Introduction to Sea Ice

Kenneth M. Golden
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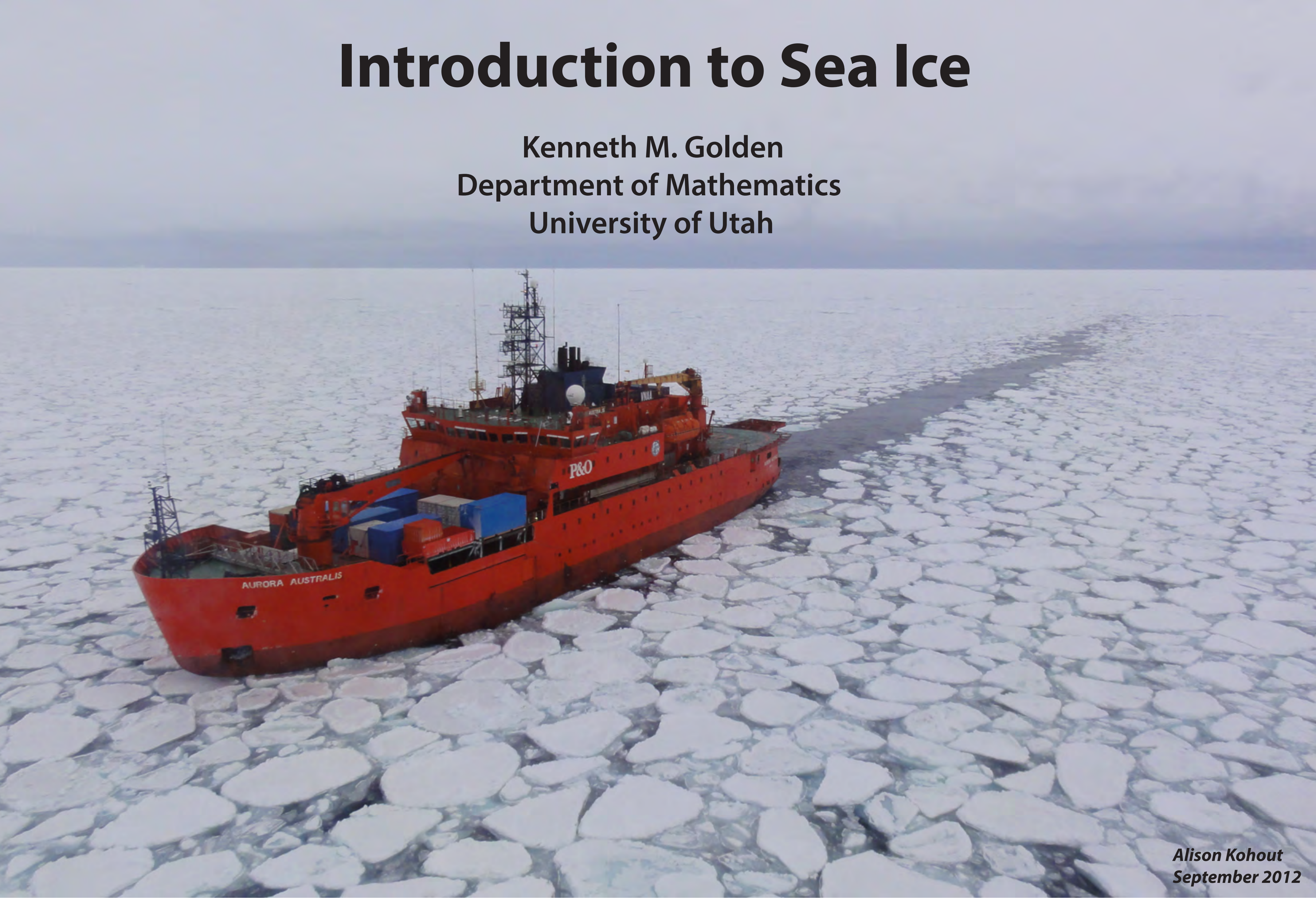
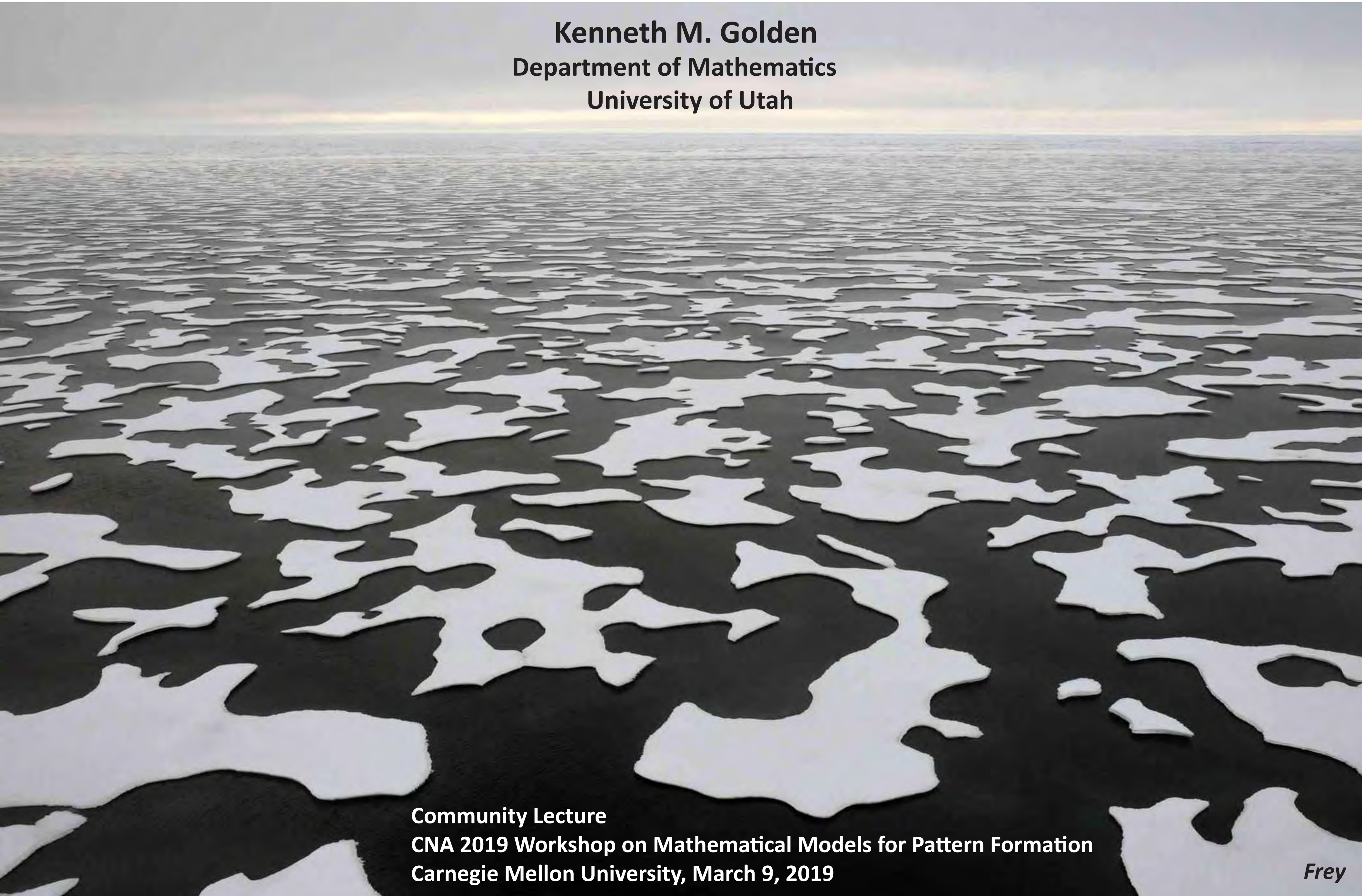


Alison Kohout
September 2012

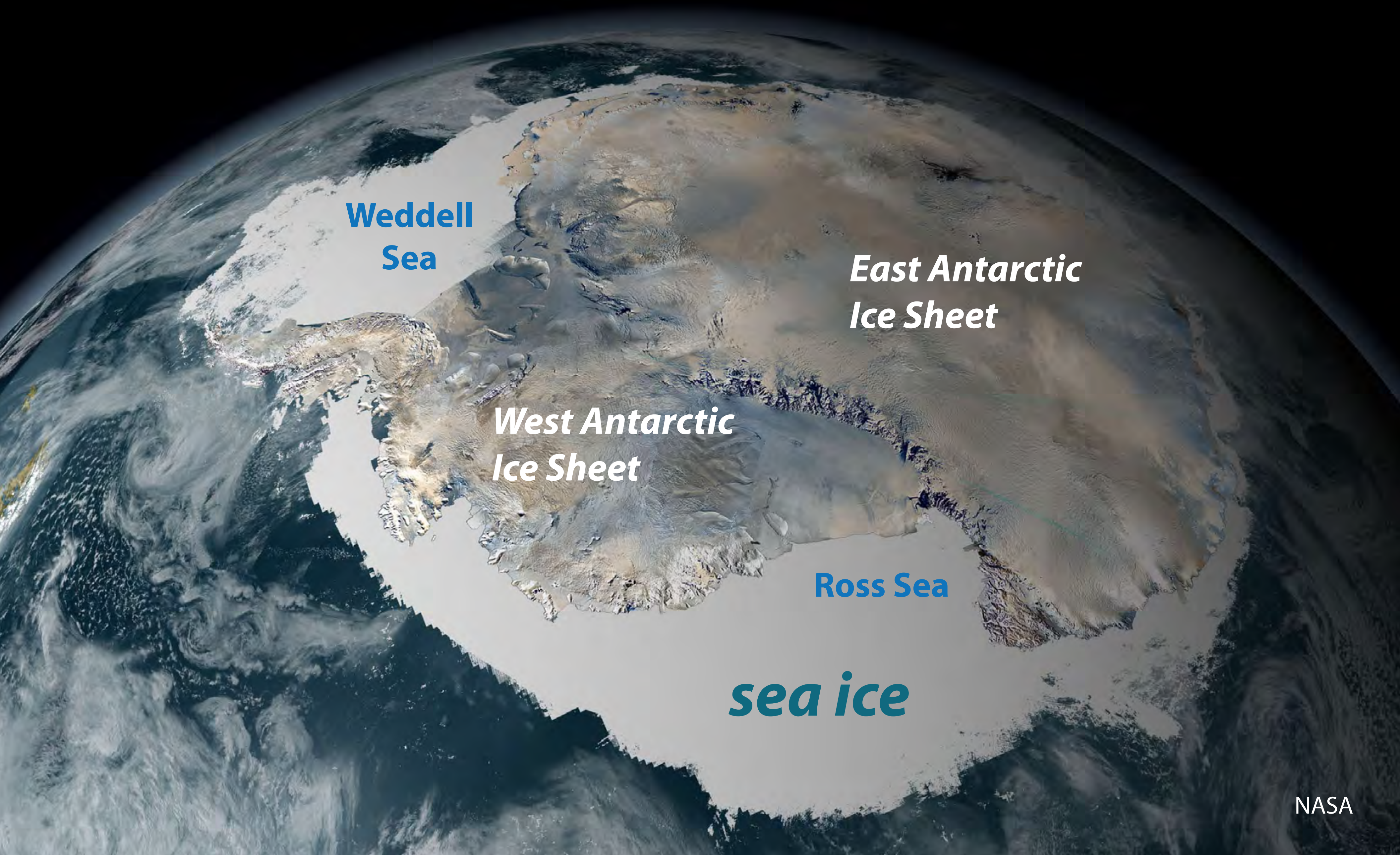
AMS Mathematics Research Community   Snowbird, Utah   June 22, 2015

Pattern Formation in Melting Arctic Sea Ice

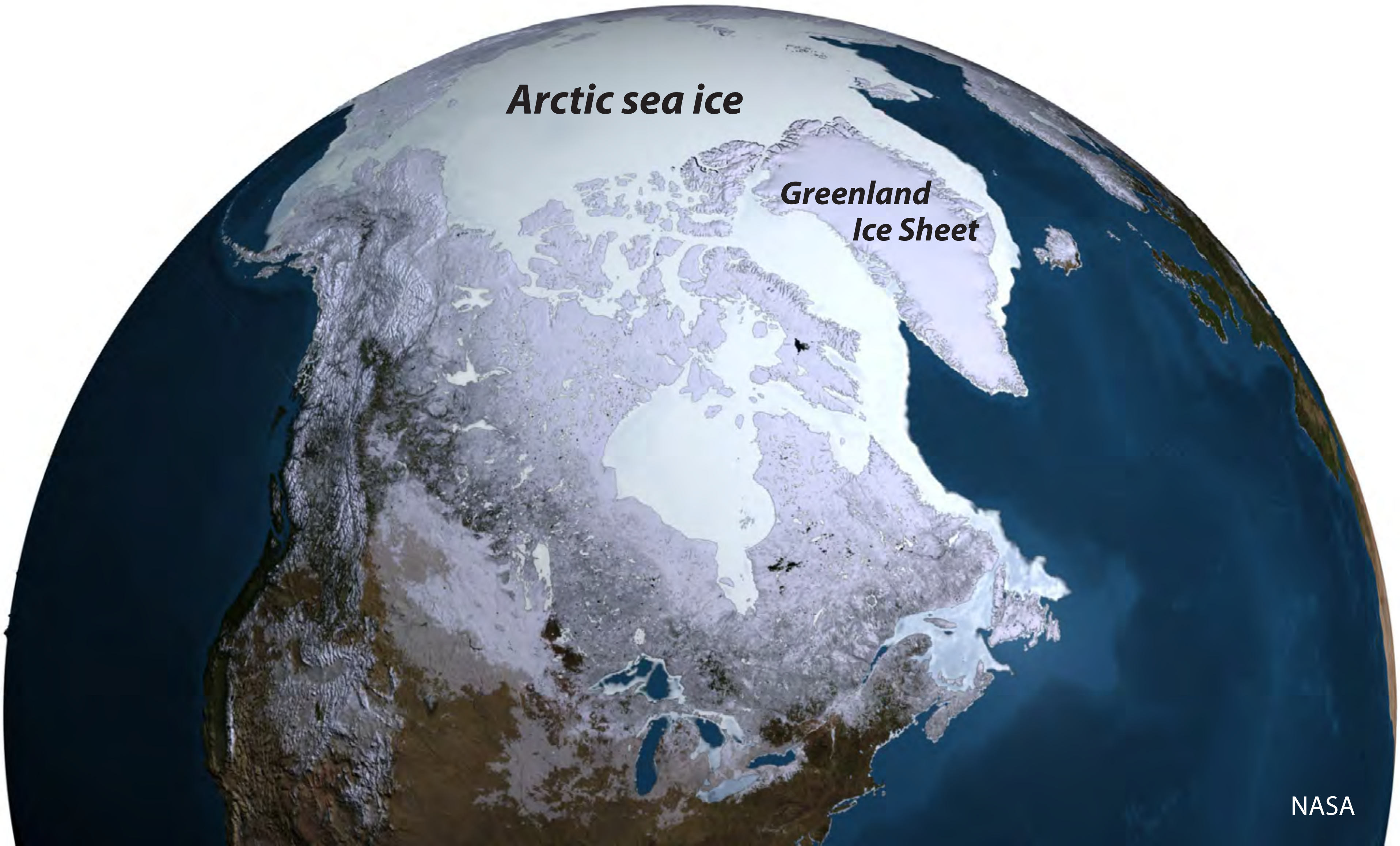


ANTARCTICA

southern cryosphere



northern cryosphere

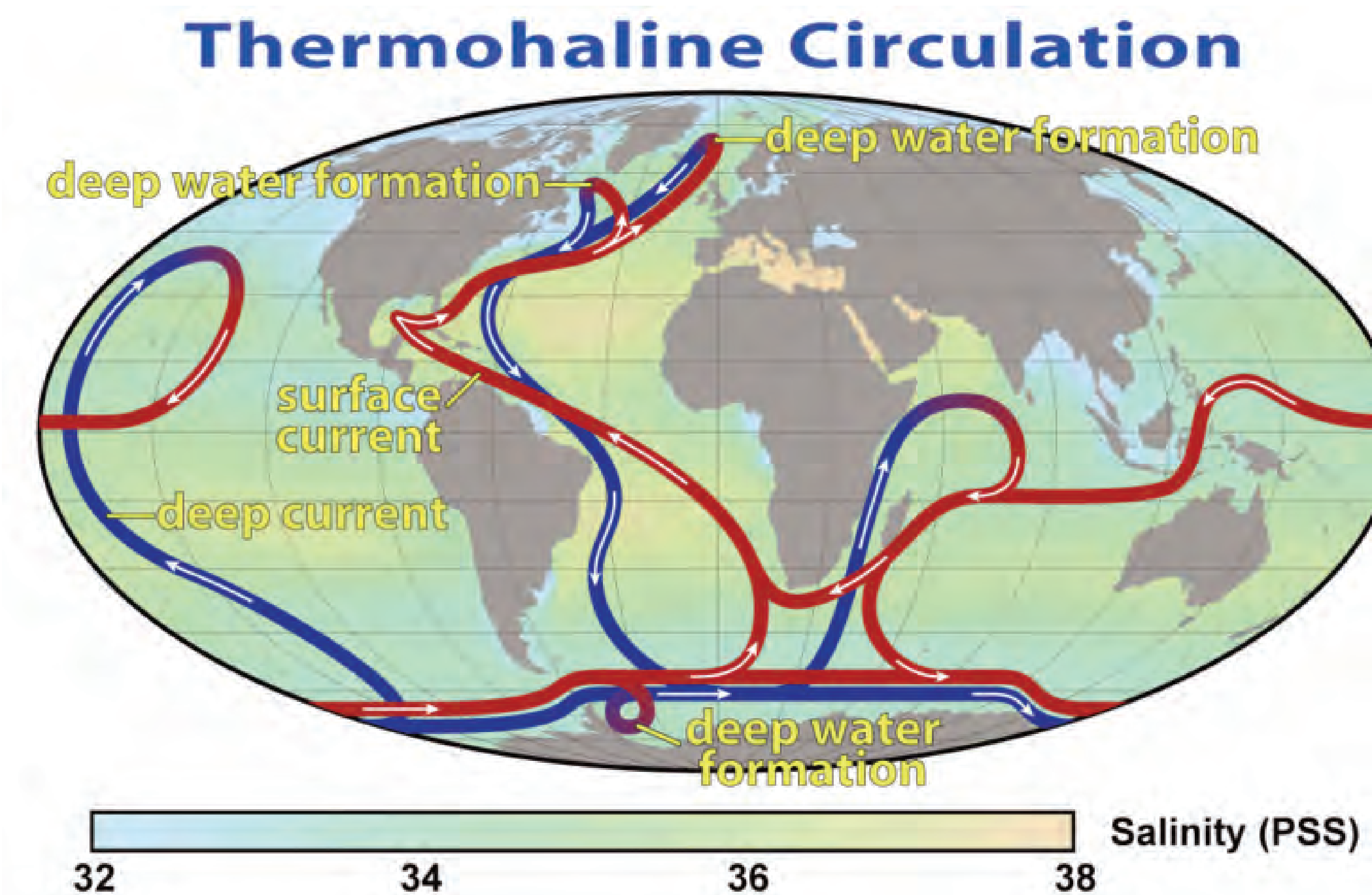


SEA ICE covers ~12% of Earth's ocean surface

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

brine expulsion from sea ice formation results in water beneath the ice becoming cooler and saltier → **this denser water sinks rapidly to great depths**

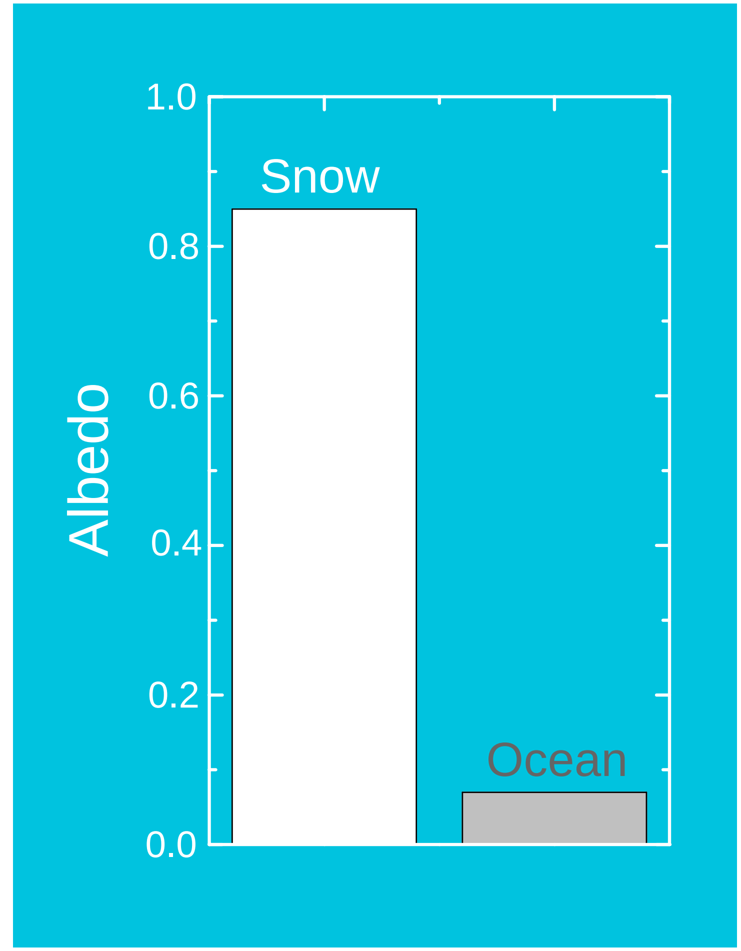
deep-water formation drives circulation in the world's oceans



