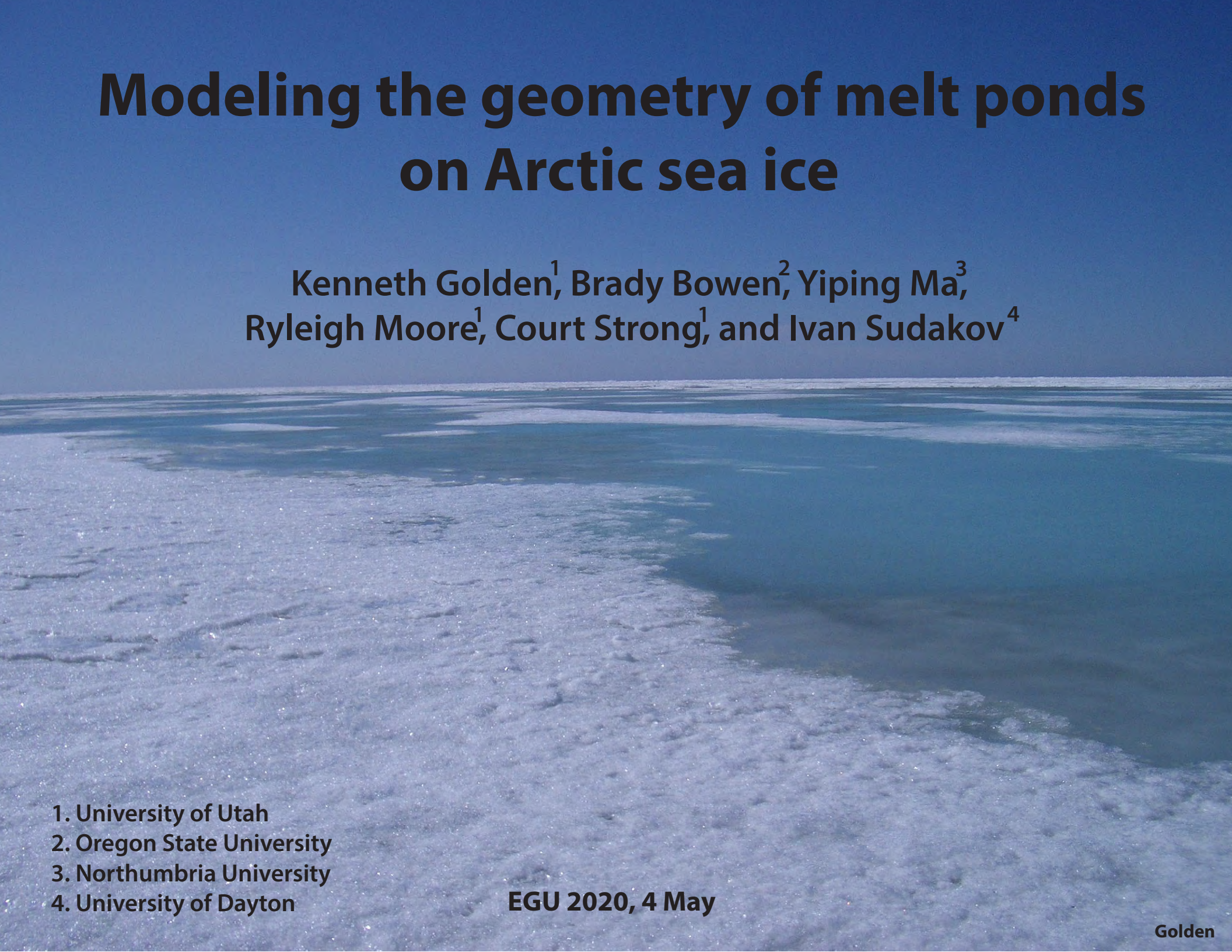
Modeling the geometry of melt ponds on Arctic sea ice

Kenneth Golden[1], Brady Bowen[2], Yiping Ma[3],
Ryleigh Moore[1], Court Strong[1], and Ivan Sudakov[4]



1. University of Utah
2. Oregon State University
3. Northumbria University
4. University of Dayton

EGU 2020, 4 May

Golden

melt pond formation and albedo evolution:

