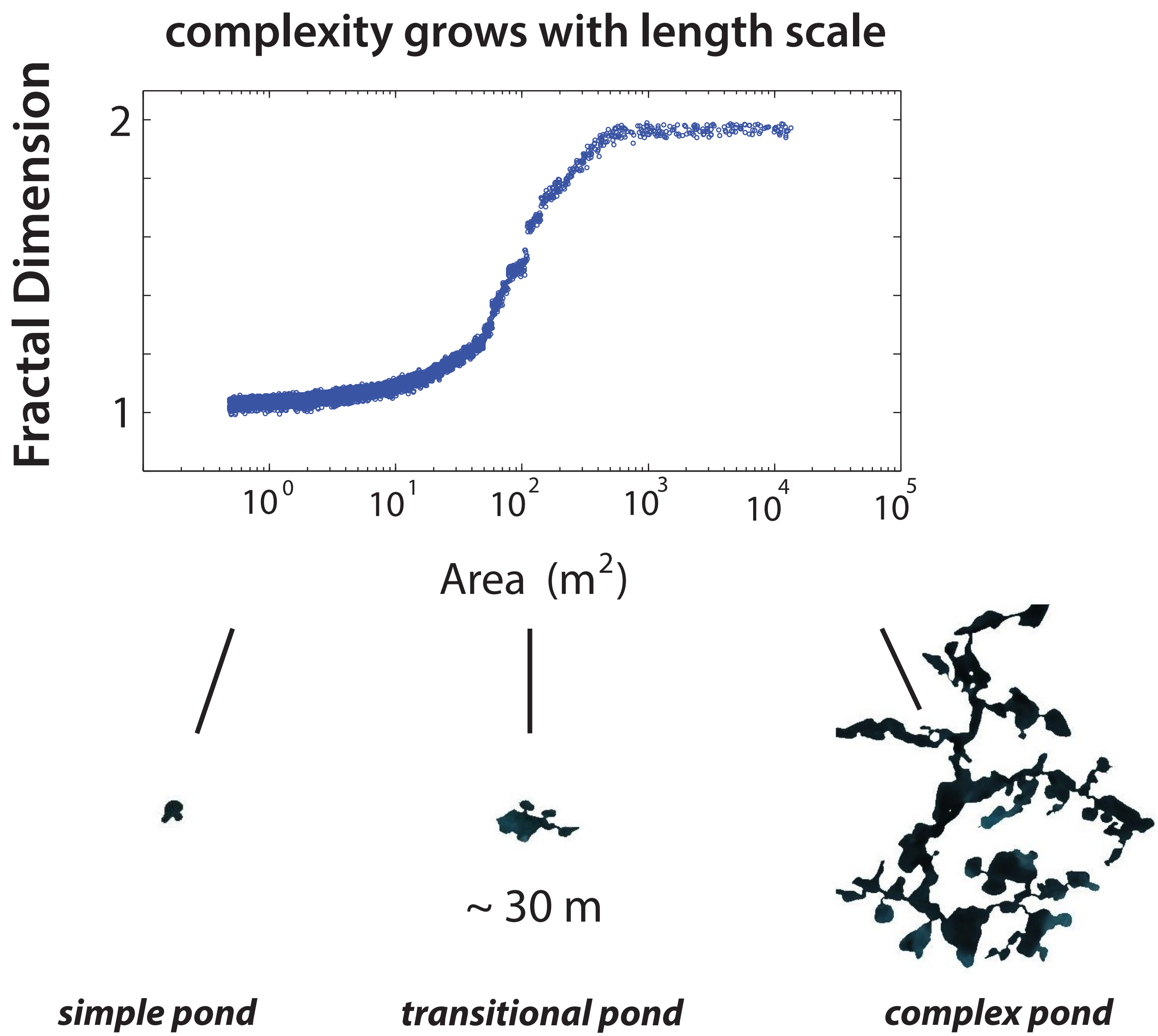


Are there universal features of the evolution similar to phase transitions in statistical physics?