GLOBAL THERMOHALINE CONVEYOR BELT

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

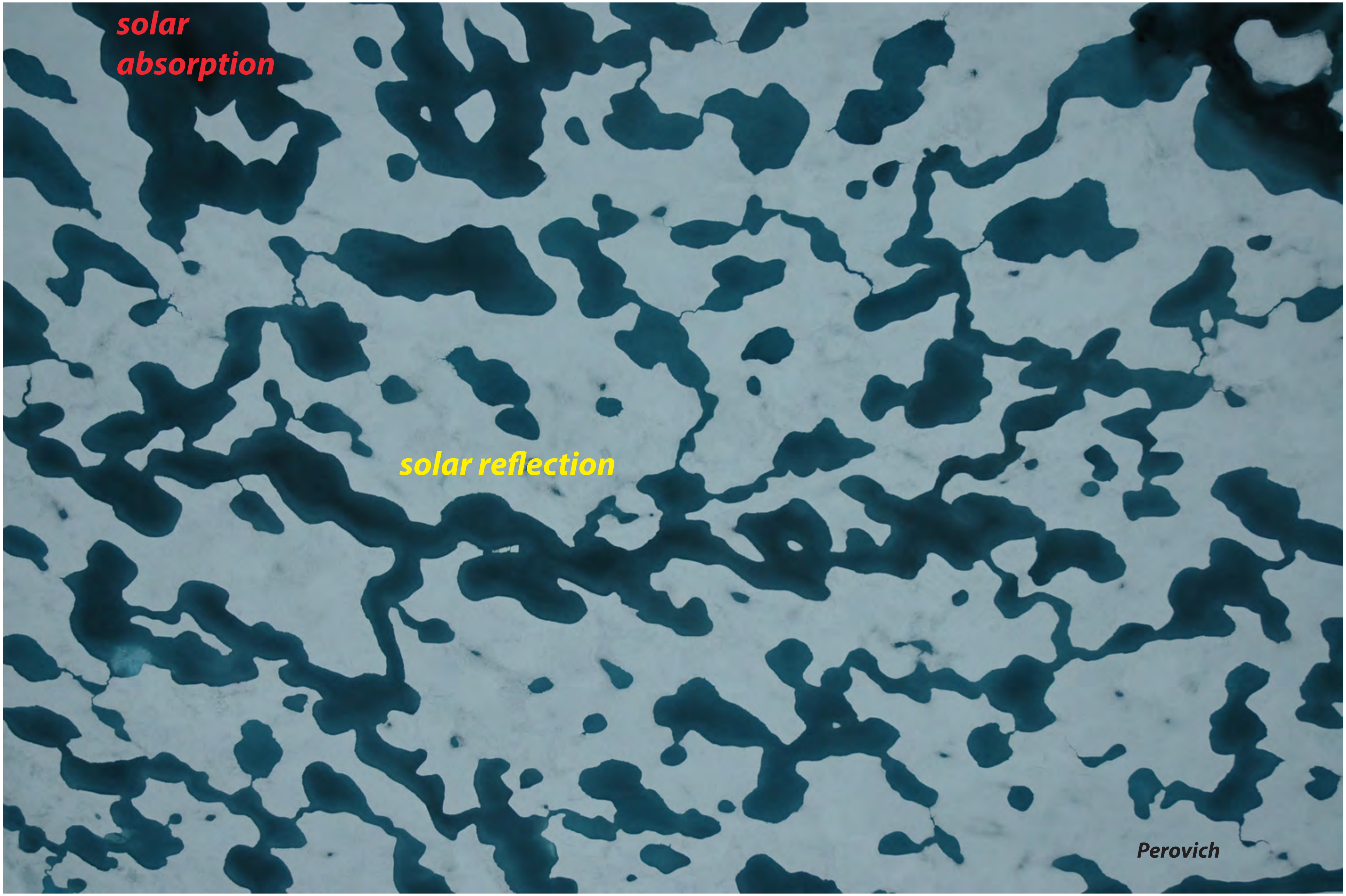
white snow and ice reflect



dark water and land absorb

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

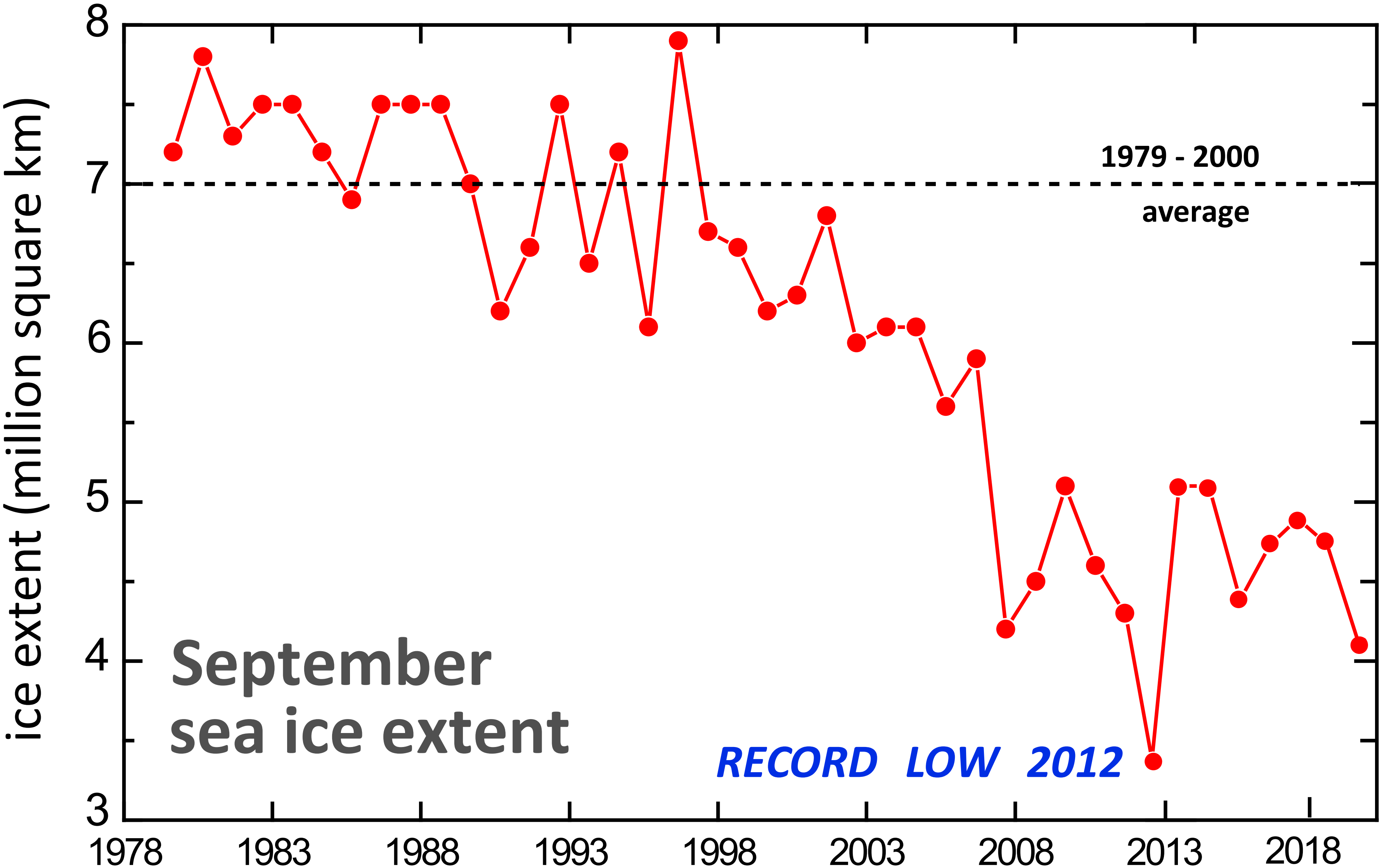
Arctic melt ponds



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

key challenge for global climate models

the summer Arctic sea ice pack is melting



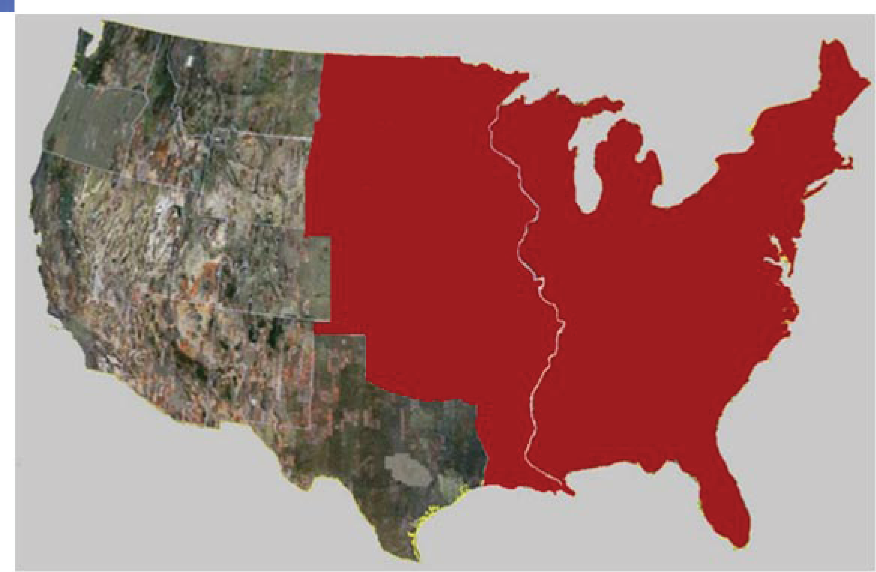
National Snow and Ice Data Center

Change in Arctic Sea Ice Extent

September 1980 -- 7.8 million km^2

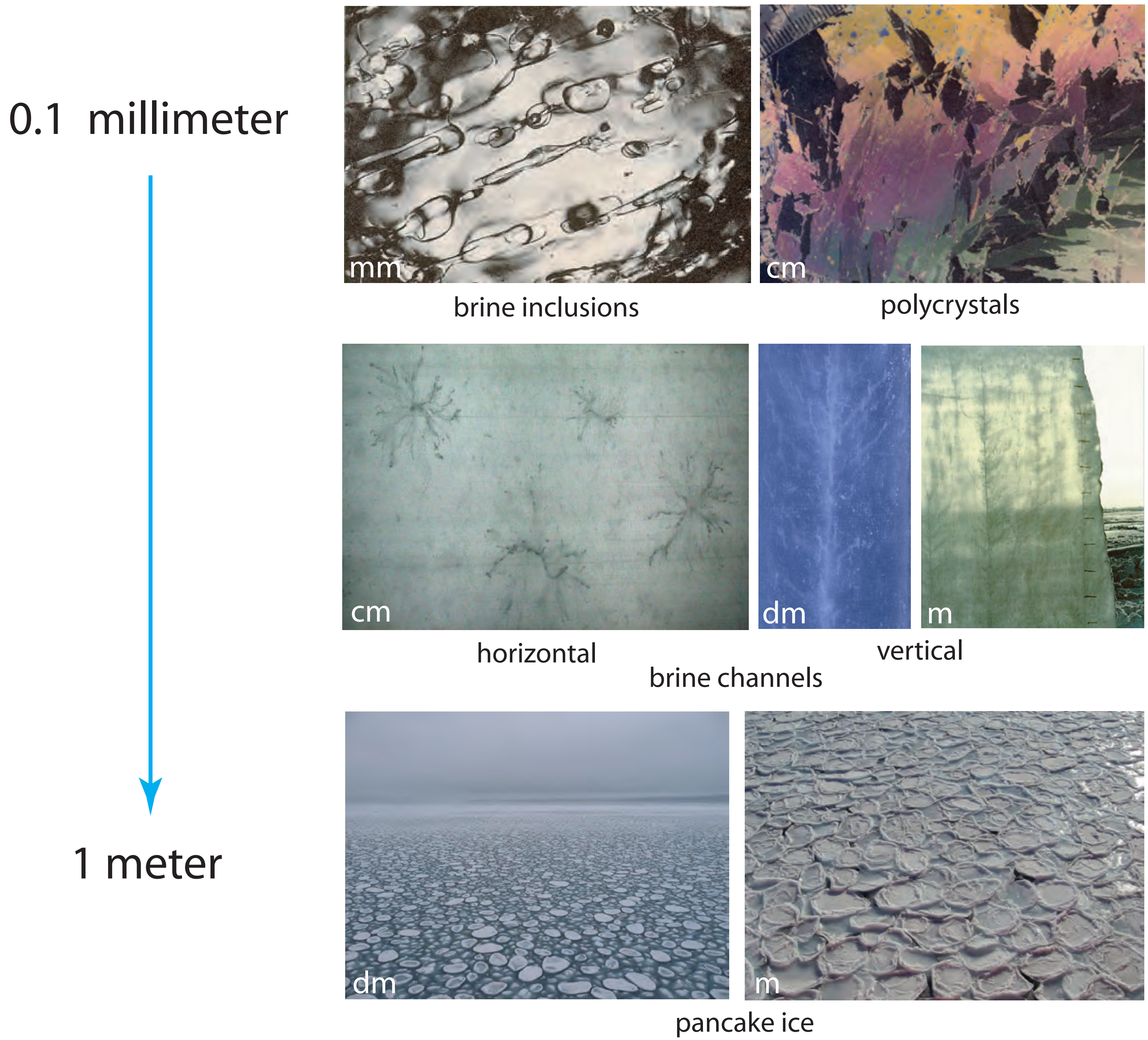
September 2012 -- 3.4 million km^2

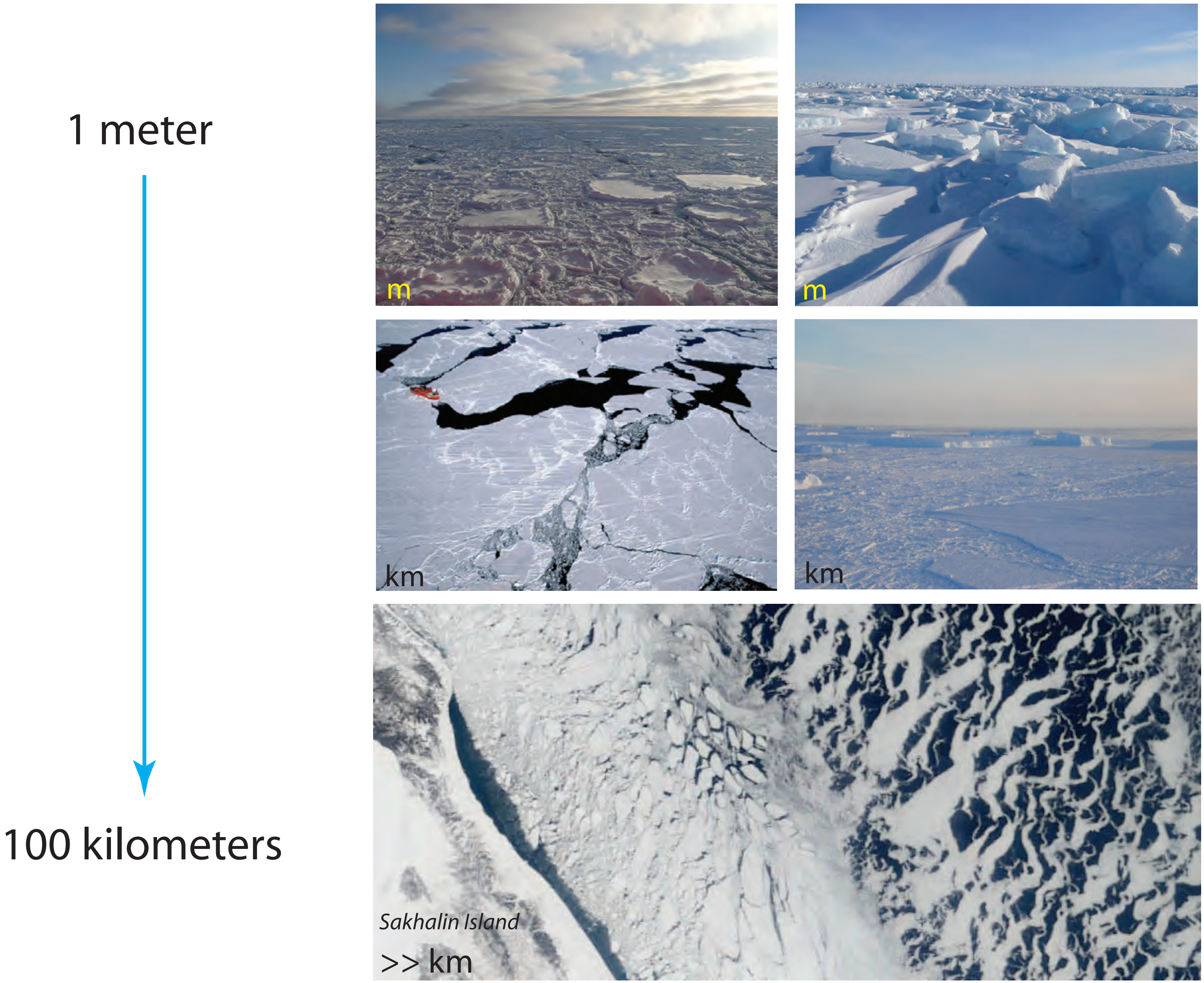
recent losses in comparison to the United States