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

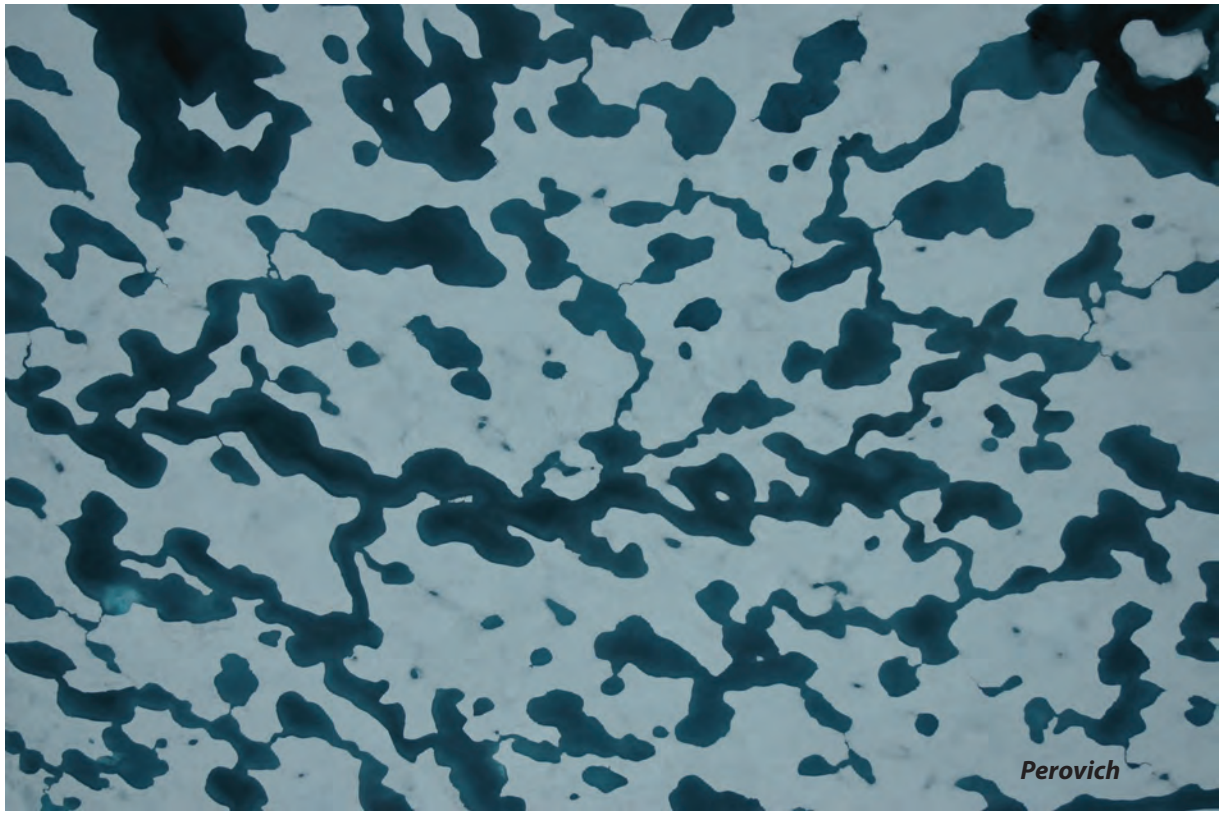
numerical models of melt pond evolution, including topography, drainage (permeability), etc.