Transition in the fractal geometry of Arctic melt ponds

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

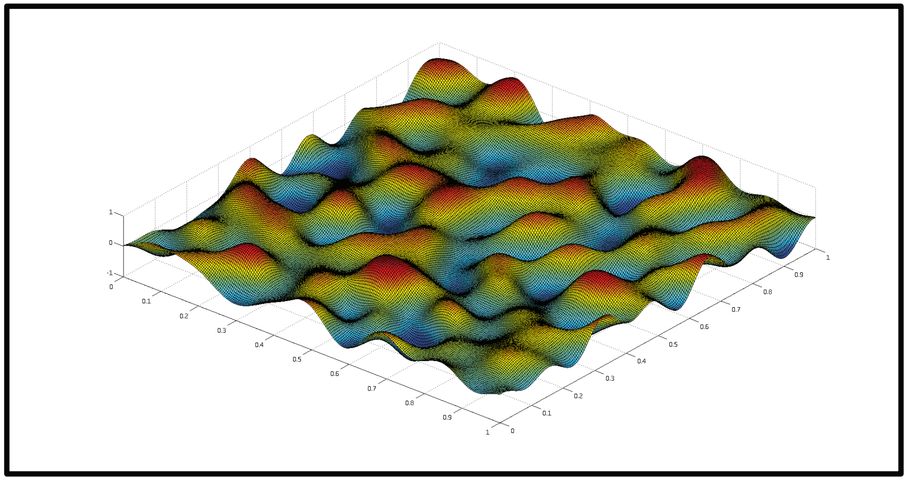
The Cryosphere, 2012



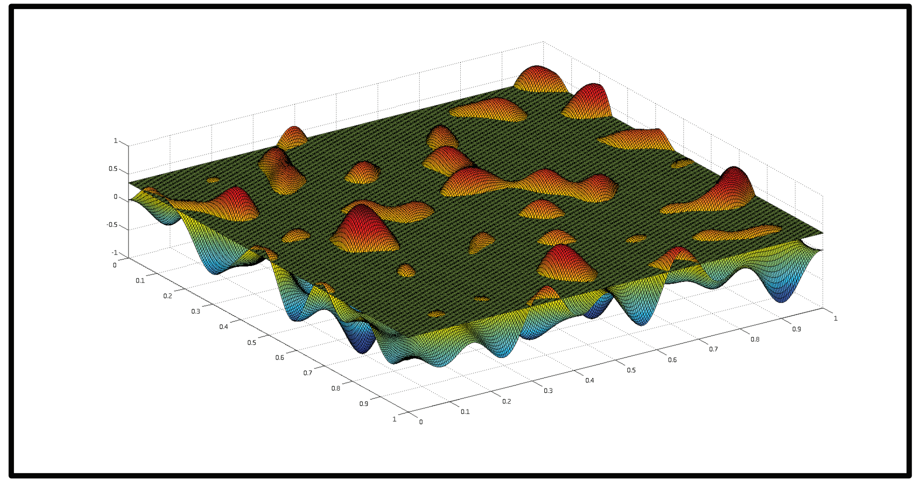
Continuum percolation model for melt pond evolution

level sets of random surfaces

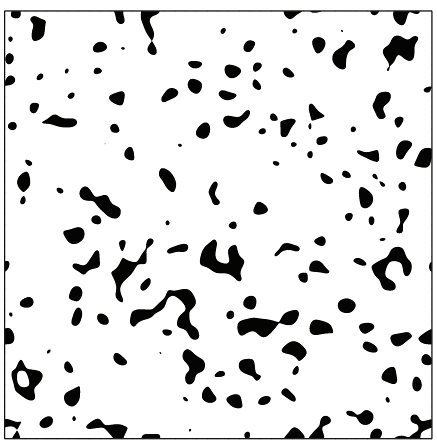
Brady Bowen, Court Strong, Ken Golden, J. Fractal Geometry 2018