Perovich

sea ice displays ***multiscale*** structure over 10 orders of magnitude



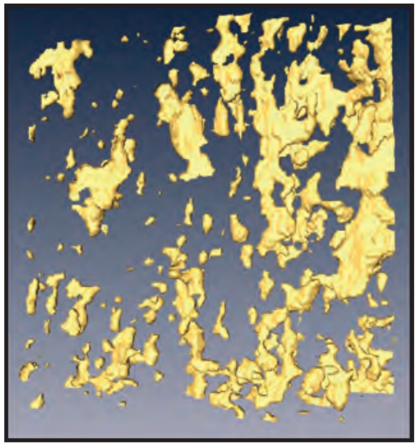

1 meter
100 kilometers
m
m
km
km
Sakhalin Island
>> km

Sea Ice is a Multiscale Composite Material

MICROSCALE

brine inclusions

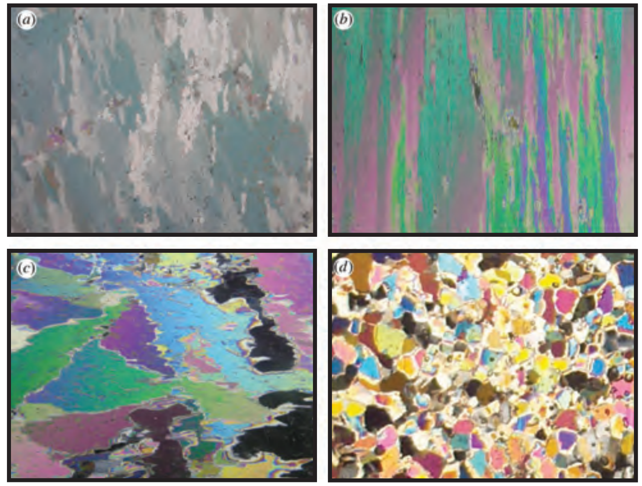
Weeks & Assur 1969



H. Eicken

Golden *et al. GRL* 2007

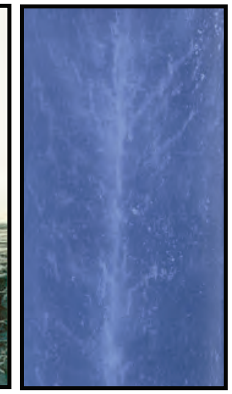
polycrystals



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

brine channels

D. Cole



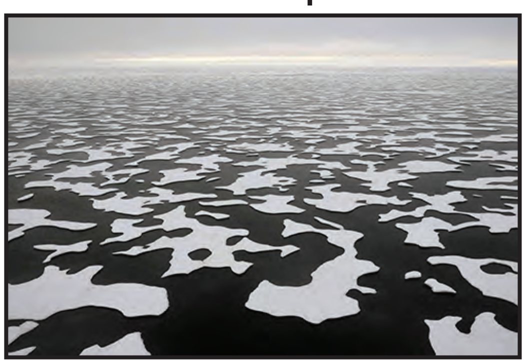
K. Golden

millimeters

centimeters

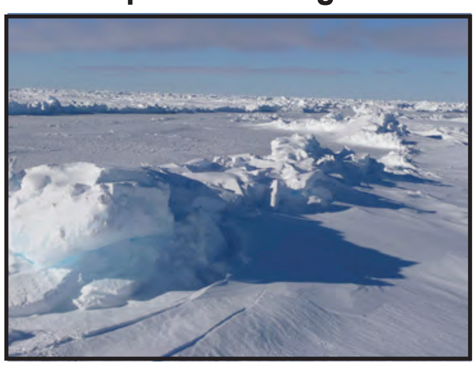
MESOSCALE

Arctic melt ponds



K. Frey

pressure ridges



K. Golden

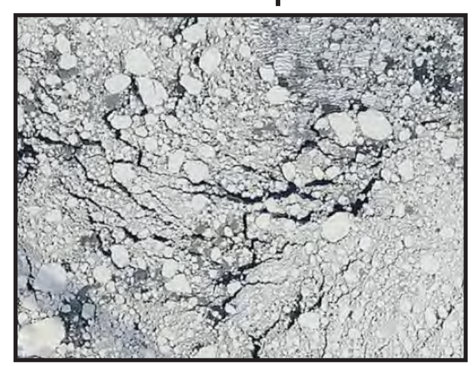
meters

MACROSCALE

sea ice floes

J. Weller

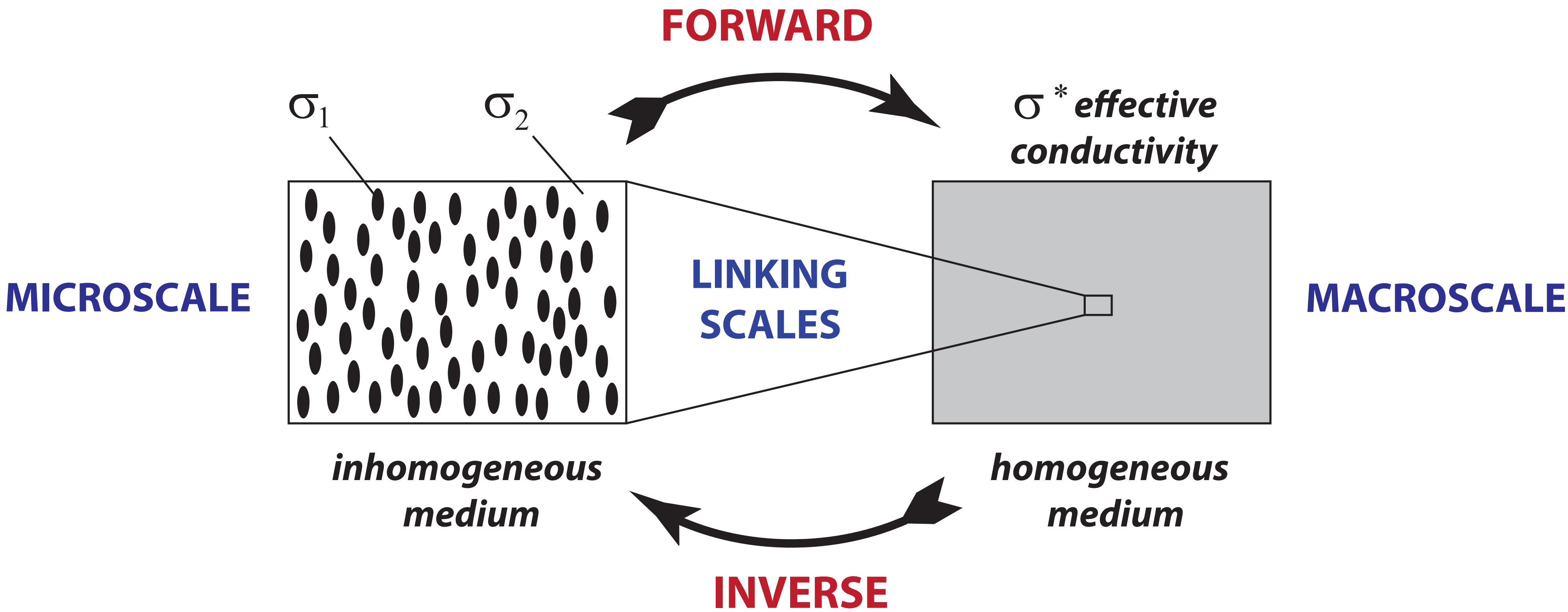
sea ice pack



NASA

kilometers

HOMOGENIZATION for Composite Materials



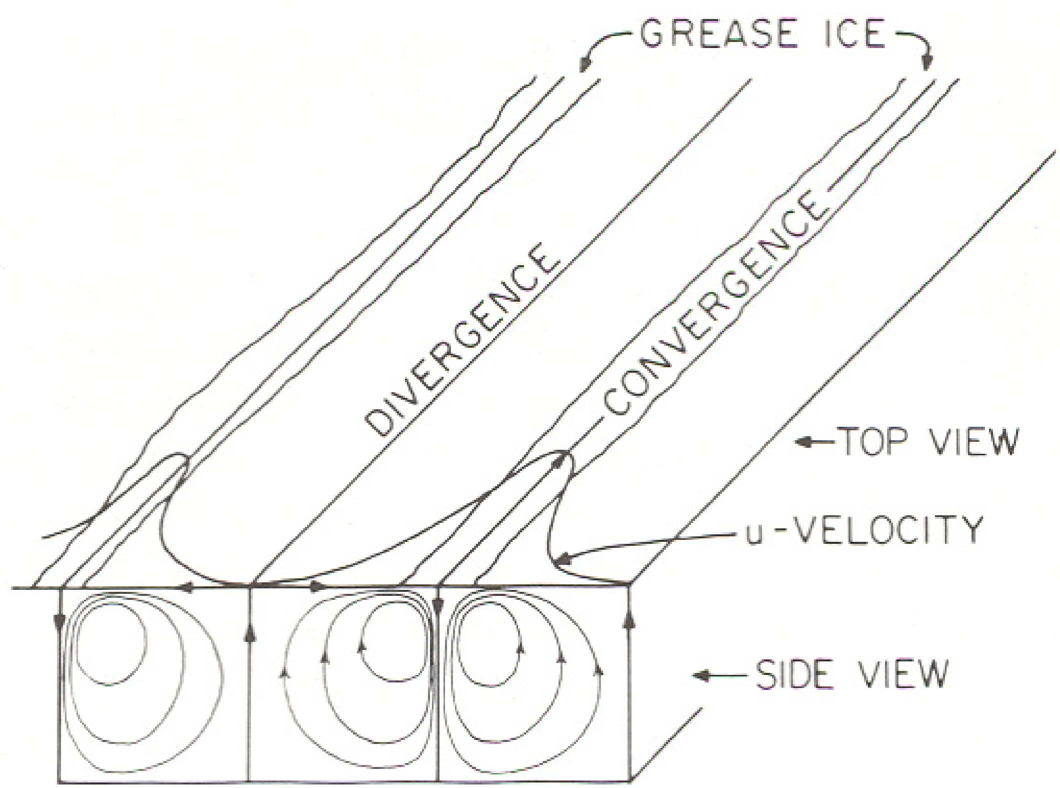
Maxwell 1873 : effective conductivity of a dilute suspension of spheres
Einstein 1906 : effective viscosity of a dilute suspension of rigid spheres in a fluid

*Wiener 1912 : arithmetic and harmonic mean **bounds** on effective conductivity*
*Hashin and Shtrikman 1962 : variational **bounds** on effective conductivity*

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

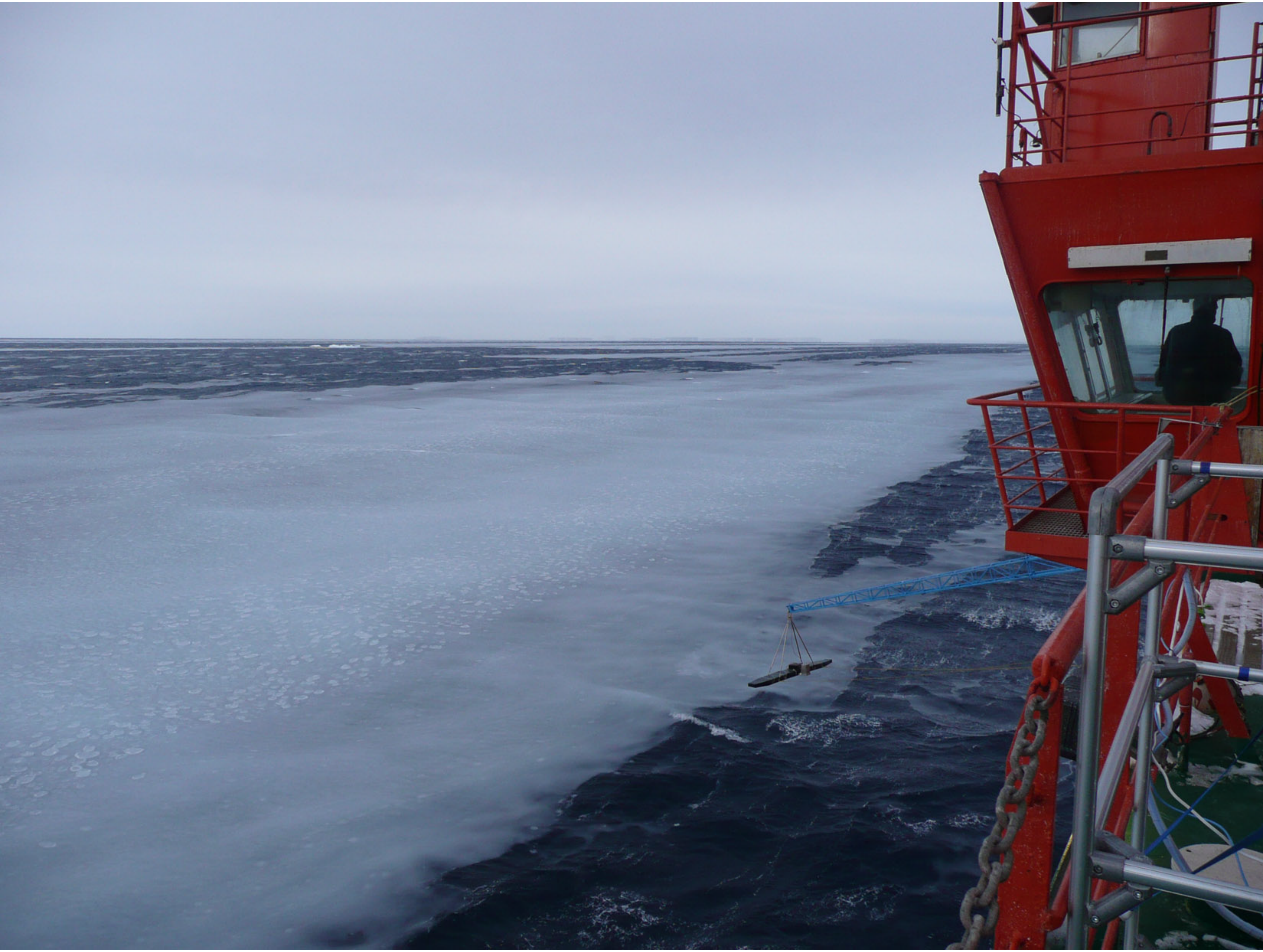
Sea ice structure, properties, and processes

sea ice formation



effect of Langmuir circulation
on grease and pancake ice

Martin and Kauffman, 1981



sea ice formation in a wave field

- turbulence in the wave field maintains the new ice as a dense suspension of frazil, rather than forming nilas
- suspension undergoes cyclic compression
- during the compression phase crystals can freeze together to form small coherent cakes of slush
- they grow larger by accretion from the frazil and more solid through continued freezing between the crystals

→ pancake ice

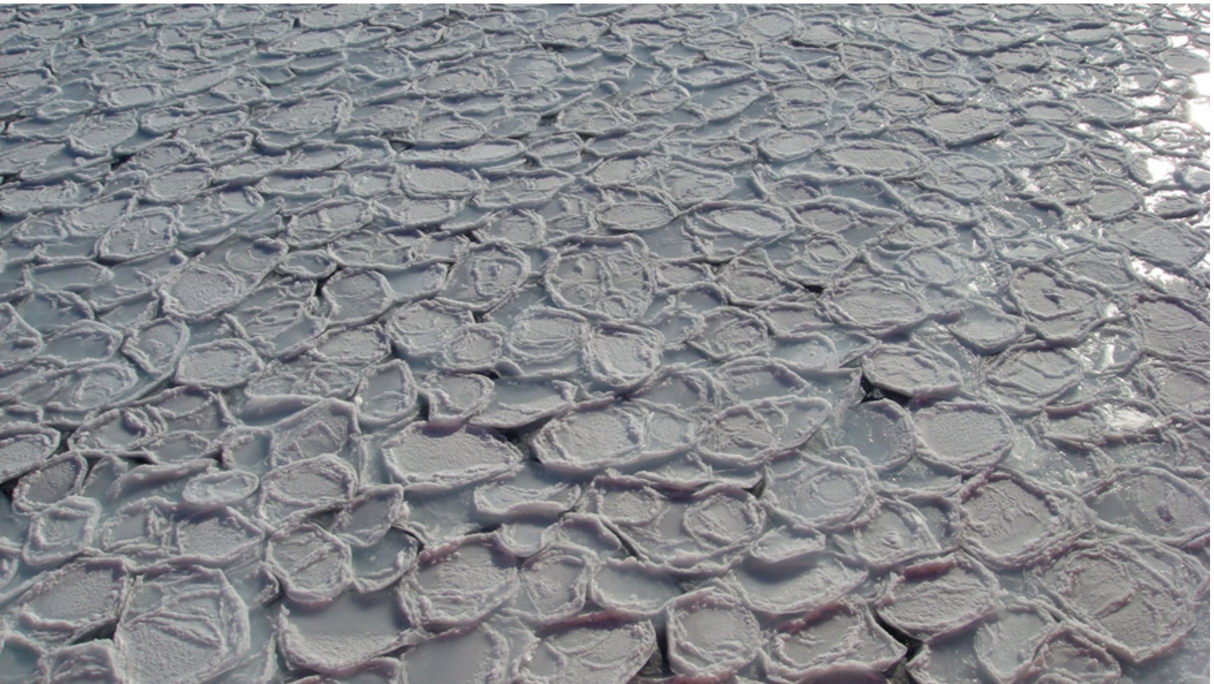
- where the wave field is calm, the pancakes begin to freeze together, eventually coalescing to first form large floes, then a continuous sheet of first-year ice known as consolidated pancake ice, with frazil as glue

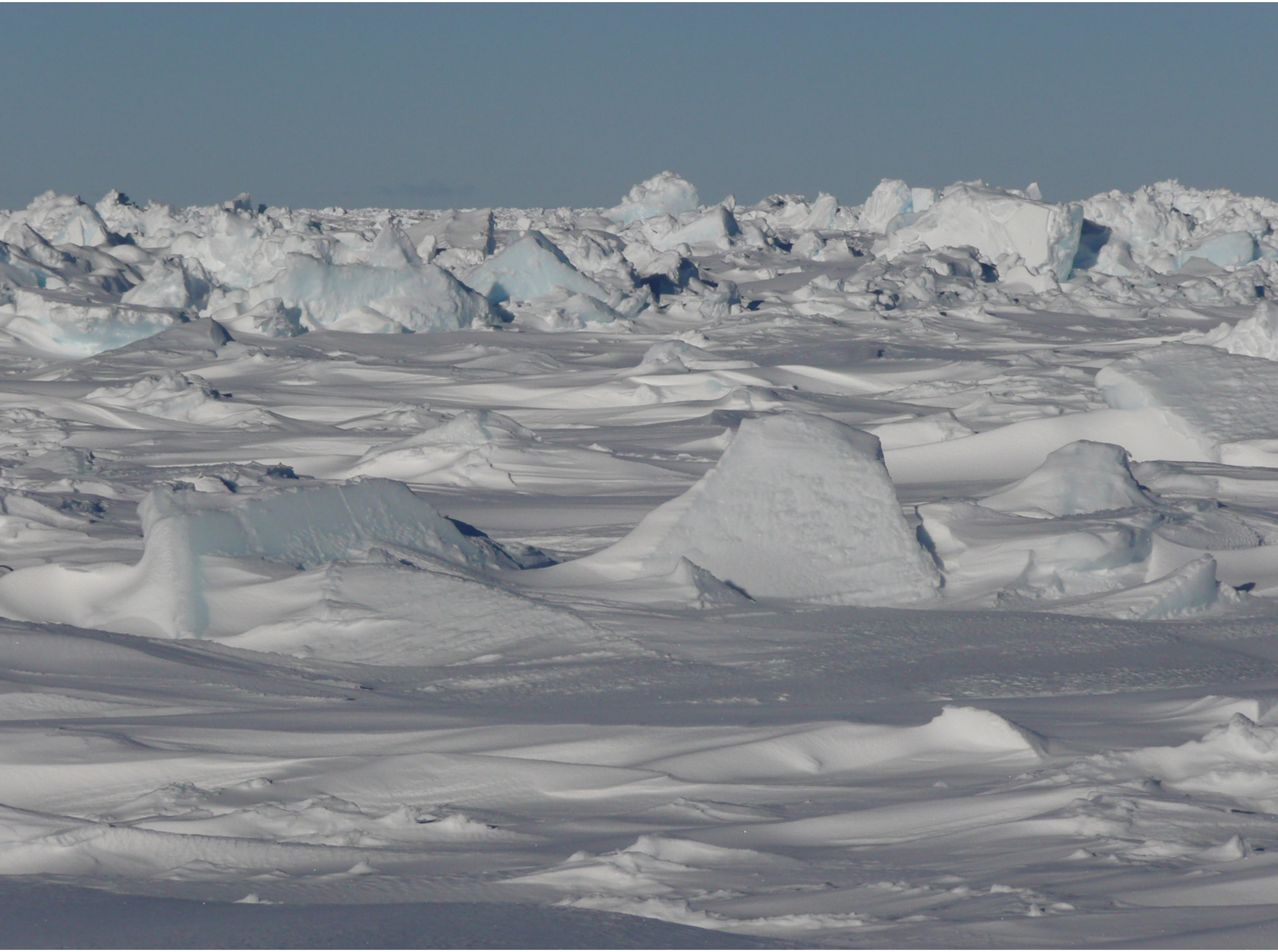
CAN PRODUCE RAPID GROWTH - DYNAMIC THICKENING

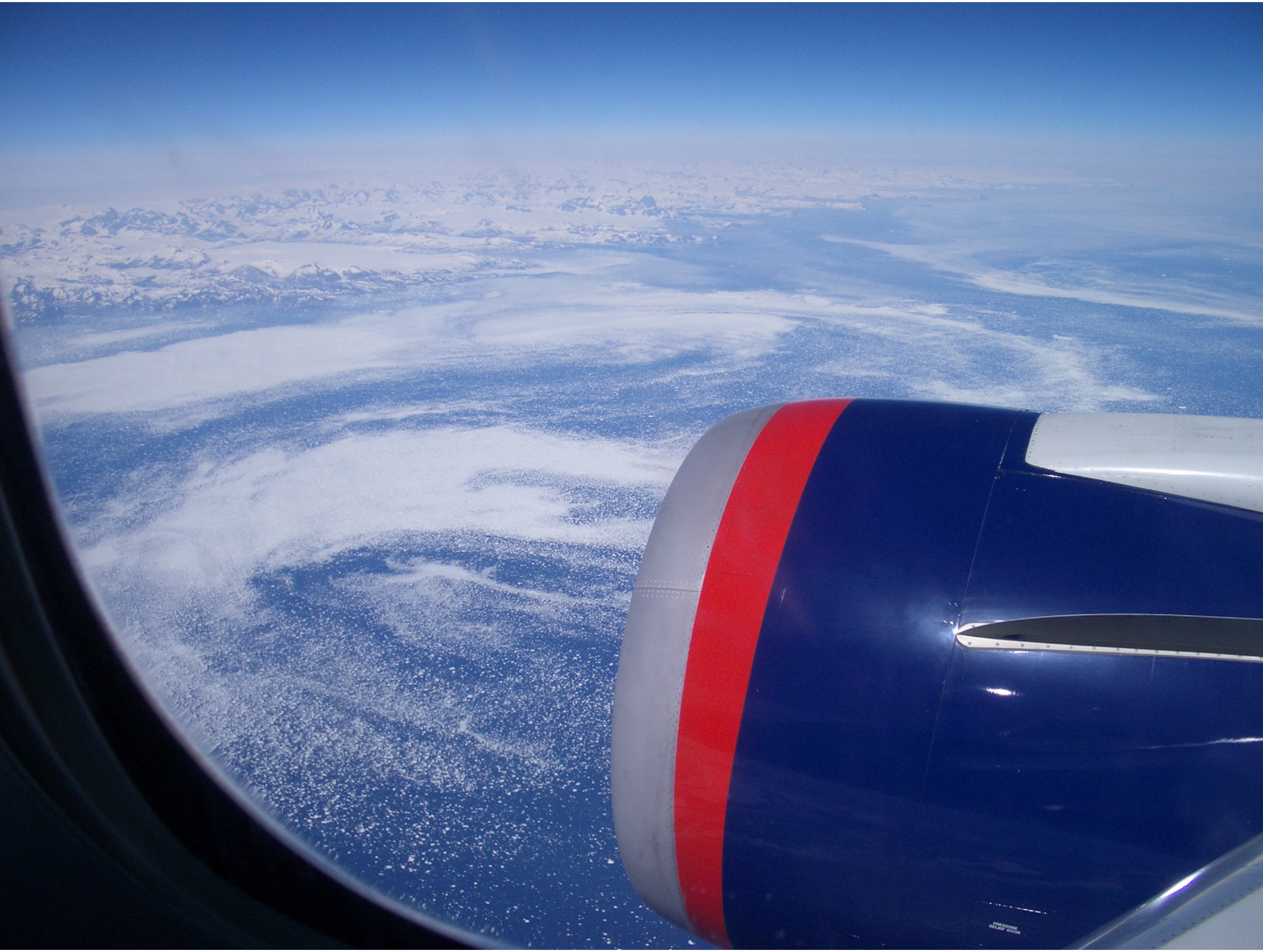
AGGREGATION PROCESS - CONNECTEDNESS TRANSITION ocean swells propagating through a vast field of pancake ice