Lüthje, Feltham, Taylor, Worster 2006

Flocco, Feltham 2007

Skyllingstad, Paulson, Perovich 2009

Flocco,Schroeder, Feltham, Hunke 2012



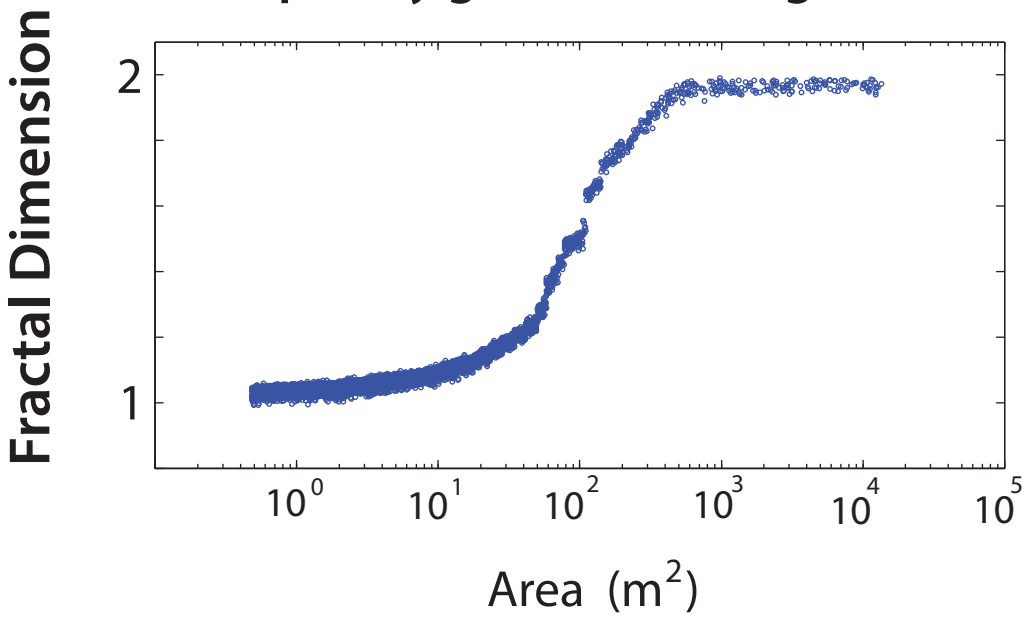
Are there universal features of the evolution similar to phase transitions in statistical physics?

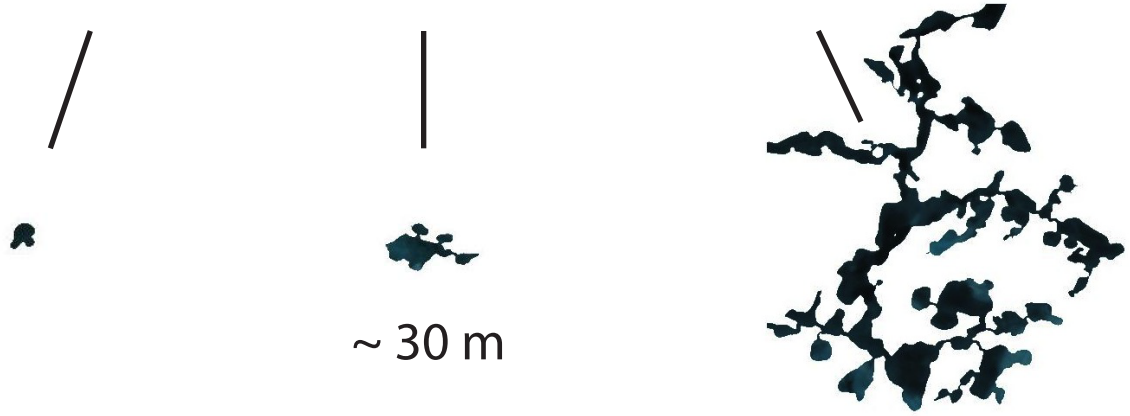
Transition in the fractal geometry of Arctic melt ponds