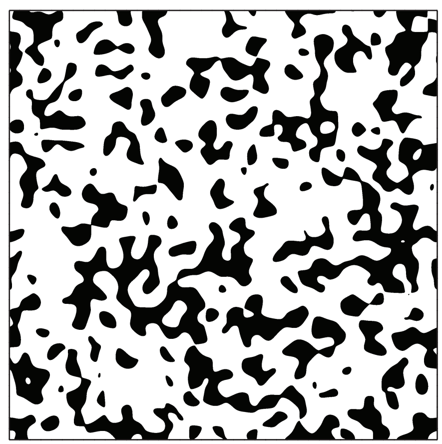


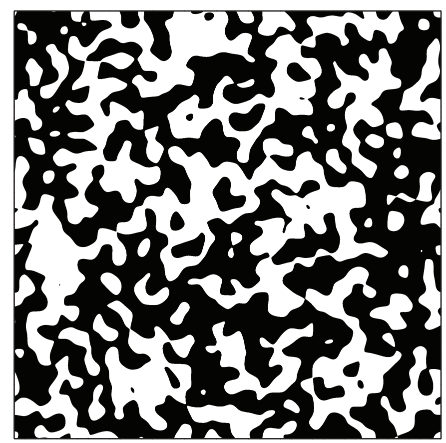
random Fourier series representation of surface topography



intersections of a plane with the surface define melt ponds





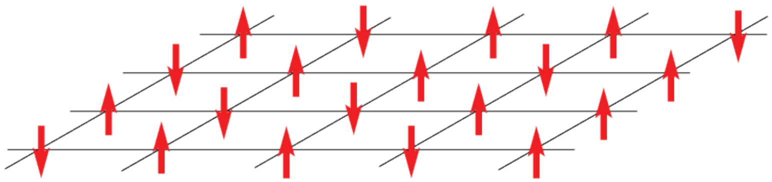


electronic transport in disordered media

diffusion in turbulent plasmas

Isichenko, Rev. Mod. Phys., 1992

Ising Model for a Ferromagnet



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

blue
white

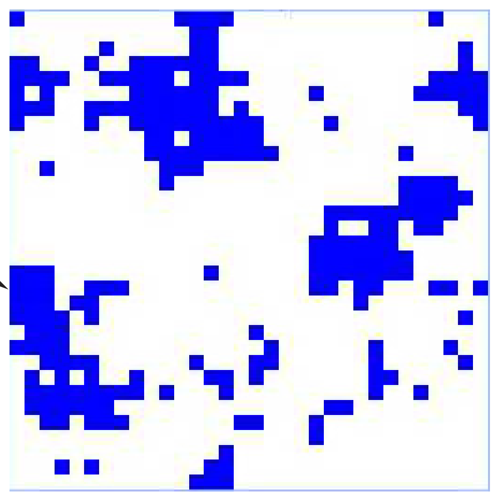
applied magnetic field H

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

nearest neighbor Ising Hamiltonian

ferromagnetic interaction $J \geq 0$

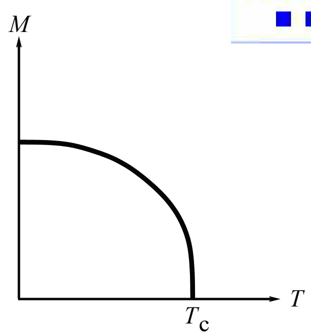
islands or ponds of like spins



magnetization

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

homogenized parameter like effective conductivity



Curie point critical temperature

Stieltjes integral representation for M

Baker, PRL 1968

Ising model for ferromagnets ⟶ Ising model for melt ponds

Ma, Sudakov, Strong, Golden, *New J. Phys.*, 2019

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

random magnetic field represents snow topography

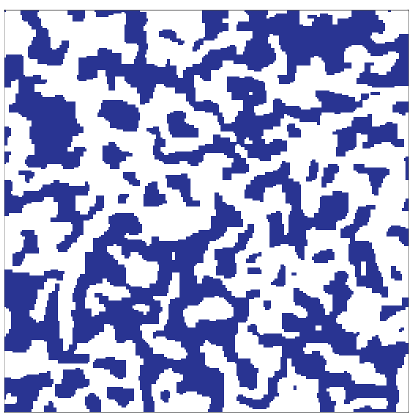
magnetization M **pond coverage** $\dfrac{(M+1)}{2}$