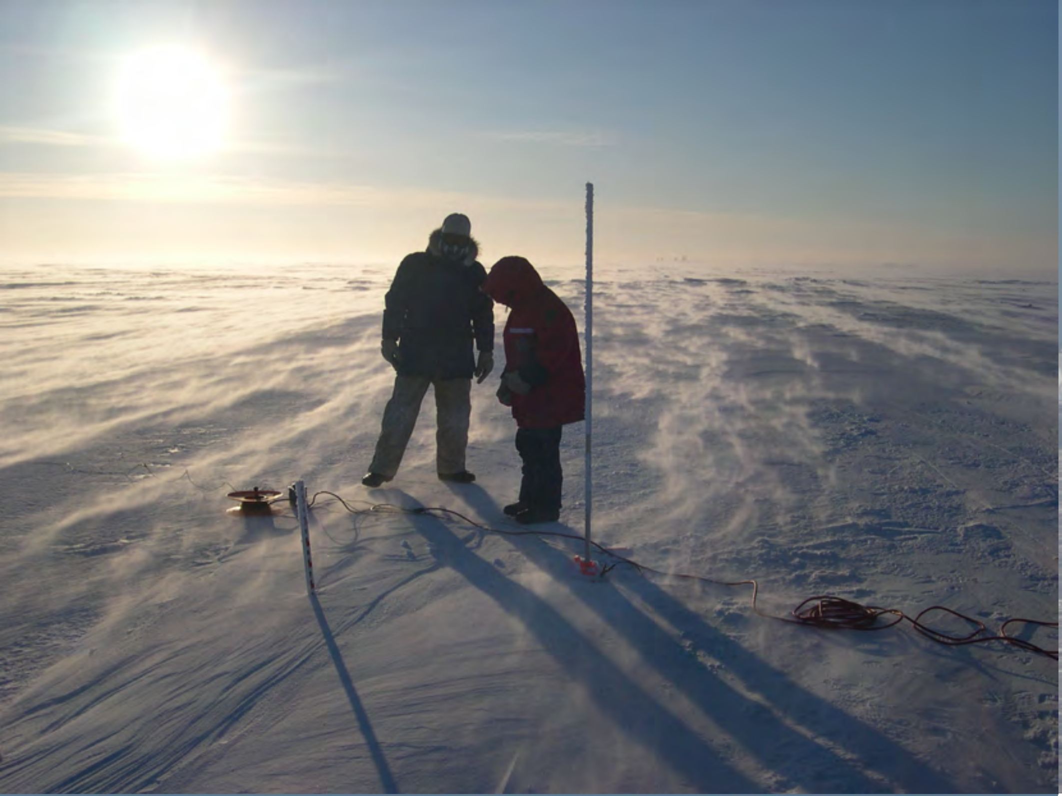
HOMOGENIZATION: long wave sees an effective medium, not individual floes, like long EM wave interacting with brine inclusion microstructure

pancake ice



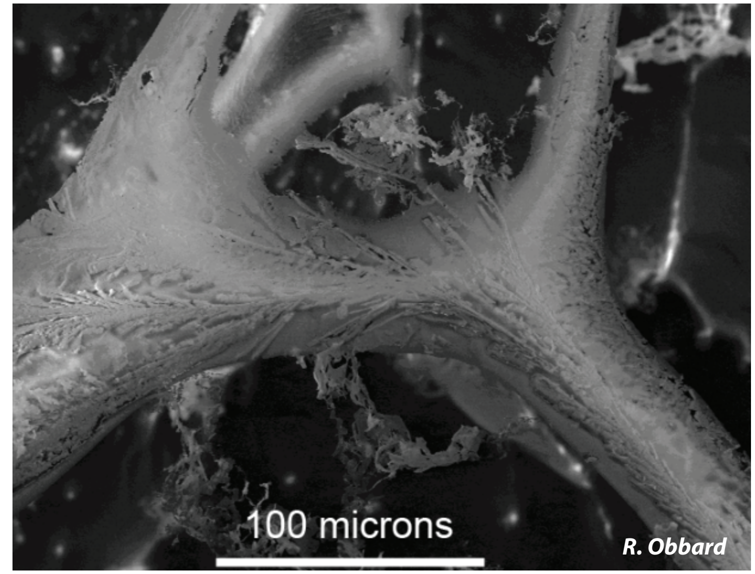






sea ice may appear to be a barren, impermeable cap ...

brine inclusions in sea ice (mm)



micro - brine channel (SEM)

brine channels (cm)

sea ice is a porous composite

pure ice with brine, air, and salt inclusions

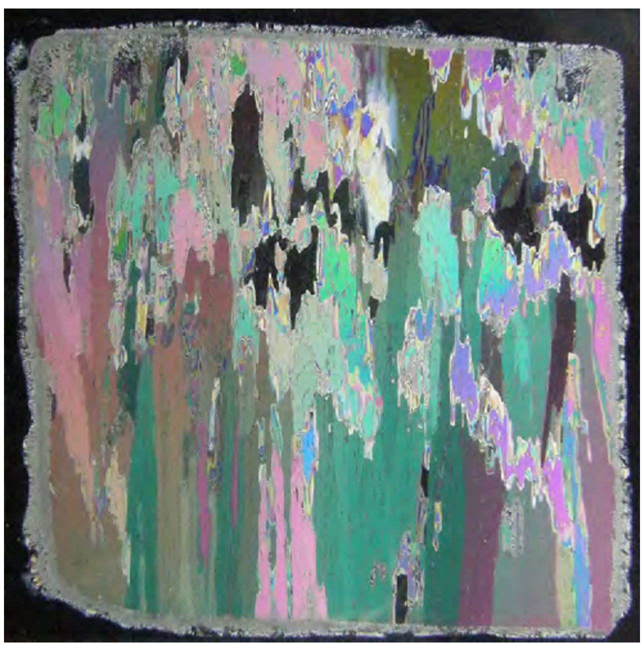
horizontal section

vertical section

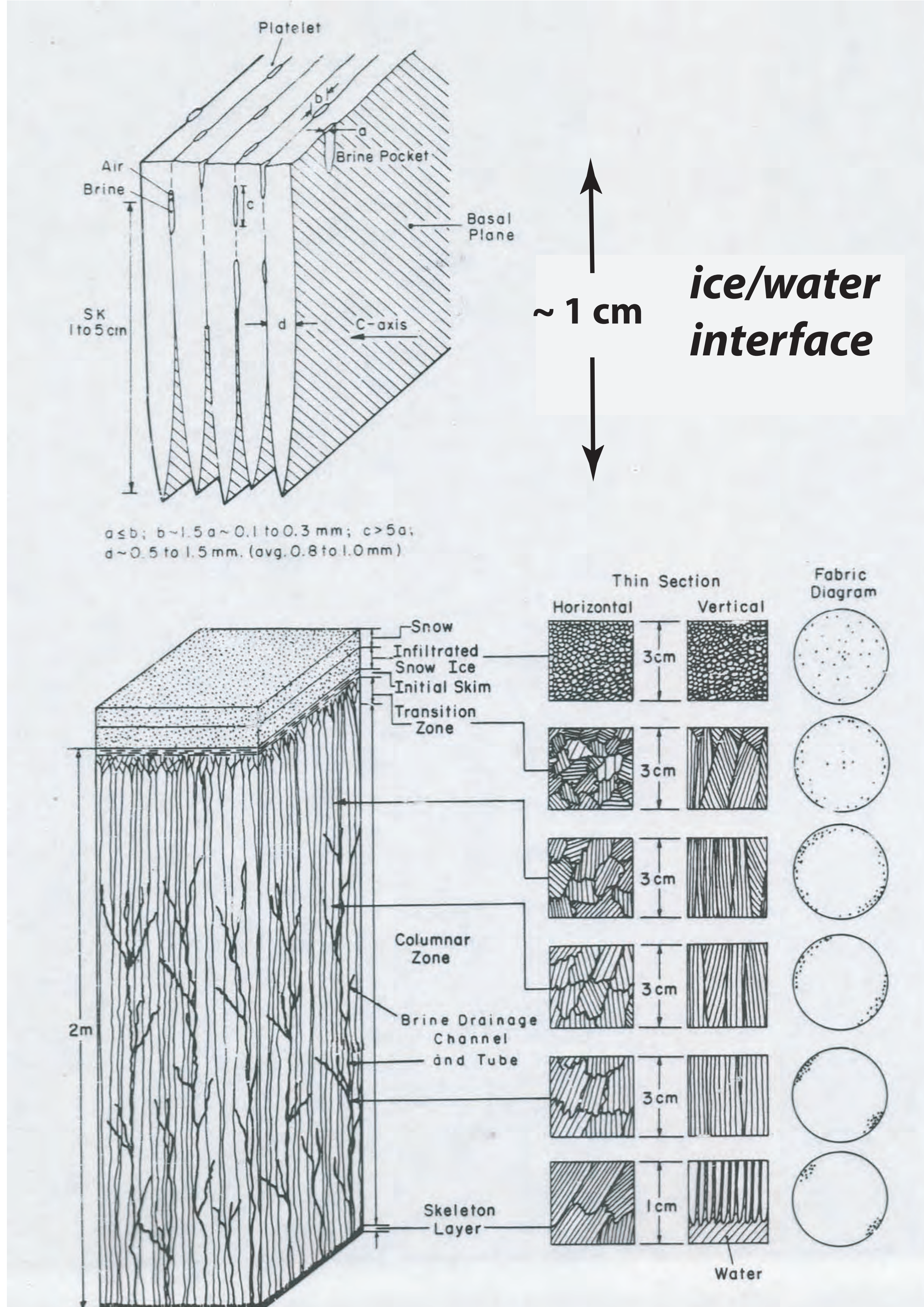
cross-sections of sea ice structure

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

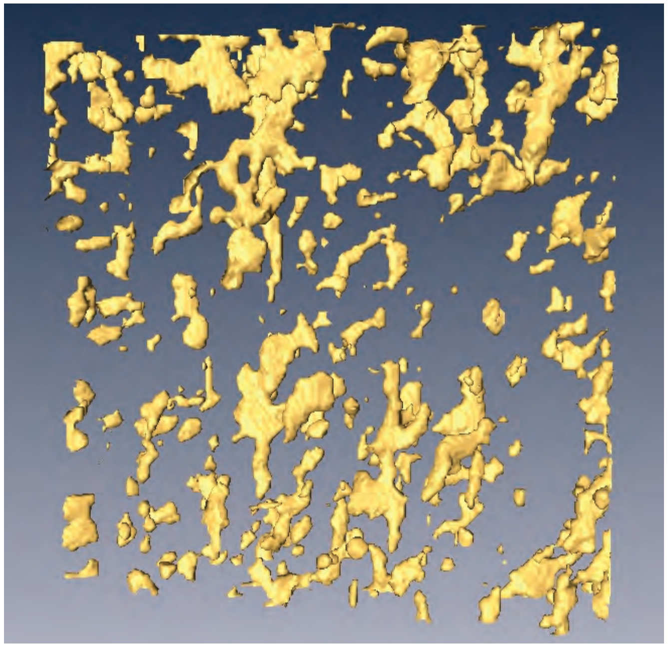
crystallographic texture



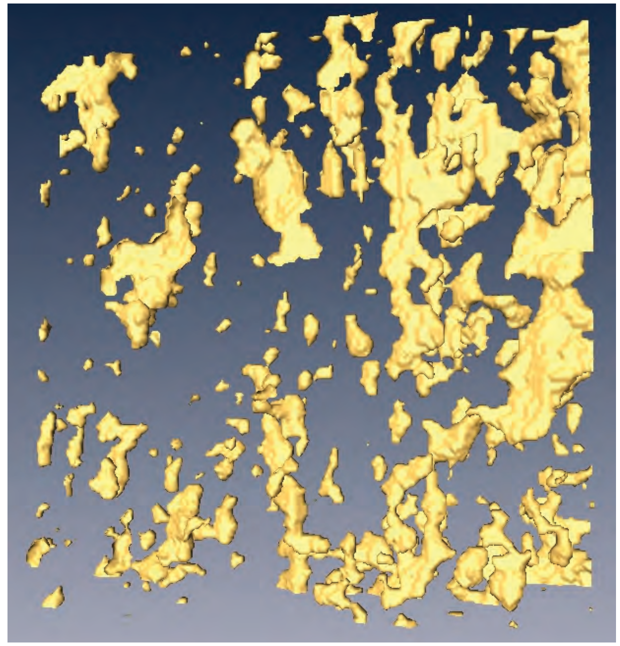
vertical thin section



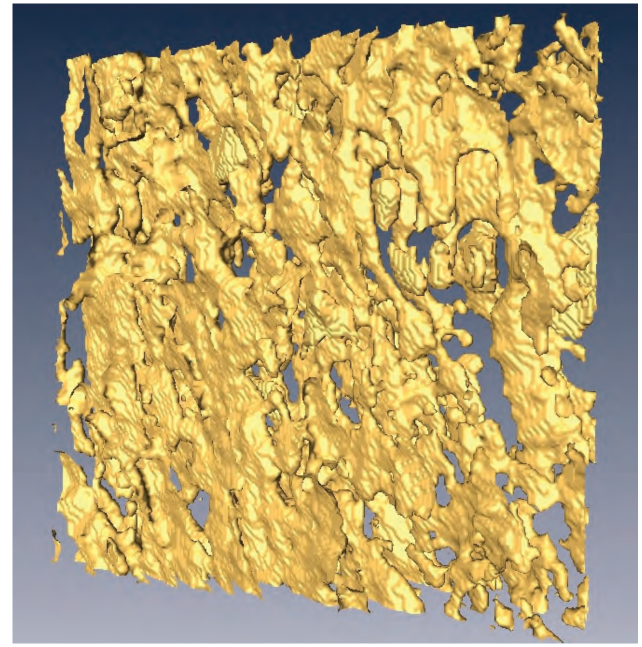
brine volume fraction and ***connectivity*** increase with temperature



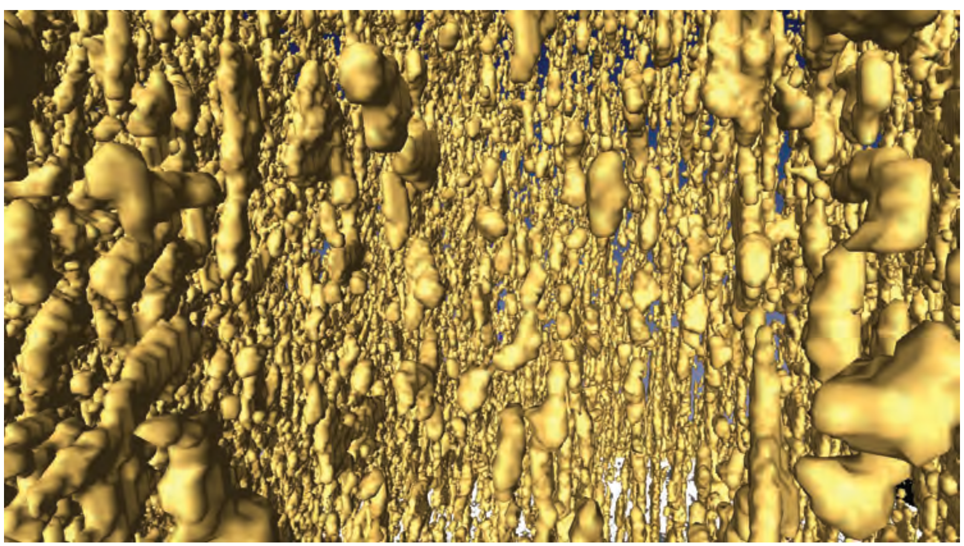
T = -15 °C, $\phi = 0.033$



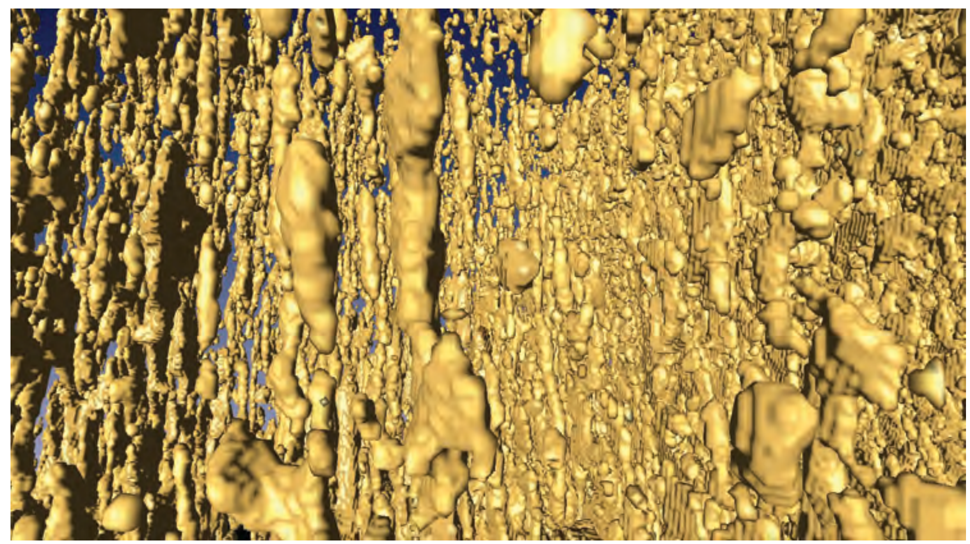
T = -6 °C, $\phi = 0.075$



T = -3 °C, $\phi = 0.143$



T = -8 °C, $\phi = 0.057$



T = -4 °C, $\phi = 0.113$

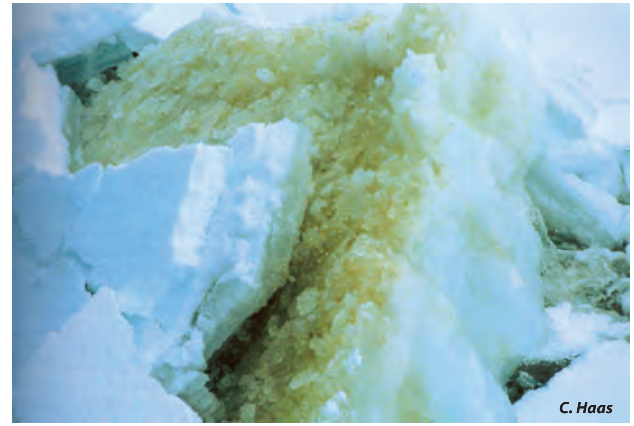
X-ray tomography for brine in sea ice

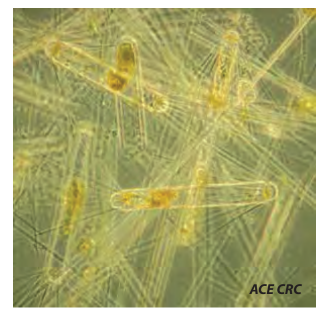
Golden *et al.*, *Geophysical Research Letters*, 2007