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

The Cryosphere, 2012

complexity grows with length scale



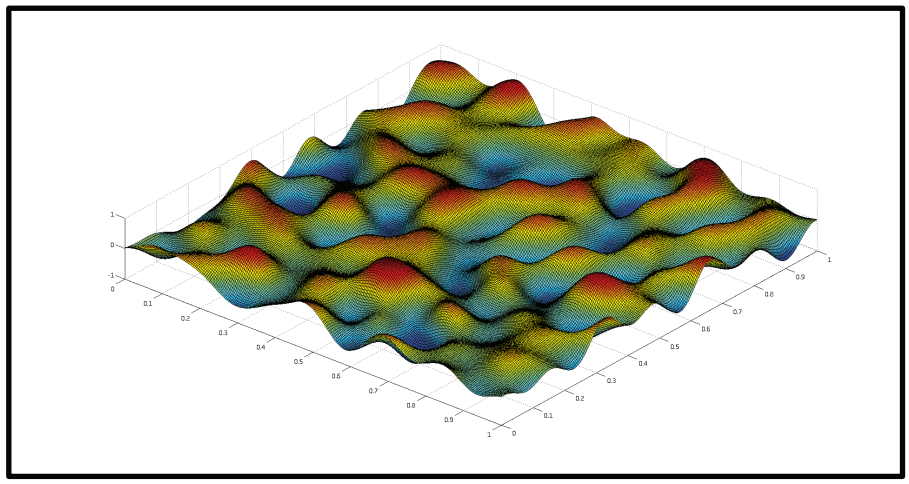


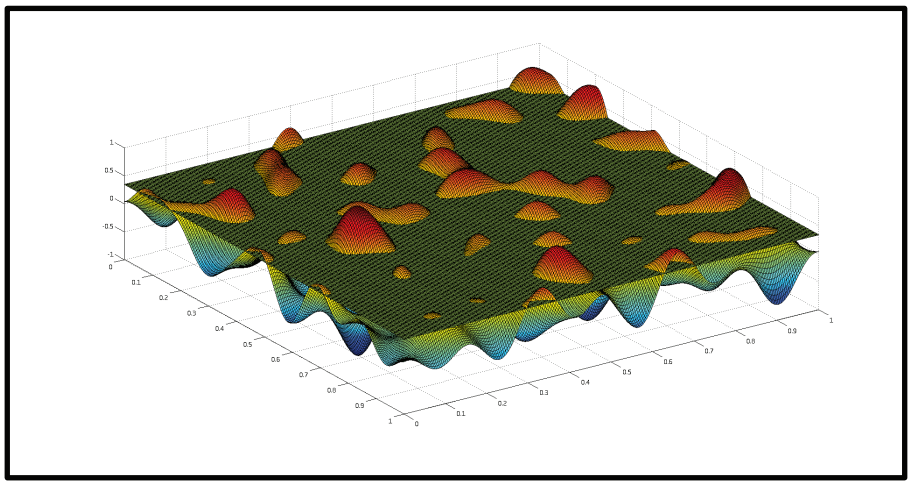
simple pond ***transitional pond*** ***complex pond***

Continuum percolation model for melt pond evolution

level sets of random surfaces

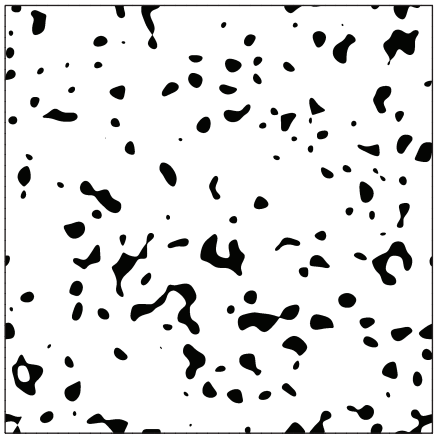
Brady Bowen, Court Strong, Ken Golden, J. Fractal Geometry 2018