~ albedo

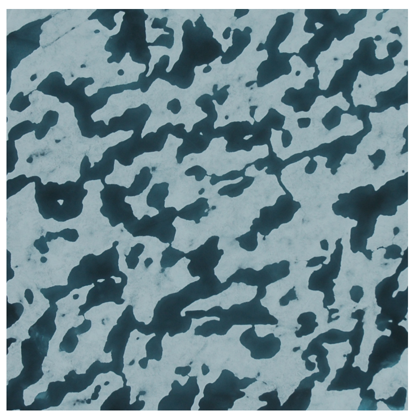
only nearest neighbor patches interact

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

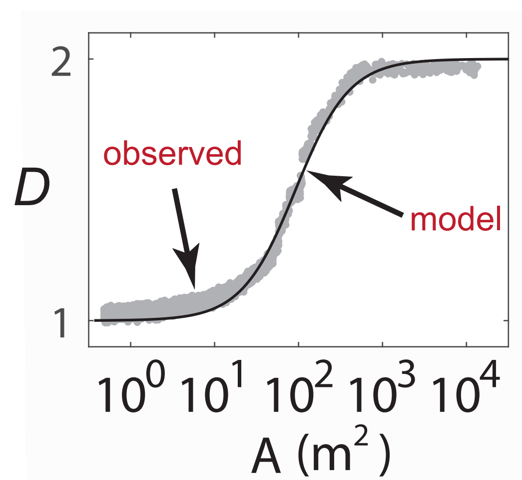
Order from Disorder



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

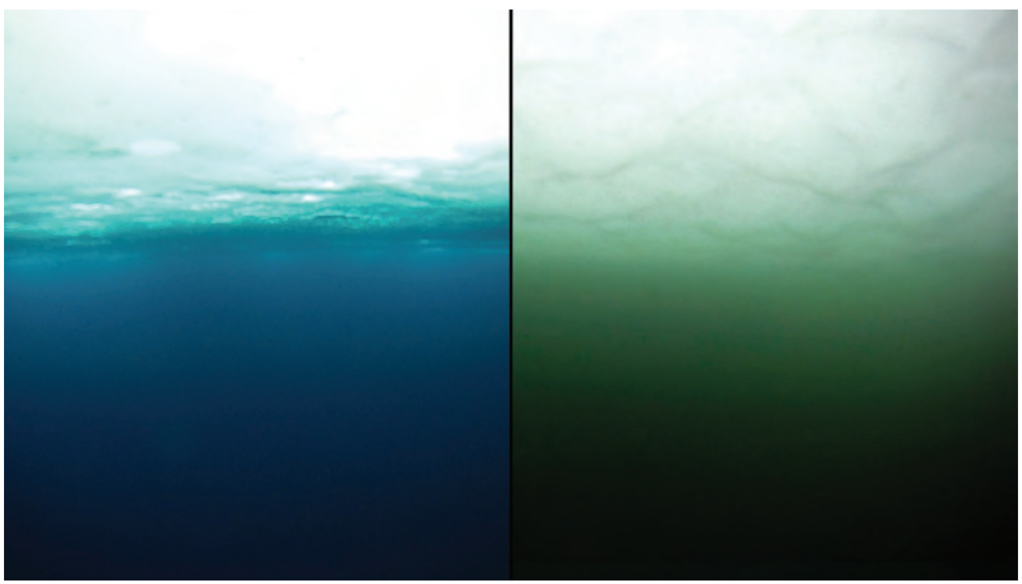
2011 massive under-ice algal bloom

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

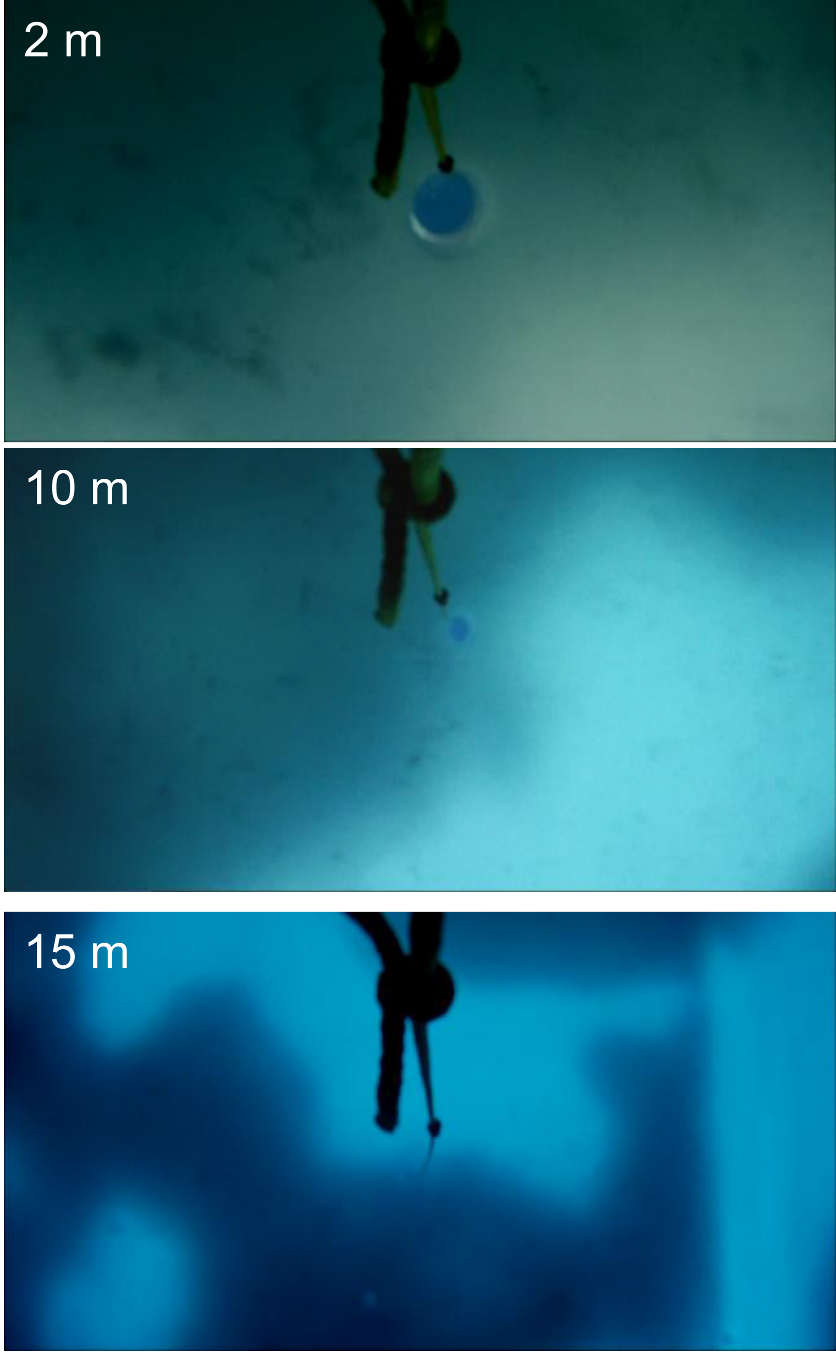
Horvat, Rees Jones, Iams, Schroeder, Flocco, Feltham, ***Science Advances***, 2017

The distribution of solar energy under ponded sea ice

Horvat, Flocco, Rees Jones, Roach, Golden, 2020

(2015 AMS MRC @ Snowbird)

the view from underneath



melt ponds are WINDOWS

light reaches the upper ocean

Perovich

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

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

- Model for initiation of light-limited phytoplankton bloom (depth of mixed layer, ice thickness, melt pond area fraction, ...)
- Thinner summertime Arctic sea ice is increasingly covered in melt ponds, which permit more light penetration.
- Marked increase in light conditions conducive to sub-ice blooms.
- As little as 20 years ago, conditions for sub-ice blooms may have been uncommon; frequency has increased so that nearly 30% of the ice-covered Arctic Ocean in July permits sub-ice blooms.