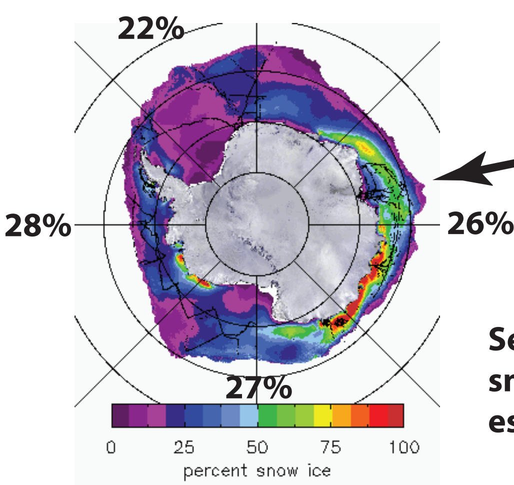
fluid flow through the porous microstructure of sea ice governs key processes in polar climate and ecosystems

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

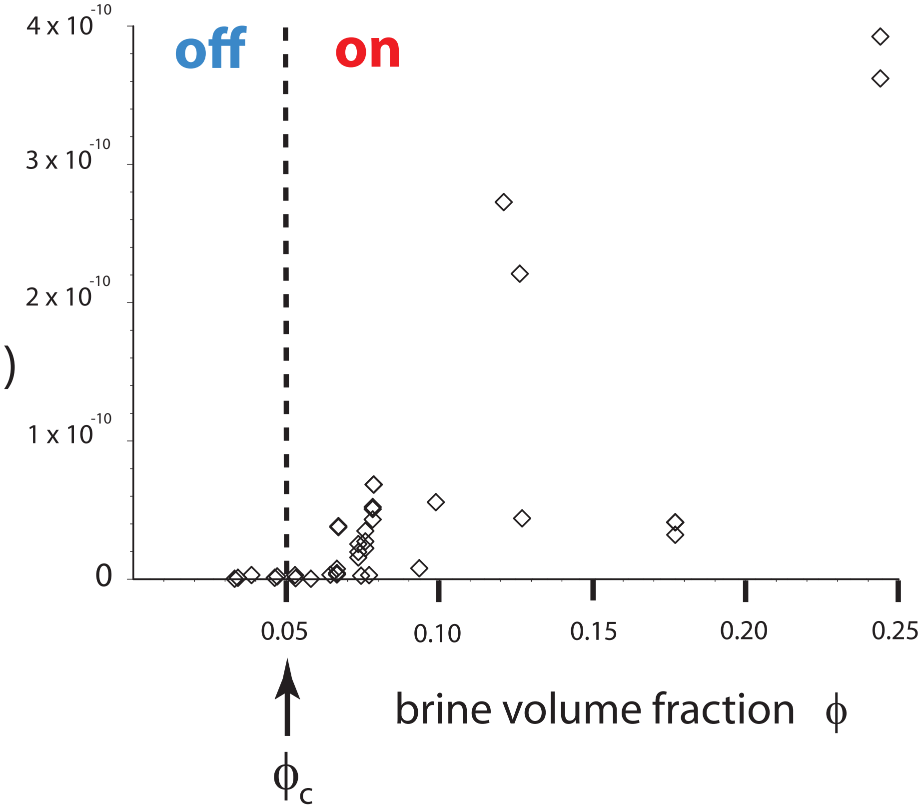
- ocean-ice-air exchanges of heat, CO_2

Critical behavior of fluid transport in sea ice

impermeable permeable

Arctic field data

vertical fluid permeability k (m^2)



"on - off" switch for fluid flow

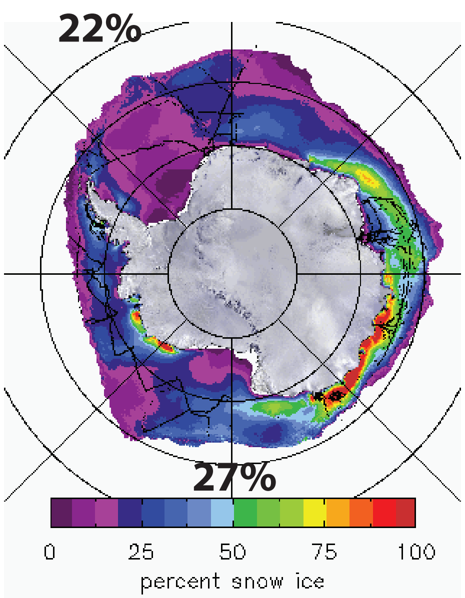
critical brine volume fraction $\phi_c \approx 5\%$ ⟷ $T_c \approx -5^\circ C$, $S \approx 5$ ppt

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

rule of fives constrains:

Antarctic surface flooding and snow-ice formation

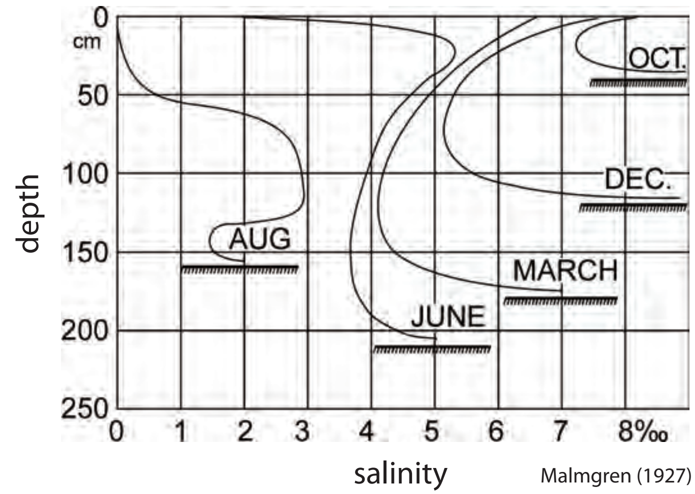


September snow-ice estimates

Antarctic snow-to-ice conversion from passive microwave imagery

T. Maksym and T. Markus, 2008

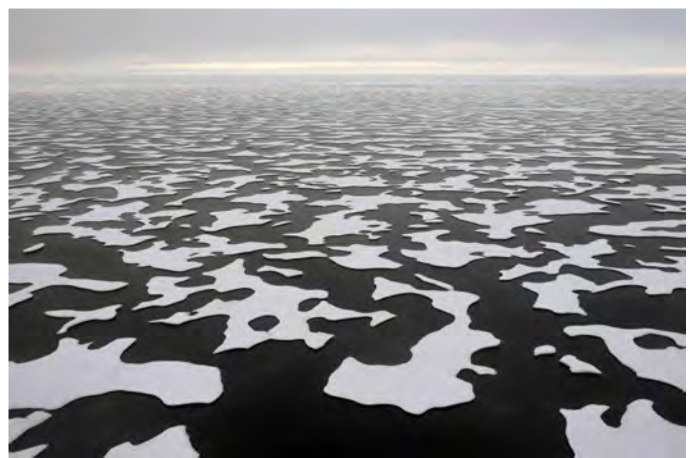
evolution of salinity profiles



currently assumed constant in climate models

convection - enhanced thermal conductivity

Lytle and Ackley, 1996
Trodahl, et. al., 2000, 2001
Wang, Zhu, Golden, 2012



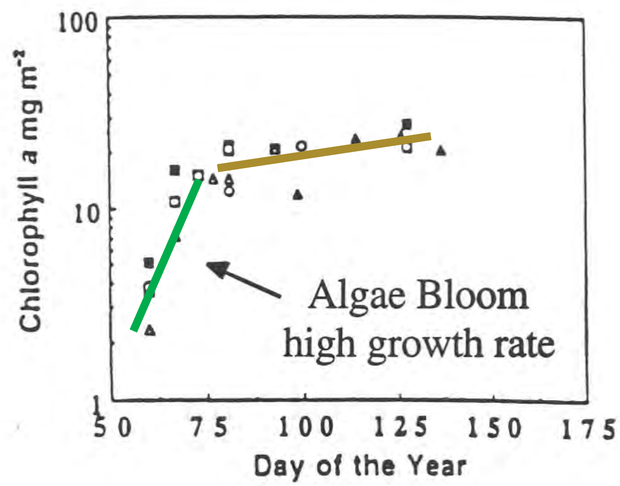
sea ice algal communities

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

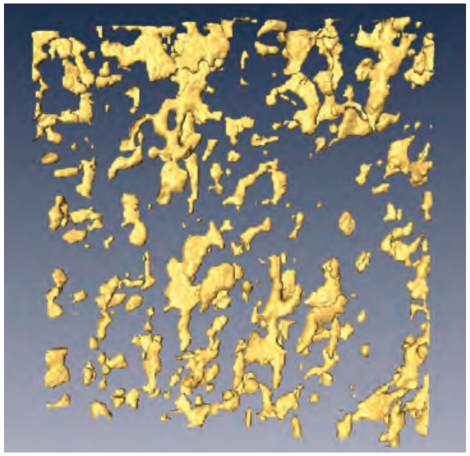


Convection-fueled algae bloom
Ice Station Weddell

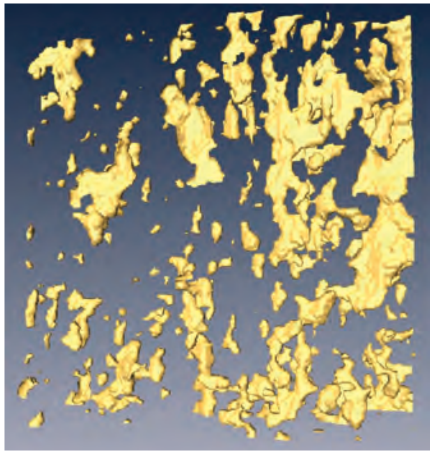
Golden, Ackley, Lytle ***Science 1998***

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

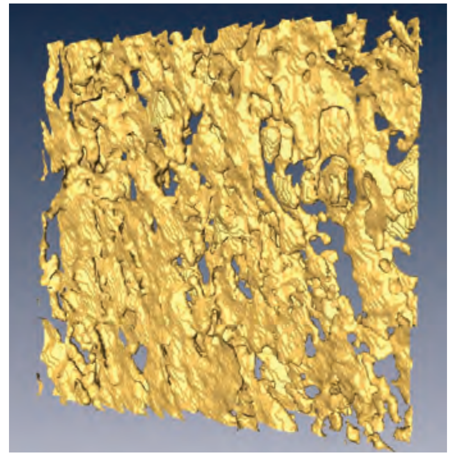
brine volume fraction and ***connectivity*** increase with temperature



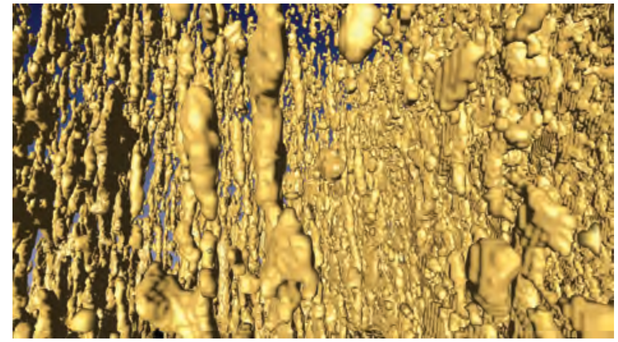
T = -15 °C, $\phi = 0.033$



T = -6 °C, $\phi = 0.075$



T = -3 °C, $\phi = 0.143$



T = -4 °C, $\phi = 0.113$

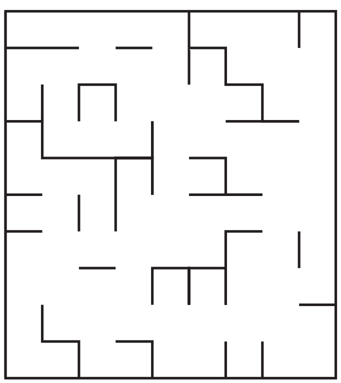
X-ray tomography for brine phase in sea ice

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

PERCOLATION THRESHOLD $\quad \phi_c \approx 5\ \%$

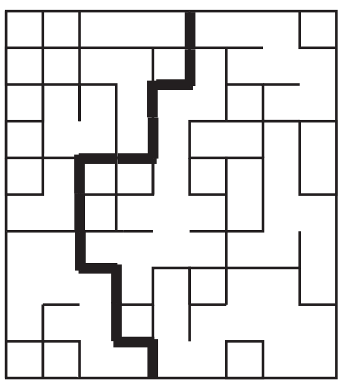
Golden, Ackley, Lytle, *Science* 1998

impermeable



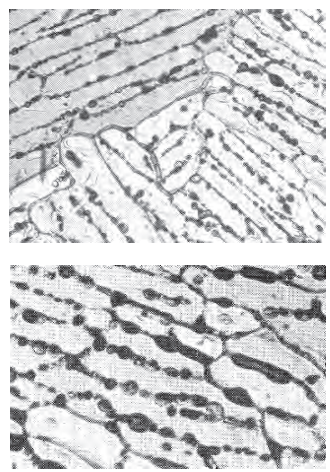
$p = 1/3$

permeable

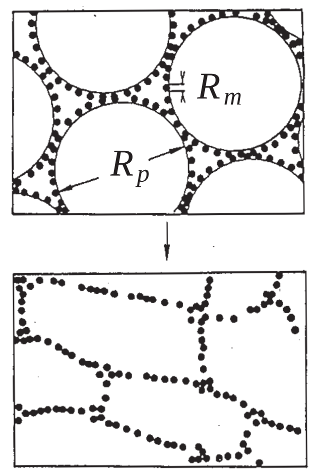


$p = 2/3$

lattice percolation



sea ice



compressed powder

Kusy, Turner
Nature 1971

stealth

continuum percolation

The Melt Pond Conundrum:

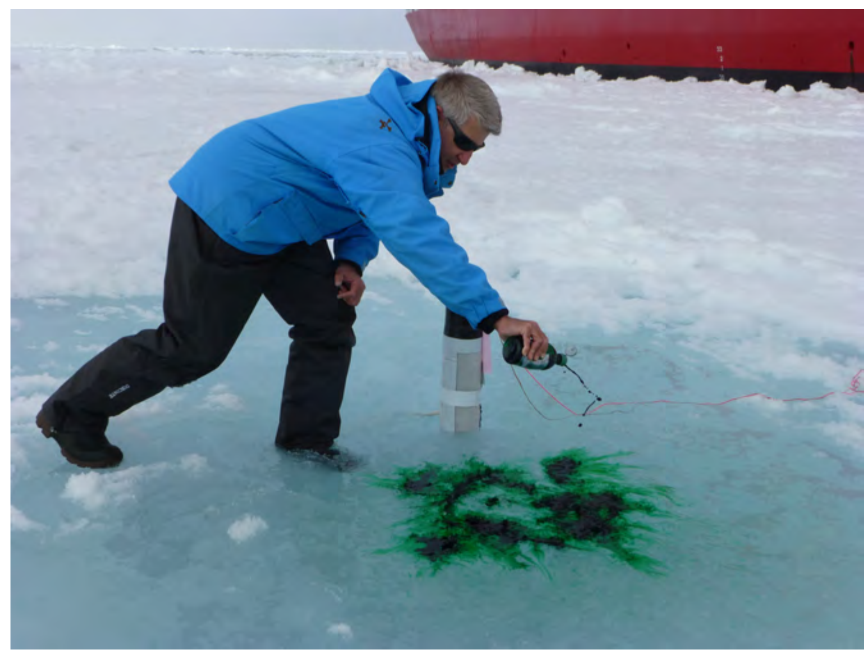
How can ponds form on top of sea ice that is highly permeable?

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

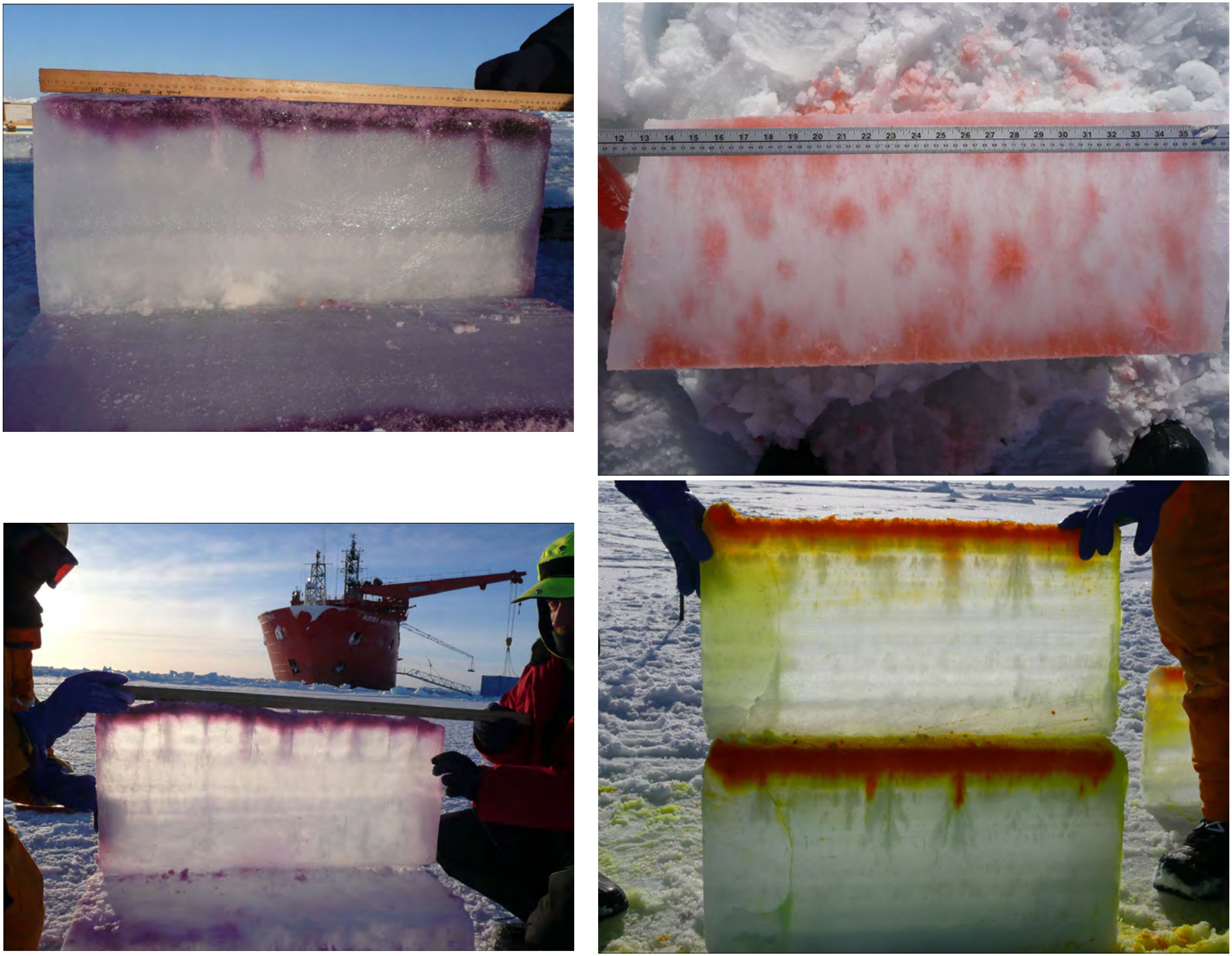
Percolation Blockage: A Process that Enables Melt Pond Formation on First Year Arctic Sea Ice

J. Geophys. Res. Oceans 2017

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

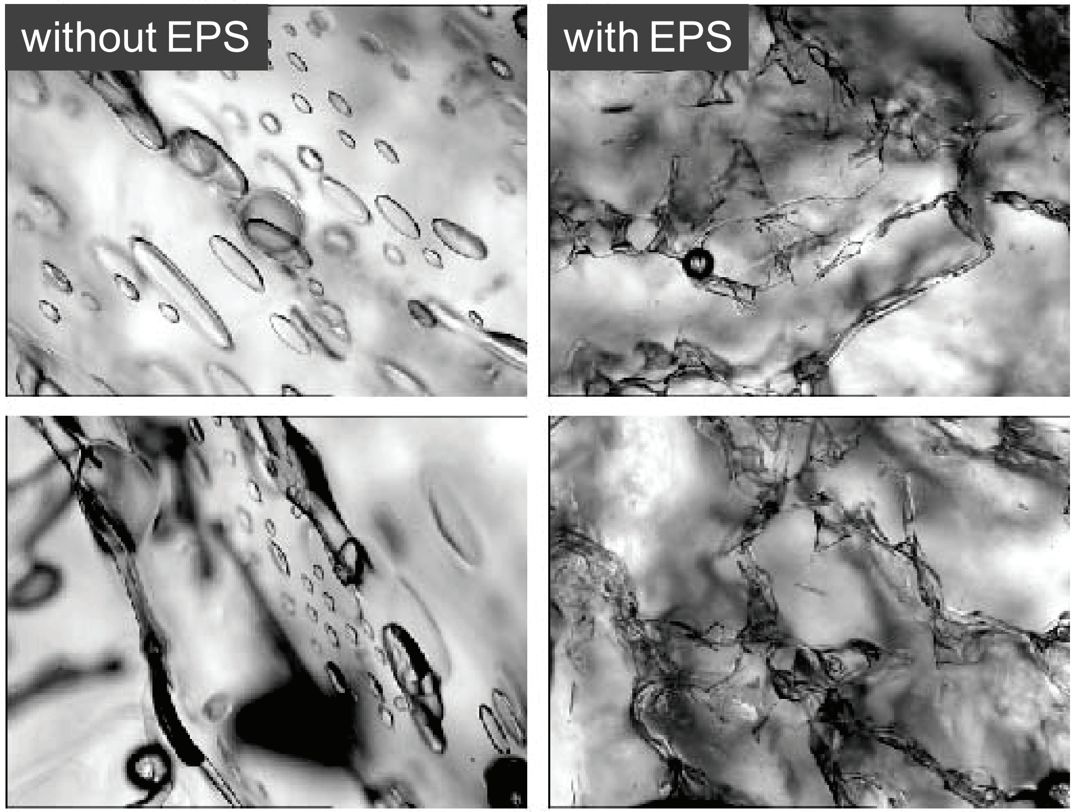


tracers flowing through inverted sea ice blocks



Sea ice algae secrete extracellular polymeric substances (EPS)