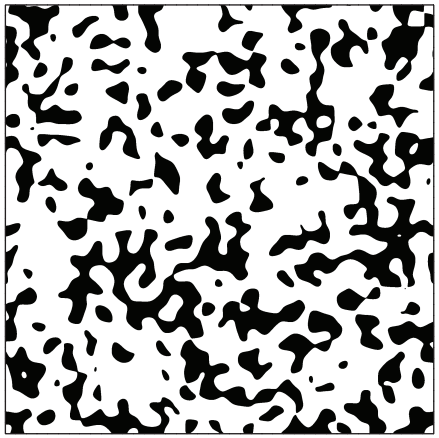


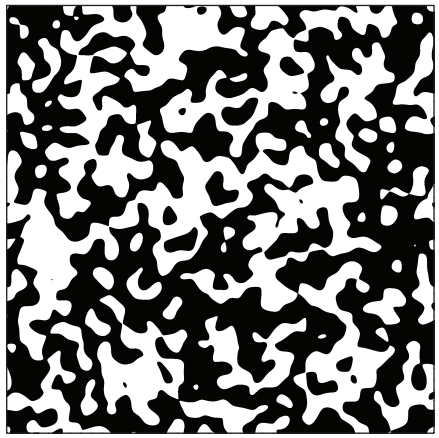


random Fourier series representation of surface topography

intersections of a plane with the surface deÿne melt ponds

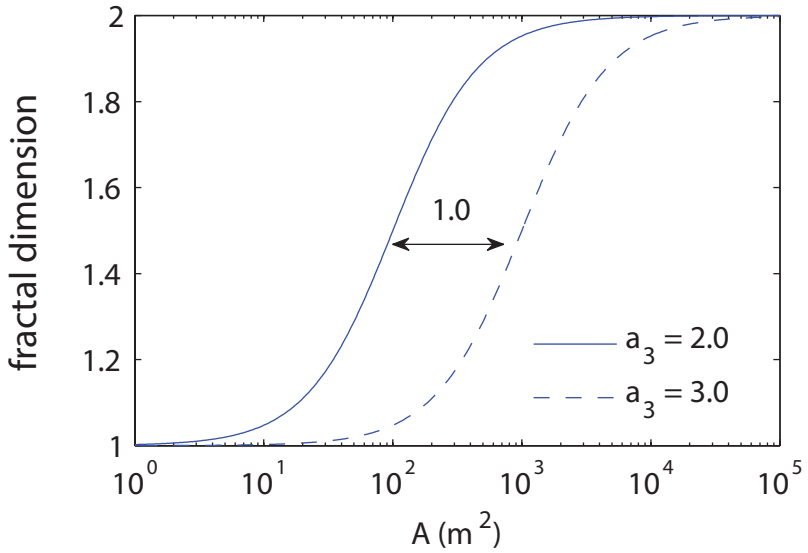


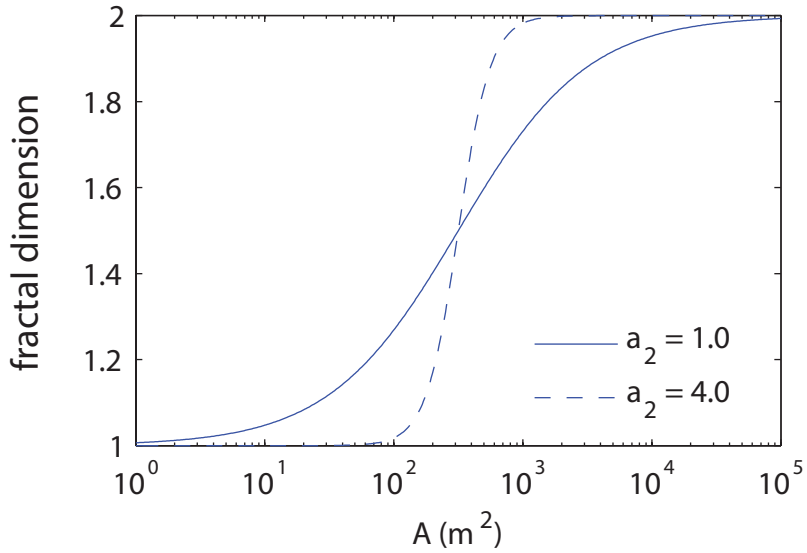




electronic transport in disordered media *diffusion in turbulent plasmas* *Isichenko, Rev. Mod. Phys., 1992*

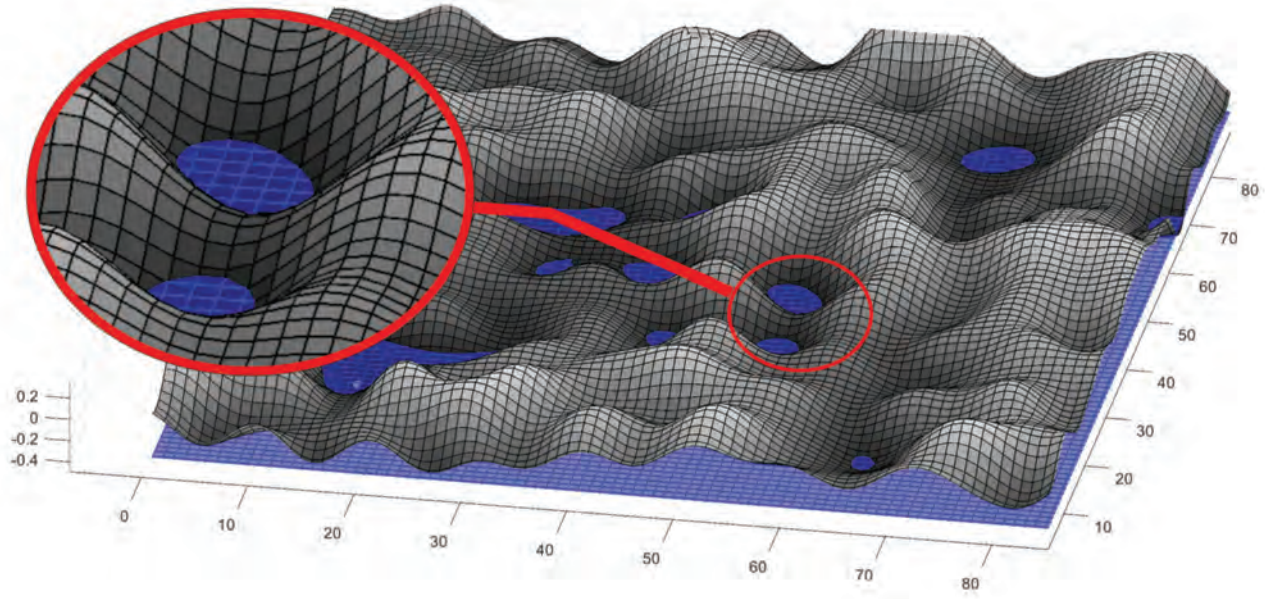
fractal dimension curves depend on statistical parameters defining random surface