Recent climate change may have significantly altered the ecology of the Arctic Ocean.

The distribution of solar energy under ponded first-year sea ice

Horvat, Flocco, Rees Jones, Roach, Golden, *Geophys. Res. Lett.* 2020

- Model for 3D light field under ponded sea ice.

- Distribution of solar energy at depth influenced by ***shape and connectivity*** of melt ponds, as well as area fraction.

- Aggregate properties of the sub-ice light field, such as a significant enhancement of available solar energy under the ice, are controlled by parameter closely related to pond fractal geometry.

- Model and analysis explain how melt pond geometry ***homogenizes*** under-ice light field, affecting habitability.

Pond geometry affects the ecology of the Arctic Ocean.

The Melt Pond Conundrum:

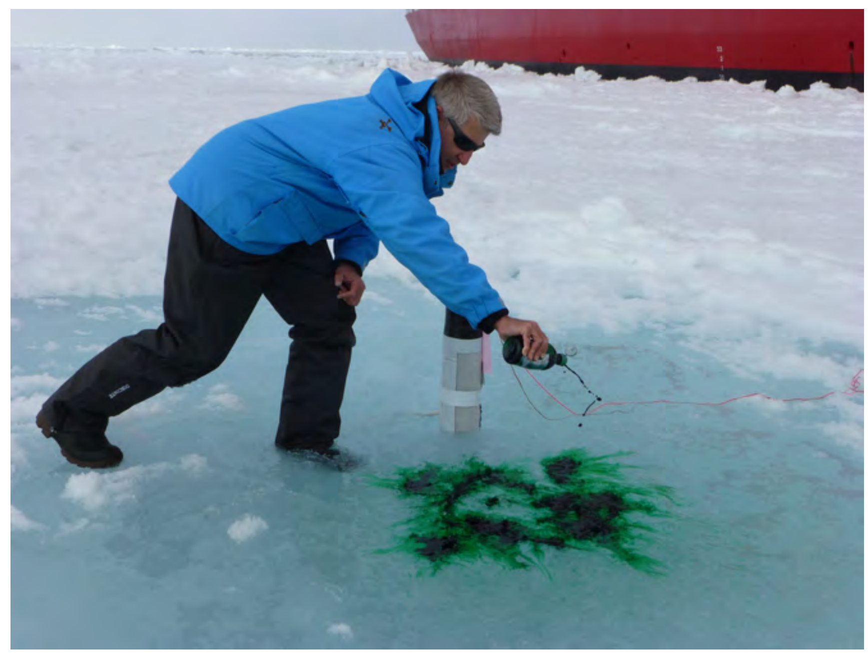
How can ponds form on top of sea ice that is highly permeable?

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



Large ecosystems in transition: bifurcations and mass extinction

I. Sudakov, S. Vakulenko, D. Kirievskaya, K. M. Golden, *Ecological Complexity,* 2017

model of multispecies populations competing for distributed resources

coupling climate and population dynamics via resources

feedback between species abundances and resources through temperature

resource competition model

Leon & Tumpson, *J. Theor. Biol.* 1975
Tilman, *Ecology*, 1977
Huisman & Weissing, *Nature*, 1999 **(solved "plankton paradox")**

$$\frac{dx_i}{dt} = x_i(-r_i + \phi_i(v) - \sum_{j=1}^{N} \gamma_{ij}\, x_j), \quad 1 \leq i \leq N$$

$$\frac{dv}{dt} = D(S - v) - \sum_{j=1}^{N} c_j\, x_j\, \phi_j(v)$$

$$\phi_j(v) = \frac{a_j v}{K_j + v}\,, \quad a_j,\ K_j > 0$$

x_i	species abundance
ϕ_i	species growth rate
r_i	species mortality rate
γ_{ij}	describe competition (e.g. toxic compounds) diagonals ~ self-regulation restricting abundances
S	supply concentration of resource
v	resource availability
D	resource turnover rate
c_j	determine how species share resource
K_j	saturation constants