EPS changes brine microstructure



ellipsoidal inclusions fractal inclusions

Krembs, Eicken, Deming *PNAS* 2011

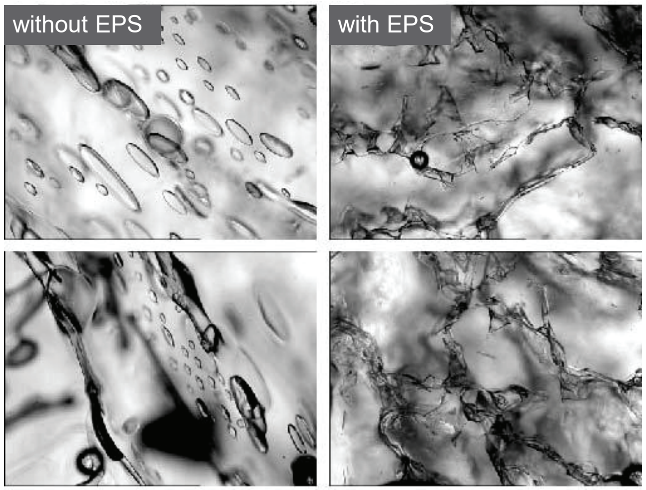
numerical model bounds on fluid permeability

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

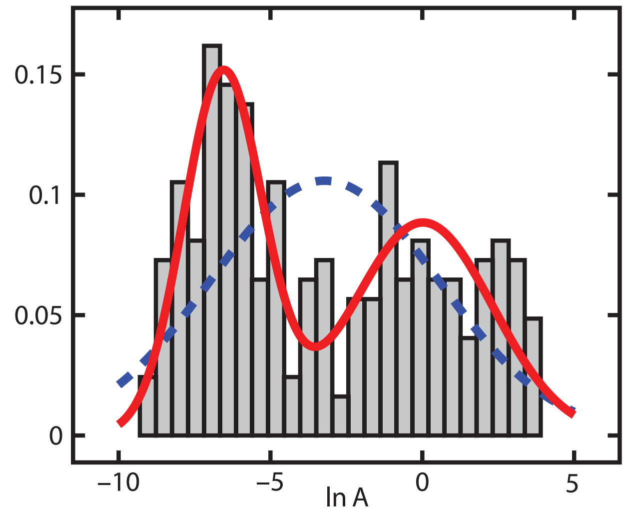
How does the biology affect the physics?

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

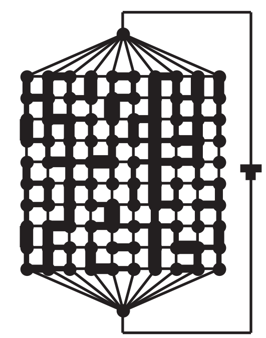
How does EPS affect fluid transport? **How does the biology affect the physics?**



Krembs, Eicken, Deming, PNAS 2011

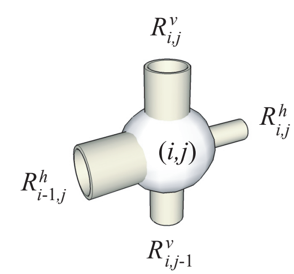


RANDOM PIPE MODEL



- 2D random pipe model with bimodal distribution of pore sizes
- **Rigorous bound on permeability *k*; results predict observed drop in *k***

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



3D extension, effect of EPS clogging, blockage

Anna Hyde, Jingyi Zhu, Ken Golden

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

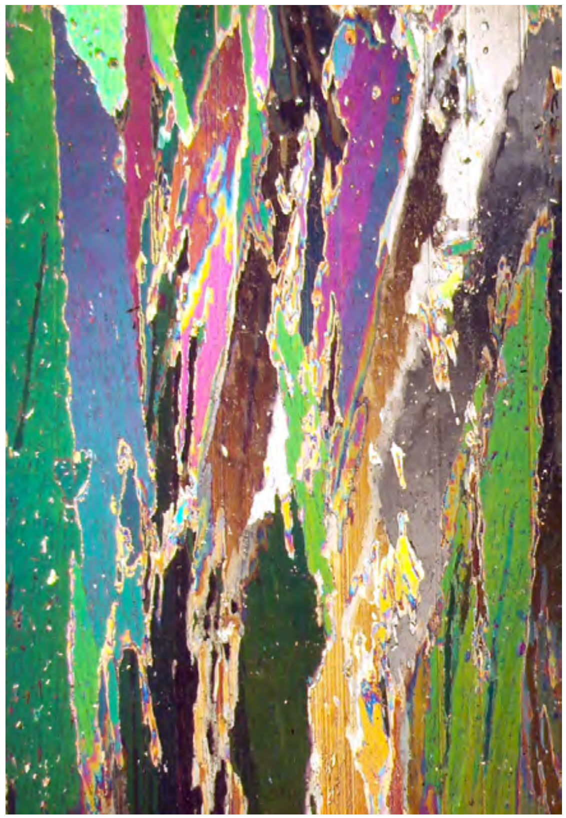
higher threshold for fluid flow in granular sea ice

microscale details impact "mesoscale" processes

nutrient fluxes for microbes
melt pond drainage
snow-ice formation

columnar | granular

5%



10%

Golden, Sampson, Gully, Lubbers, Tison 2020

electromagnetically distinguishing ice types

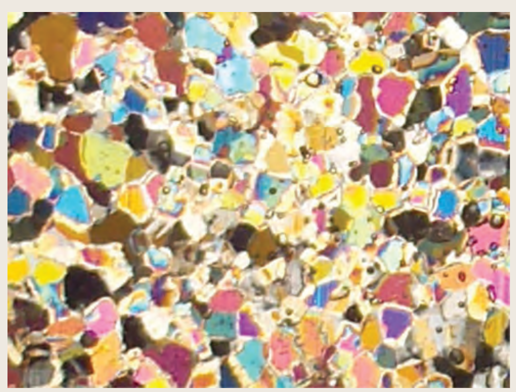
Kitsel Lusted, Elena Cherkaev, Ken Golden

Bounds on the complex permittivity of polycrystalline materials by analytic continuation

Adam Gully, Joyce Lin,
Elena Cherkaev, Ken Golden

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

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



Proc. Roy. Soc. A   8 Feb 2015

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

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

PROCEEDINGS A

350 YEARS OF SCIENTIFIC PUBLISHING

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

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

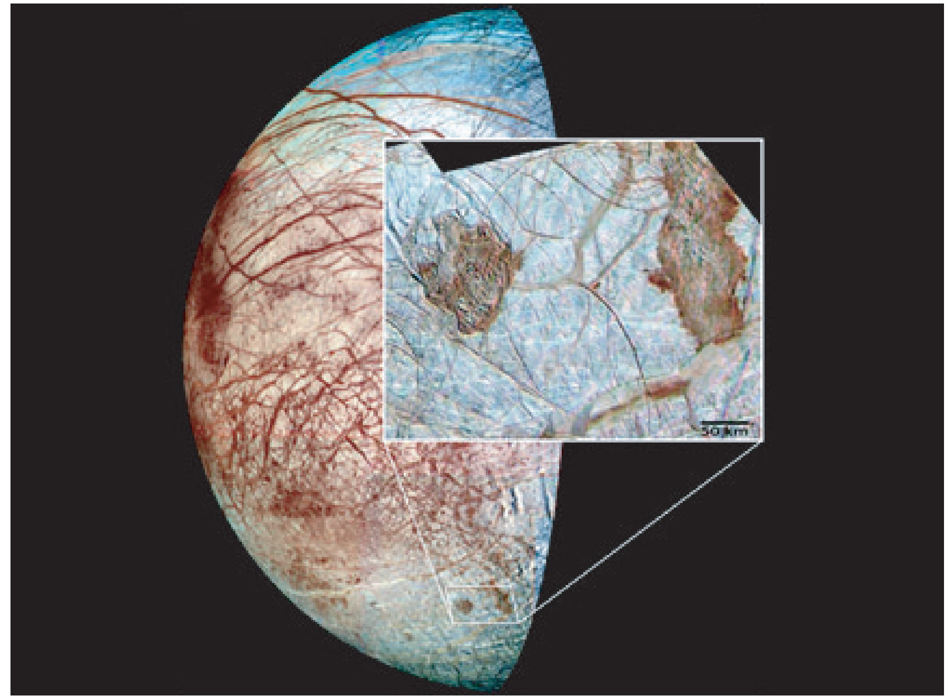
A computer model to determine how a human should walk so as to expend the least energy

THE ROYAL SOCIETY PUBLISHING

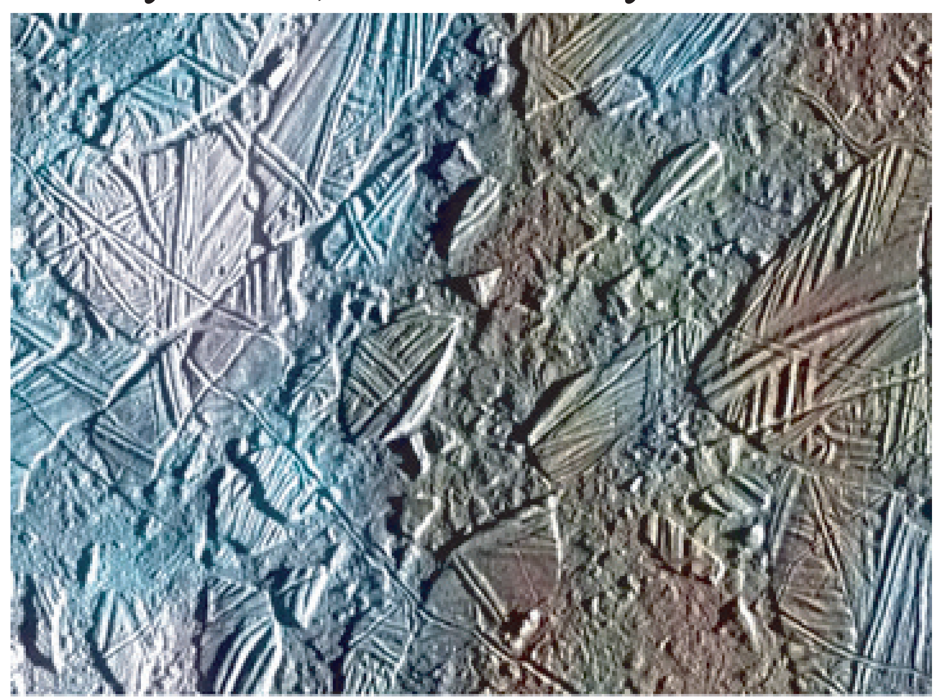
21/01/15 1:47 PM

Are sea ice algae and bacteria proxies for possible life forms on extraterrestrial, icy bodies?

(Thomas, Dieckmann, *Science,* 2002)



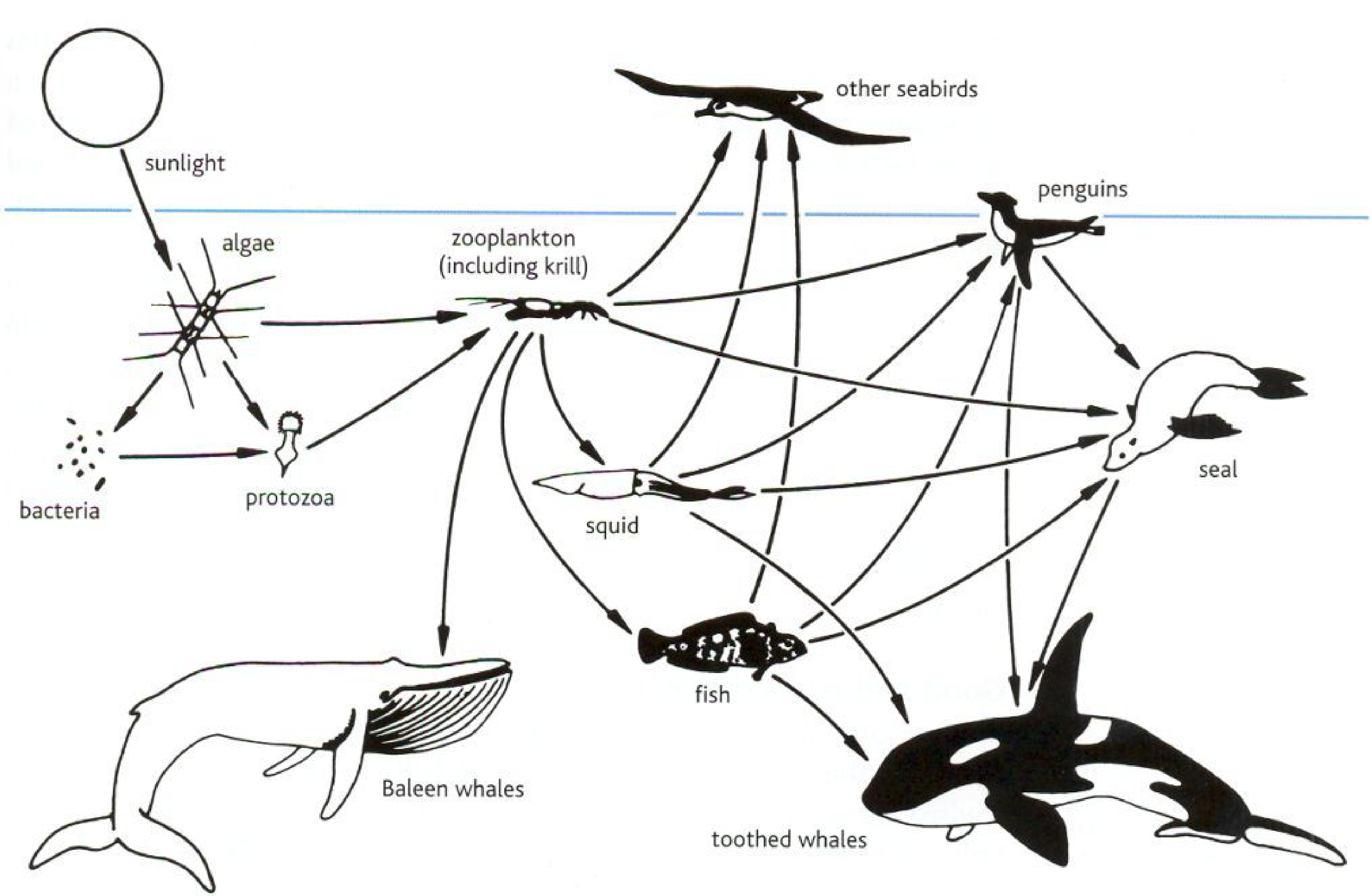
EUROPA - believed covered by deep briny ocean, with thick icy crust



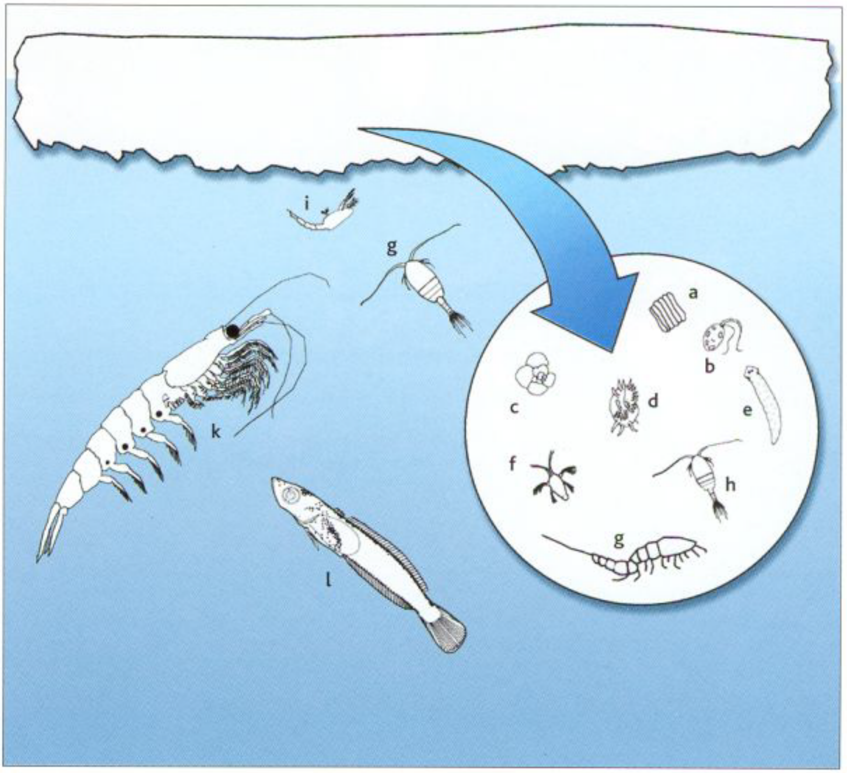
sea ice ecosystem

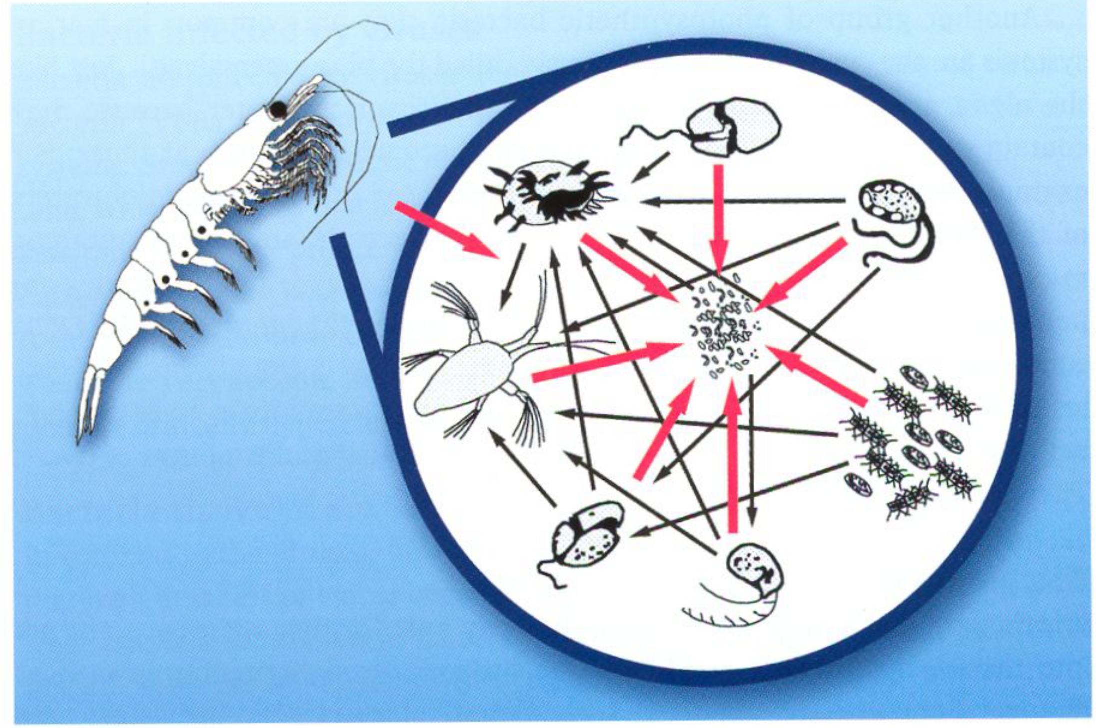
sea ice algae
support life in the polar oceans