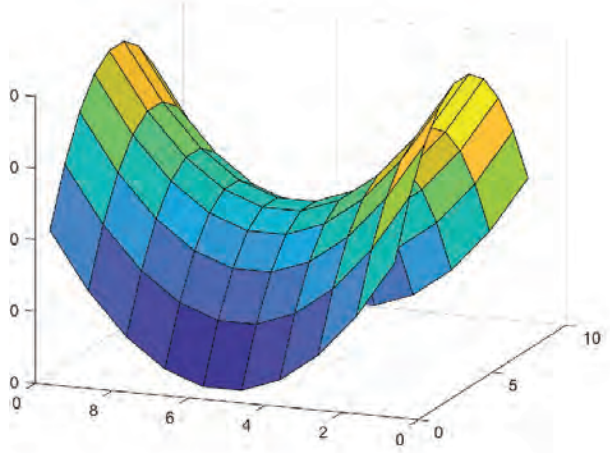




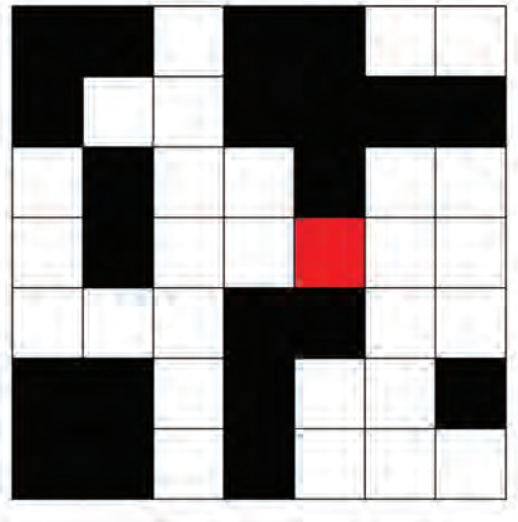
Saddle Points: The Key to Fractal Evolution