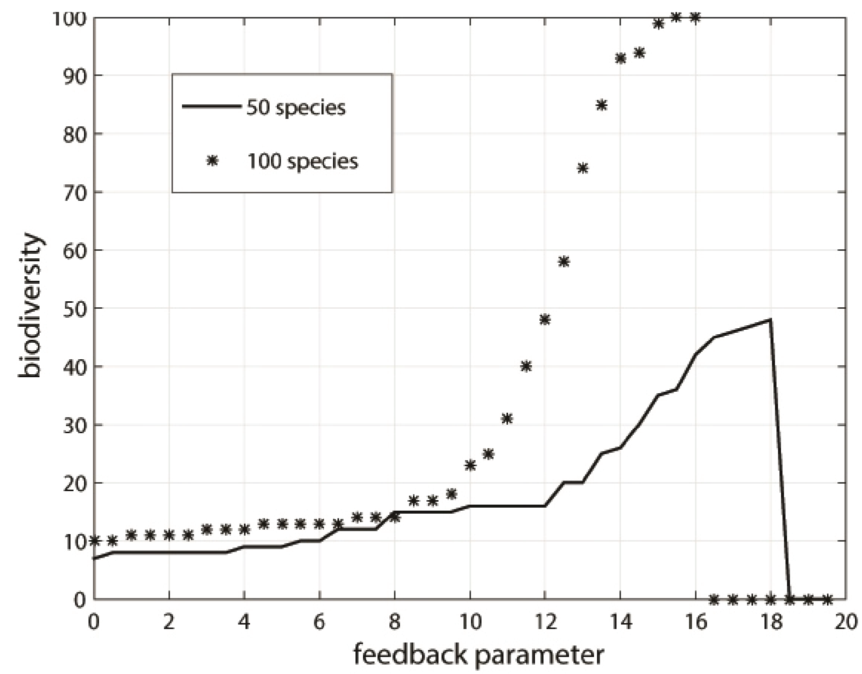
Extend model to *M* resources, whose supplies depend on temperature *T*, which depends on species abundances.

$$T = \bar{T} + \Delta T, \quad \Delta T = \sum_{k=1}^{N} \mu_{kj} x_j$$

$$S_k = \bar{S}_k(\bar{T}) + \Delta S_k + O(\Delta T^2)$$

$$\Delta S_k = \sum_{k=1}^{N} b_{kj}(\bar{T}) x_j, \quad k = 1, \ldots, M$$

$$b_{kj} = \frac{dS_k(\bar{T})}{d\bar{T}} \mu_{kj} \begin{cases} > 0 & \textit{positive feedback} \\ < 0 & \textit{negative feedback} \end{cases}$$



mass extinctions

reduction to Lotka-Volterra system

$|b_{ik}| \ll \gamma$ ***weak climate coupling***

close to 'competitive systems' - exhibit no stable periodic or chaotic regimes: almost all trajectories converge to equilibria

$|b_{ik}| \gg \gamma$ ***strong climate coupling***

$M = 1$, possible that all N species survive in equilibrium, or coexistence of many equilibria

$M = 2$, feedback coeffs have different signs, periodic sols

$M > 2$, system can produce time chaotic solutions

when the number of species increases, so does the likelihood of a sharp drop in species number as the climate changes and feedback processes grow stronger

The model exhibits coexistence of many species, yet also displays the possibility of catastrophic bifurcations, where all species become extinct under the influence of abiotic factors (strong climate coupling).

Conclusions

1. The physics of fluid transport in porous composites regulates microbial life inside sea ice.

2. The geometry of melt ponds controls light in the upper ocean, and initiation of under-ice algal blooms.

3. Resource competition models provide tools to study the complexity of these microbial communities.

THANK YOU

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Buchanan Bay, Antarctica   Mertz Glacier Polynya Experiment   July 1999