Antarctic marine food web



D. Thomas 2004



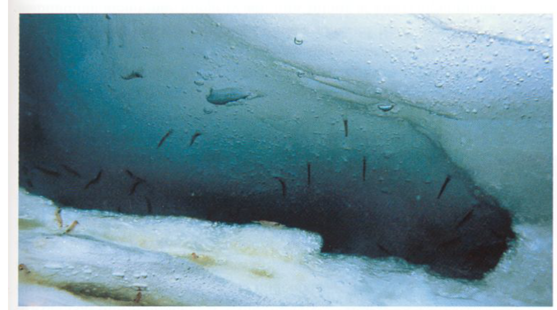


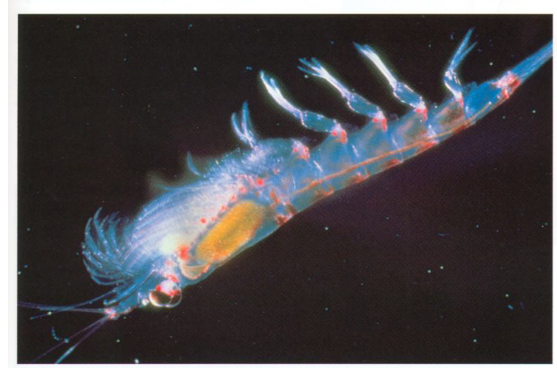
all organisms in food web produce dissolved organic matter which fuels bacterial growth in the ice

life within and at the edges of Antarctic sea ice floes

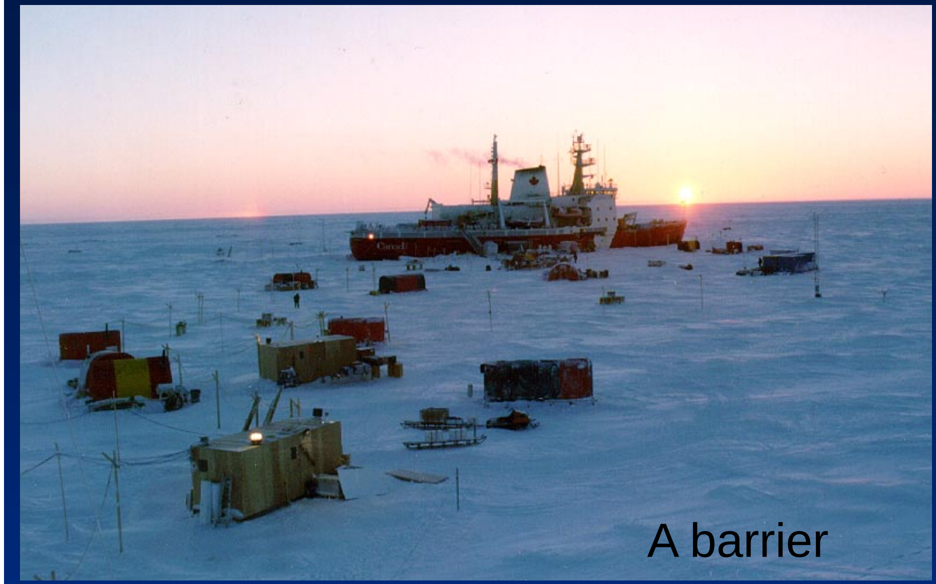
(a) diatoms (b) flagellates (c) foraminiferans (d) ciliates (e) turbellarians (f) crustaceans (g,h) copepods (i) crustacean larvae (k) krill (l) young fish (bottom) amphipod *Gammarus wilkitzkii*

krill





The Arctic sea ice cover



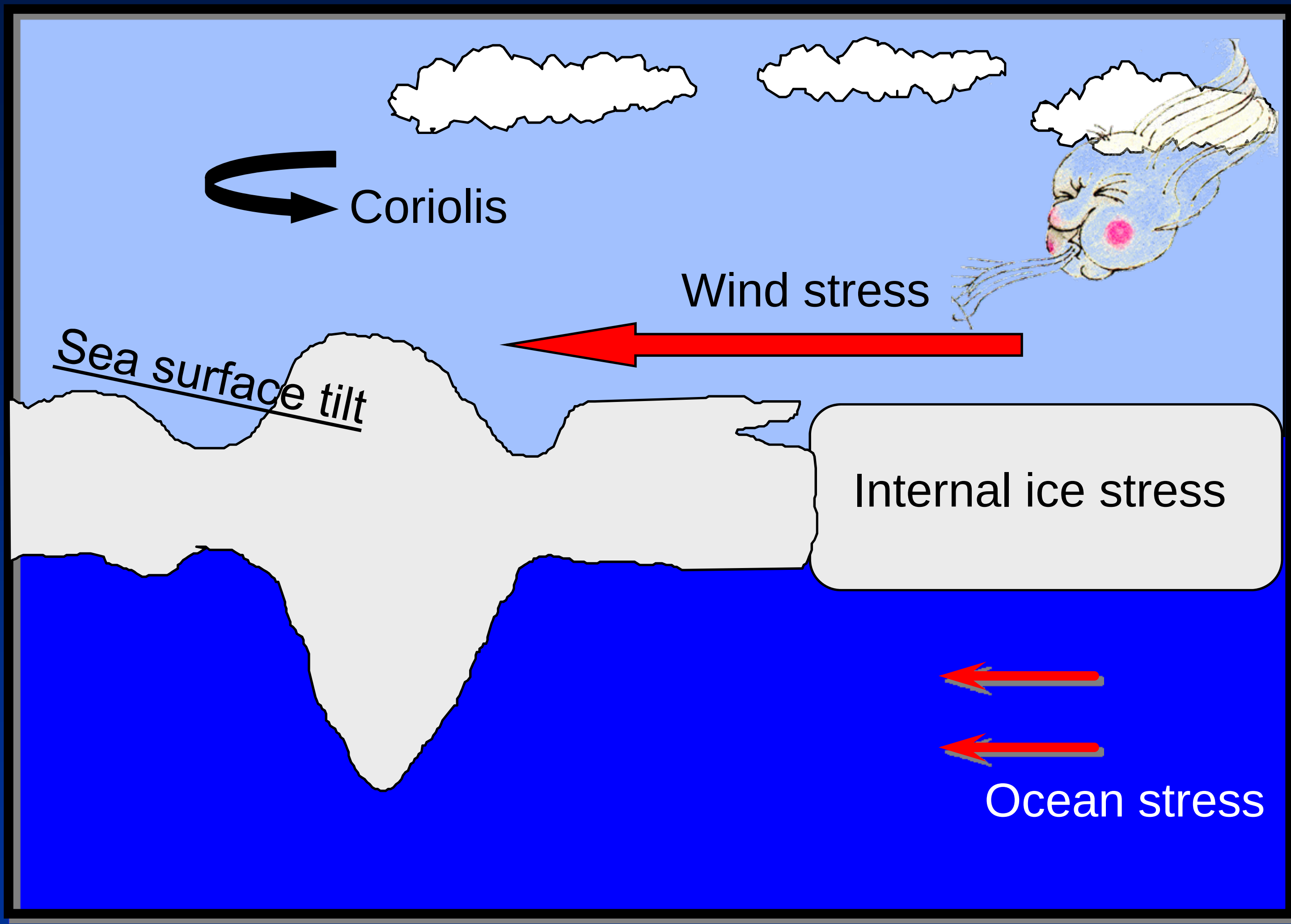
Of scientific, economic, societal, strategic importance

“Dynamic” duo

Dynamics

Thermodynamics

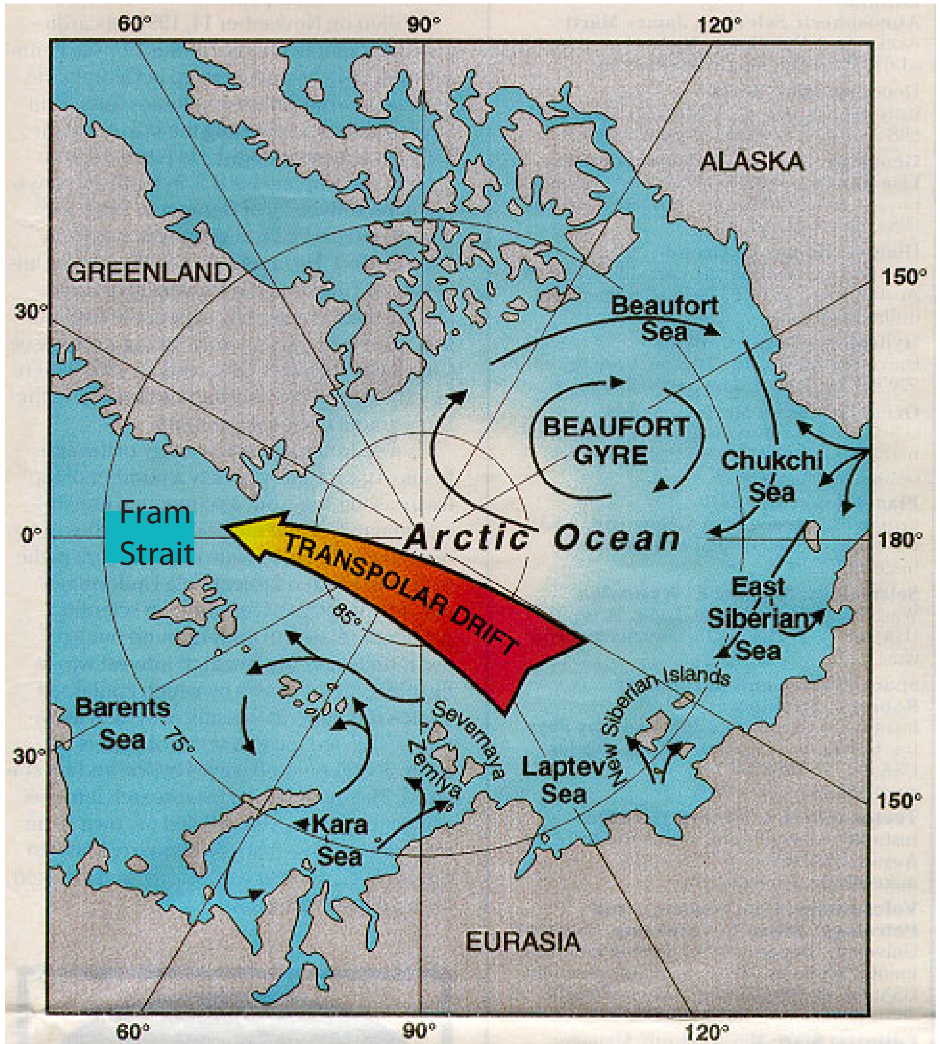
Dynamics



Momentum equation:

Ice acceleration = **<u>wind stress</u>** + ocean stress - Coriolis force - sea surface tilt + internal ice stress

Arctic Ice Dynamics



large scale ice dynamics and ocean circulation

Ridges

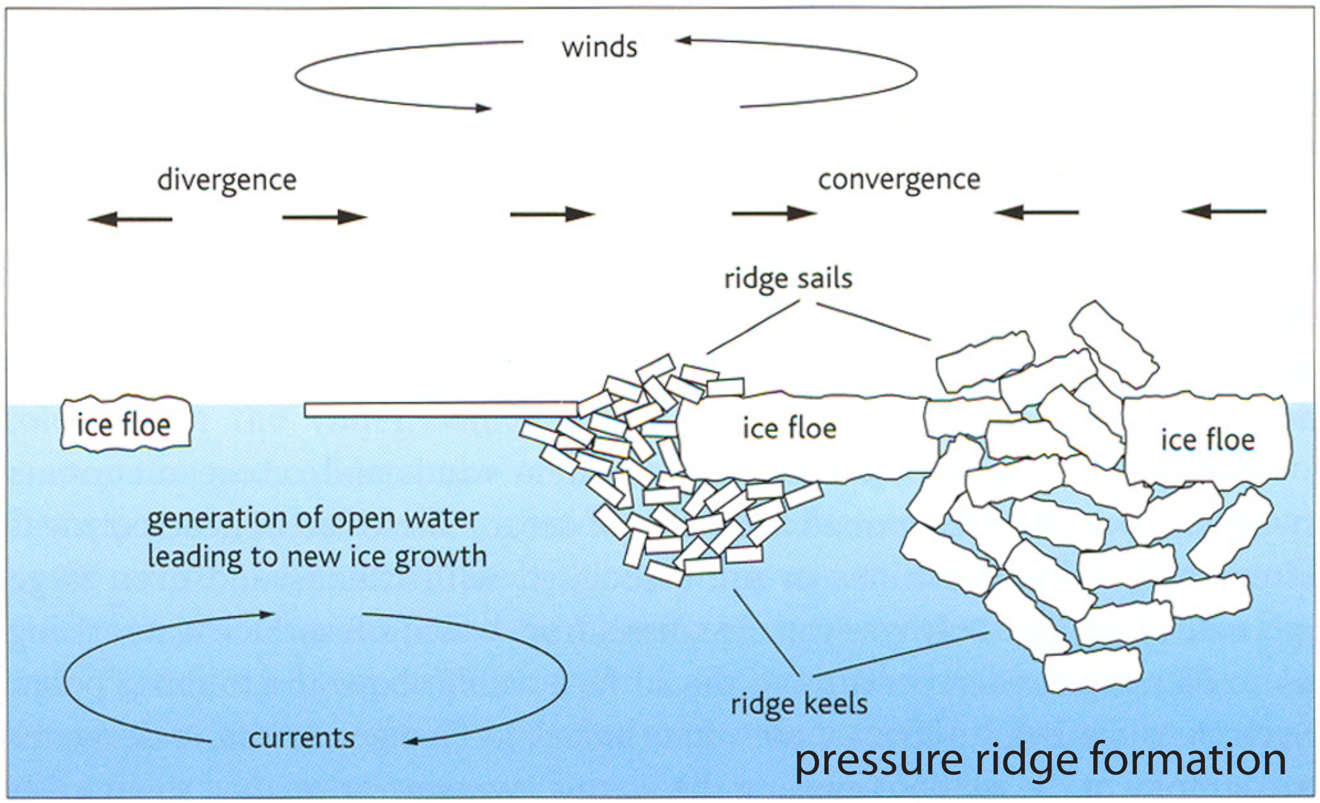
measuring ice depth in ridges off Barrow, AK

dynamic sea ice

sea ice dynamics

plate tectonics on a fast time scale

dynamically modifying the ice thickness distribution



thinning

thickening

David Thomas 2004

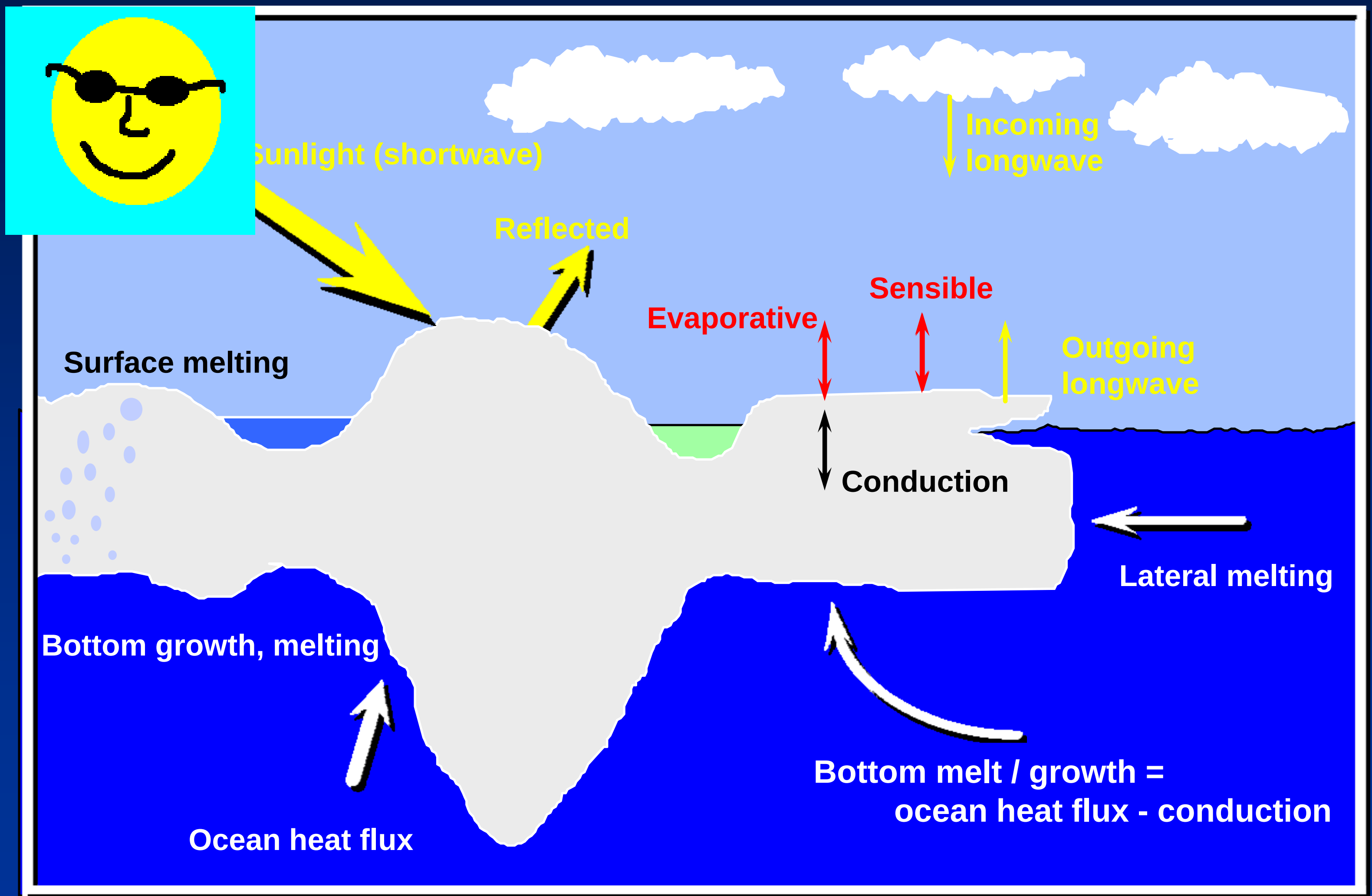
leads

heat flows directly from ocean to atmosphere

Thermodynamics: 4 ways to melt

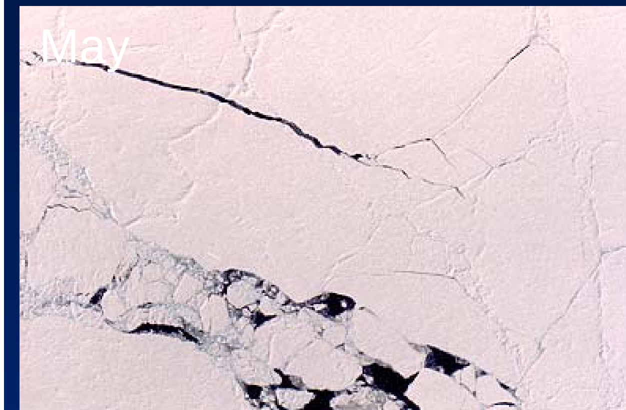
Top, bottom, lateral, internal

Heat budgets

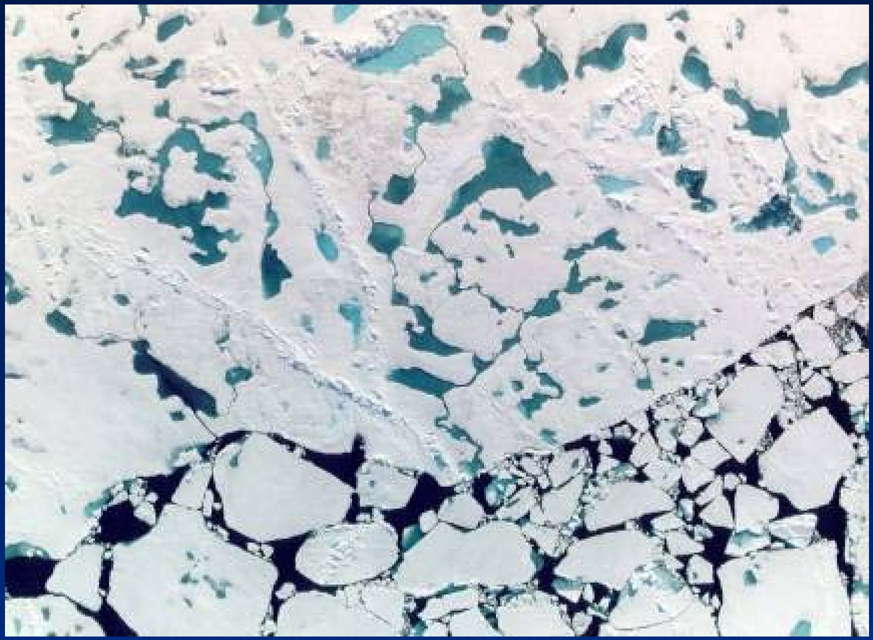


Net shortwave + incoming longwave + outgoing longwave + sensible + evaporative + conduction = melt / freeze