Ryleigh Moore, Jacob Jones, Dane Gollero, Court Strong, Ken Golden 2020



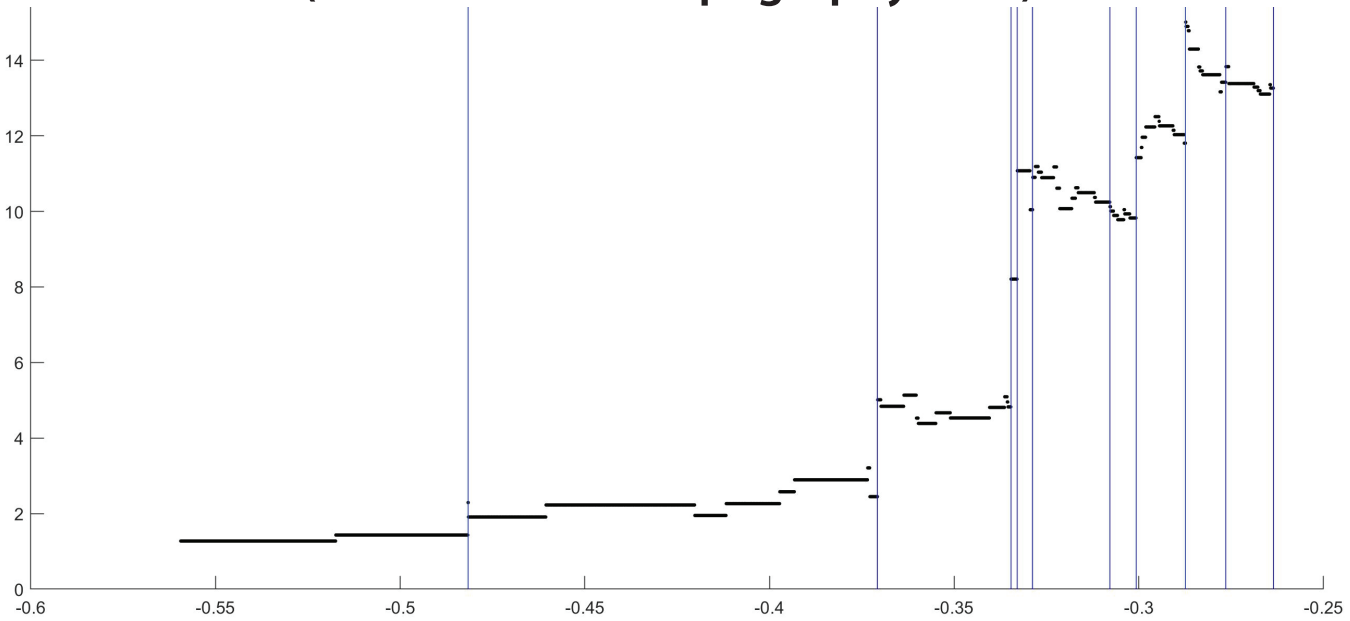


- Ponds connect through saddle points (Morse Theory).
- Red bond bond in percolation theory ~ saddle point.



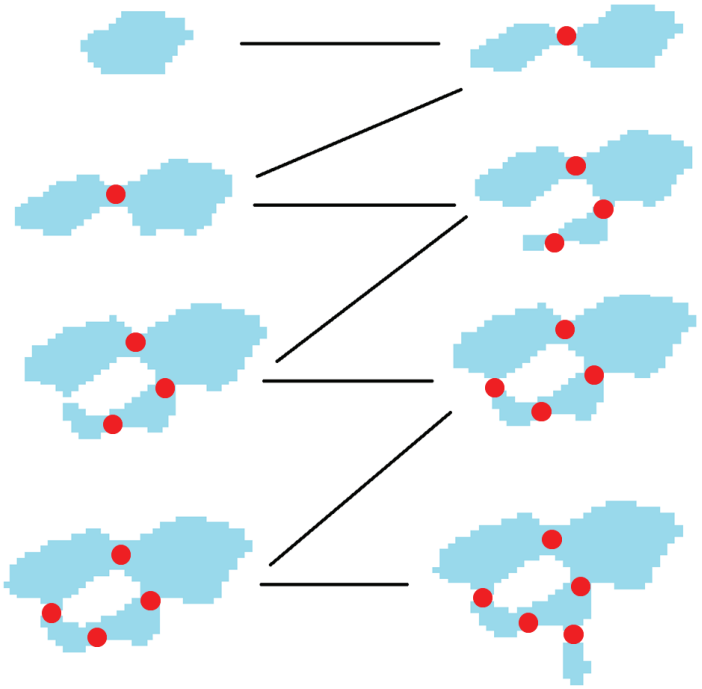
Evolution of Isoperimetric Quotient with Melt Pond Growth (from real snow topography data)

$$\frac{P^2}{4\pi A}$$



level set height

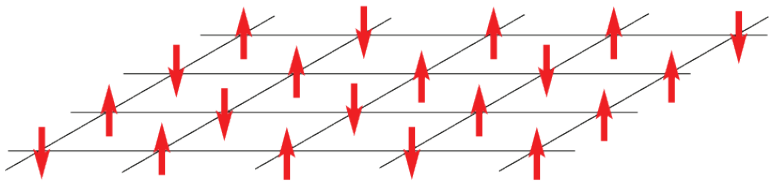
pond coalescence and thickening



In the graph, we follow a single pond's growth. The vertical lines denote when the pond goes through a saddle point.

We see that large jumps in isoperimetric ratio occur through saddle points.

Ising Model for a Ferromagnet



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

blue

white

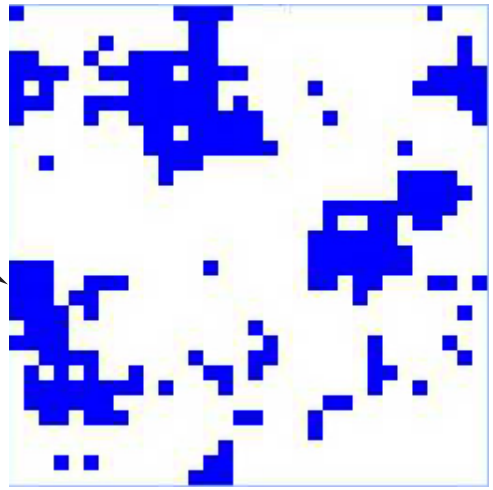
applied magnetic field H

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

nearest neighbor Ising Hamiltonian

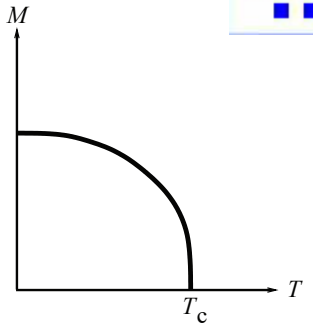
ferromagnetic interaction $J \geq 0$

islands or ponds of like spins



magnetization

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



Curie point critical temperature

homogenized parameter like effective conductivity

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

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

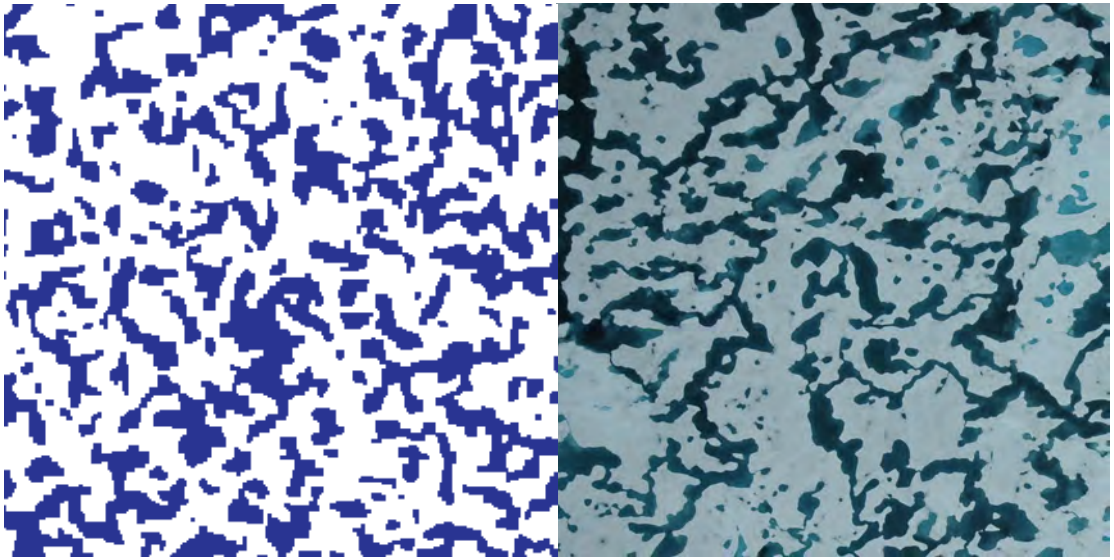
random magnetic field represents snow topography

magnetization M **pond coverage** $\frac{(M+1)}{2}$ ***~ albedo***

only nearest neighbor patches interact

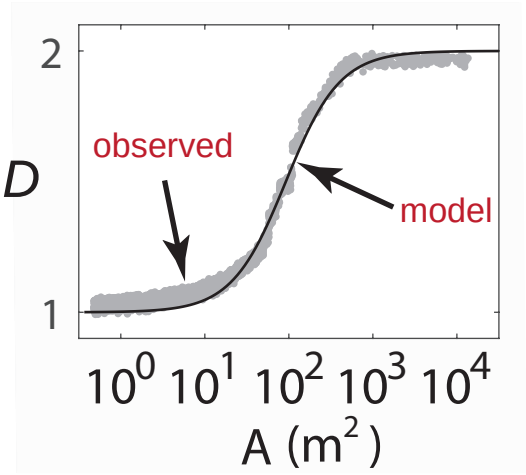
Starting with random initial configurations, as Hamiltonian energy is minimized by Glauber spin flip dynamics, system "flows" toward metastable equilibria.

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

The effect of melt pond geometry on the distribution of solar energy under 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.

Thanks to ONR and NSF.