Seasonal changes in sea ice



Melt ponds



Polynyas

Size: 100 m - 1000 km

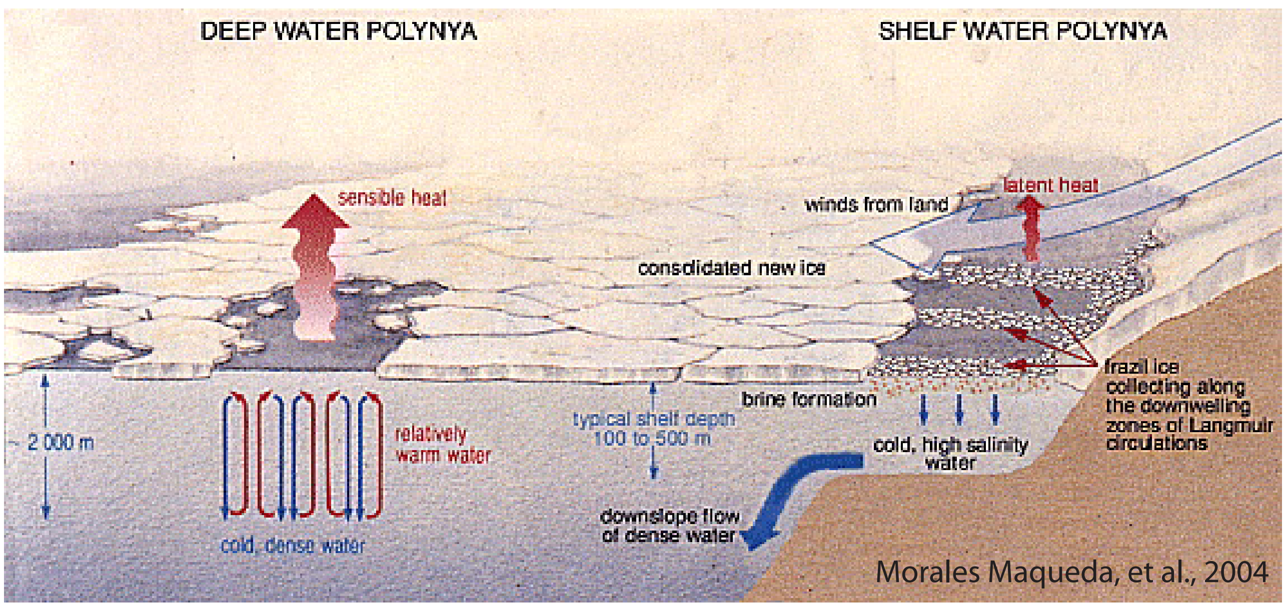
Two mechanisms can contribute to keeping polynyas open:

1. **Latent heat (or coastal) polynyas:** Mertz Glacier Polynya

   Sea ice grows in open-water and is continually removed by winds and currents (e.g. katabatic winds)
   - latent heat released to the ocean during ice formation perpetuates the process

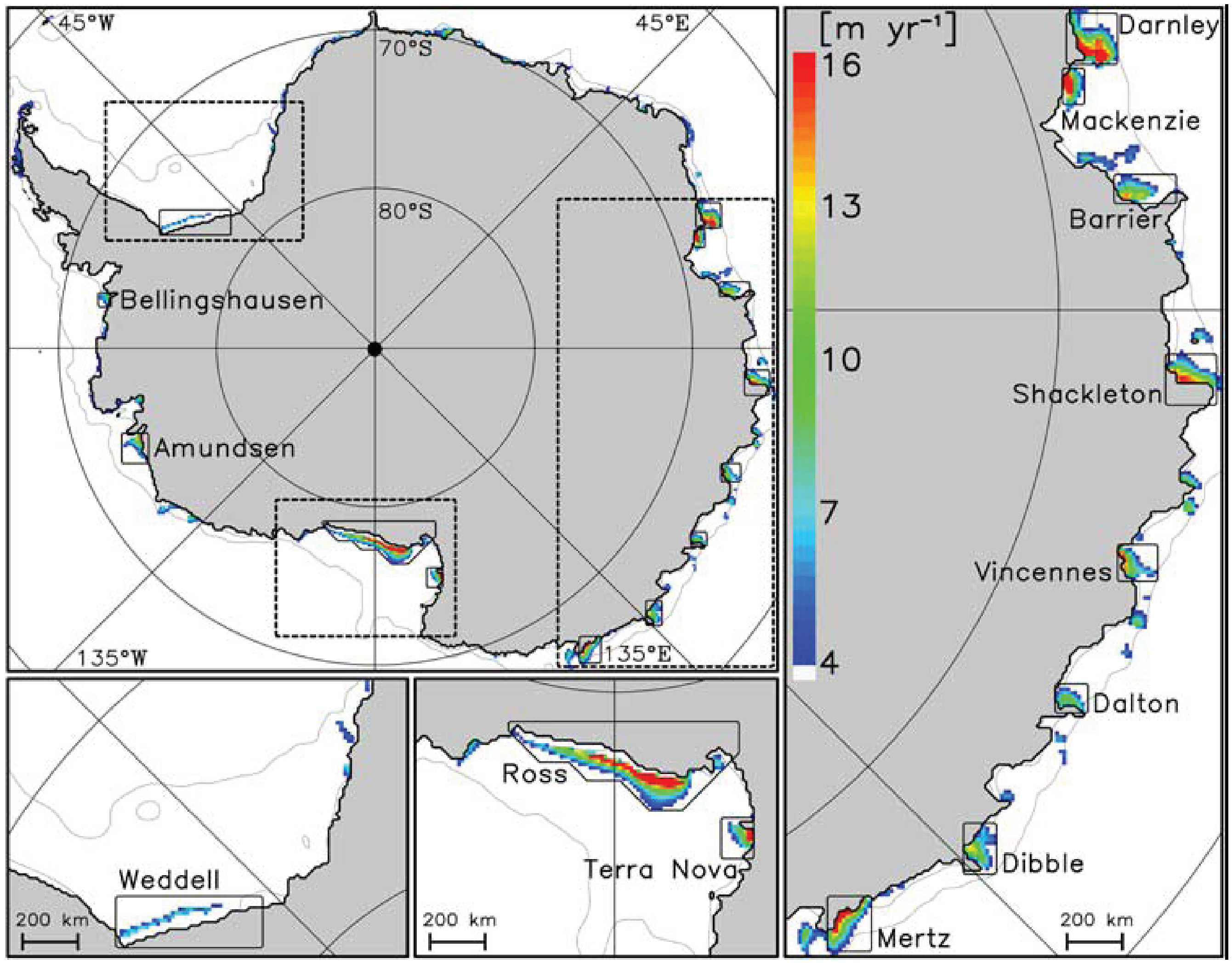
2. **Sensible heat (or open-ocean) polynyas:** Weddell Polynya

   Upwelling warm waters, vertical heat diffusion, or convection may provide enough oceanic heat flux to maintain ice-free region



Morales Maqueda, et al., 2004

Antarctic coastal polynyas = ice factories



around 10% of Southern Ocean sea ice is produced in the major Antarctic coastal polynyas

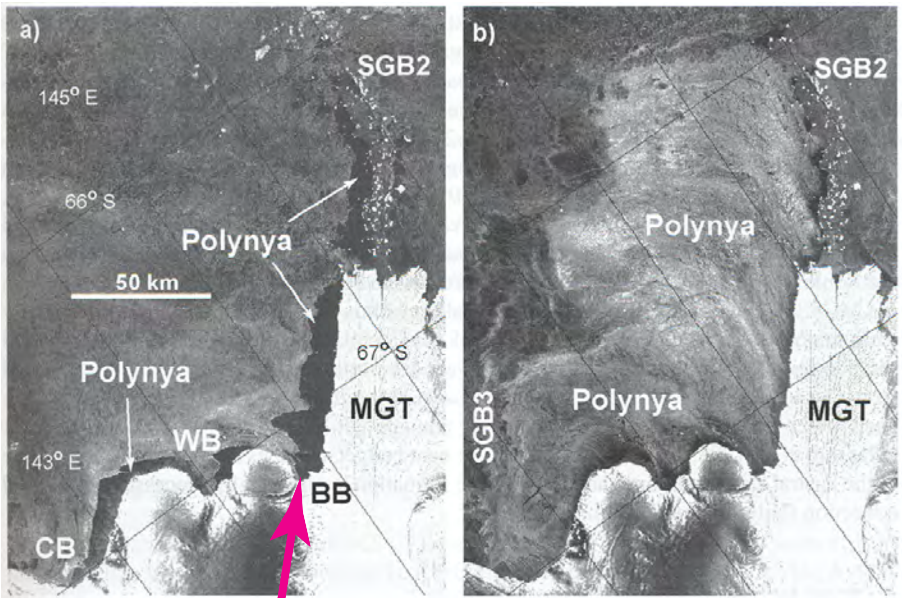
ice production in Ross Ice Shelf Polynya decreased by about 30% from the 1990's to the 2000's
(caused by atmospheric warming or decreased polynya size from calving icebergs)

candidate for causing recent freshening of AABW

Tamura, Ohshima, Nihashi, GRL 2008

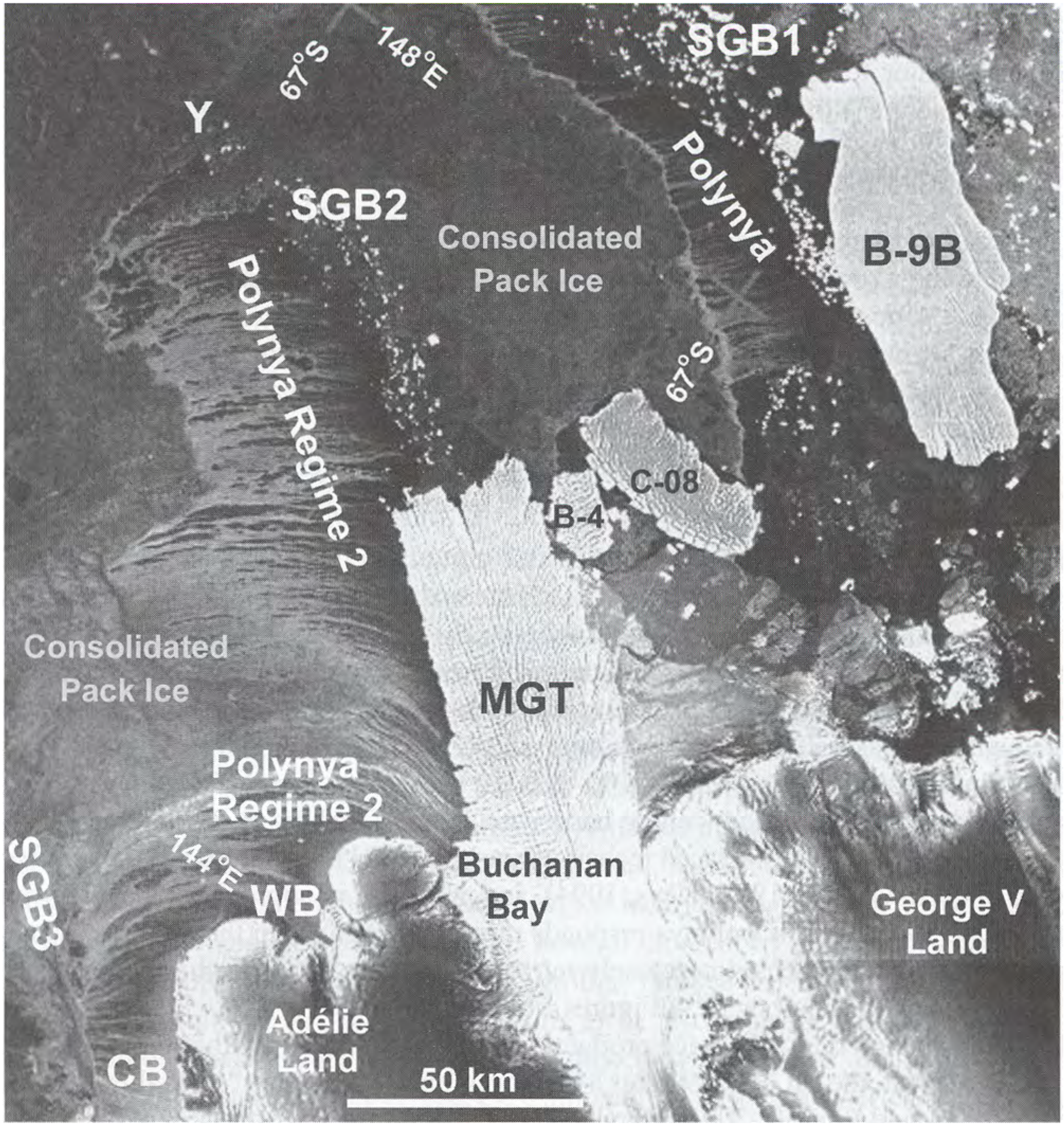
polynyas ice factories

Mertz Glacier Polynya, located in East Antarctica, covers only 0.001% of the overall Antarctic sea ice zone at its maximum winter extent, but is responsible for 1% of the total sea ice production in the Southern Ocean.



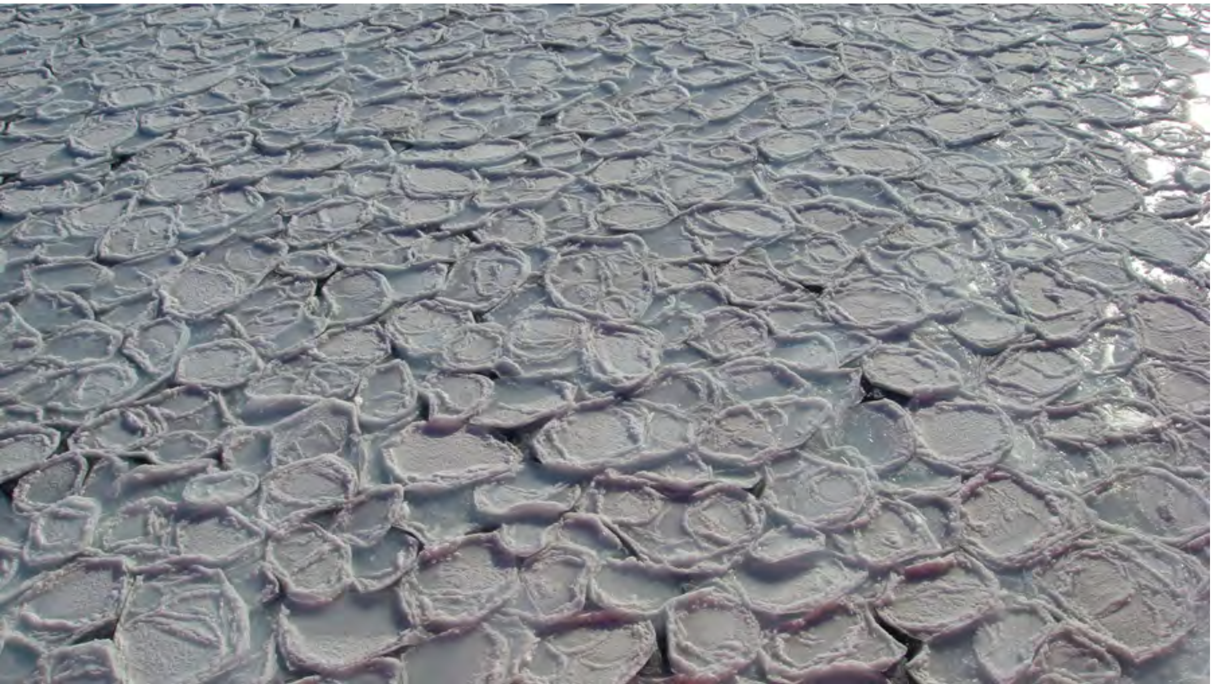
Buchanan Bay

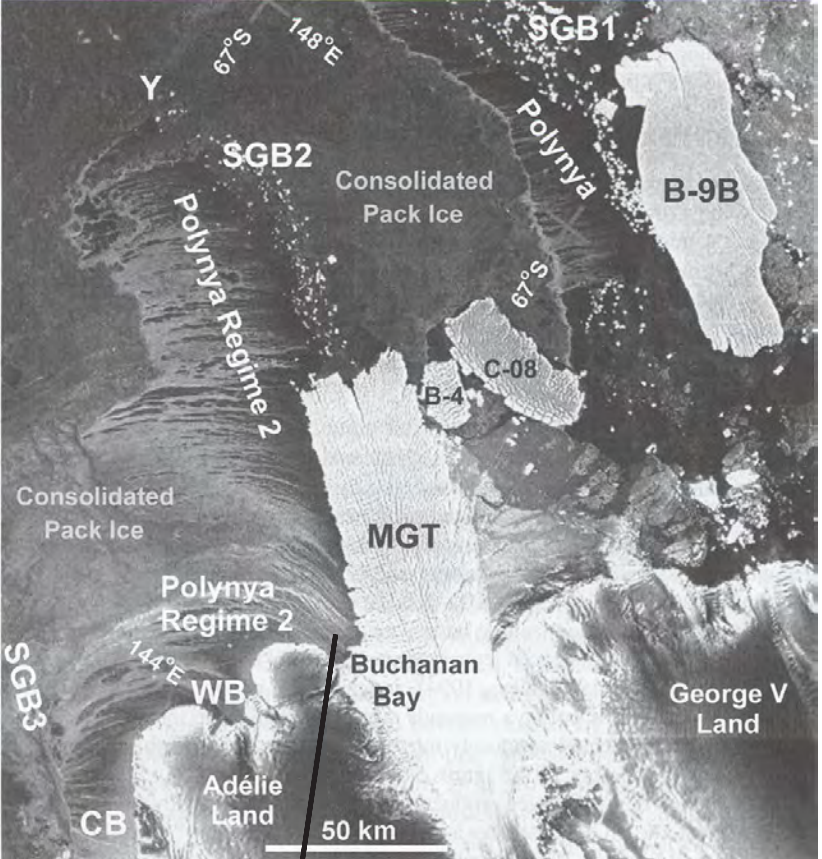
Mertz Glacier Polynya -- third largest Antarctic sea ice producer




pancake ice forming in a wave field in the Southern Ocean

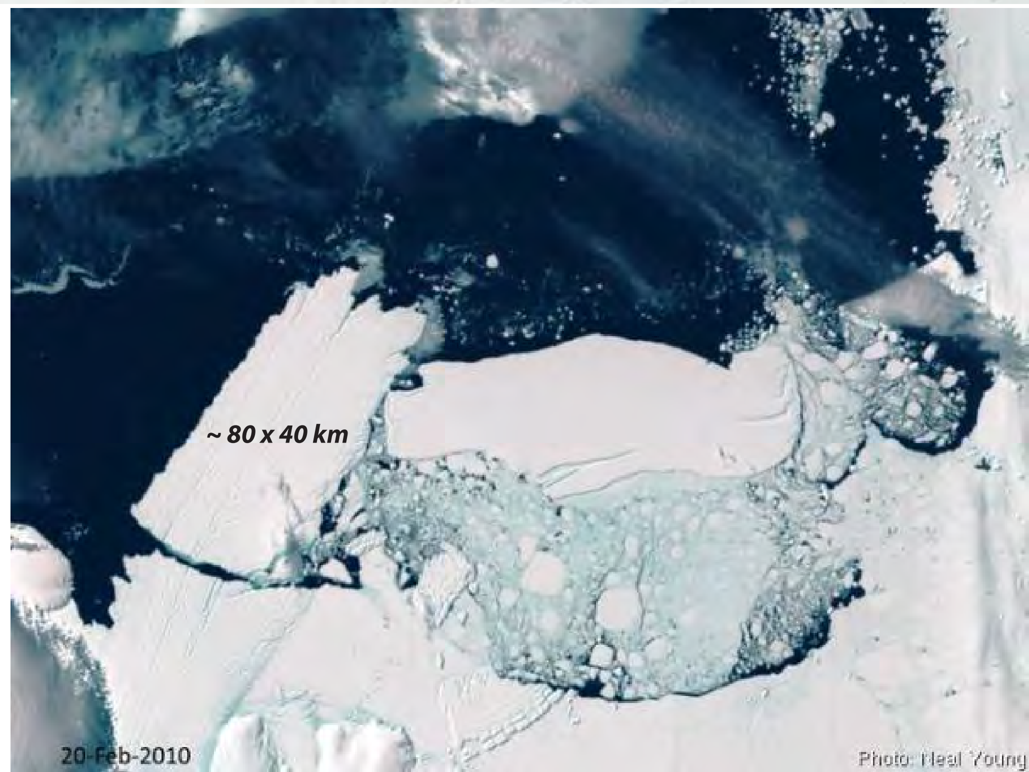
pancake ice



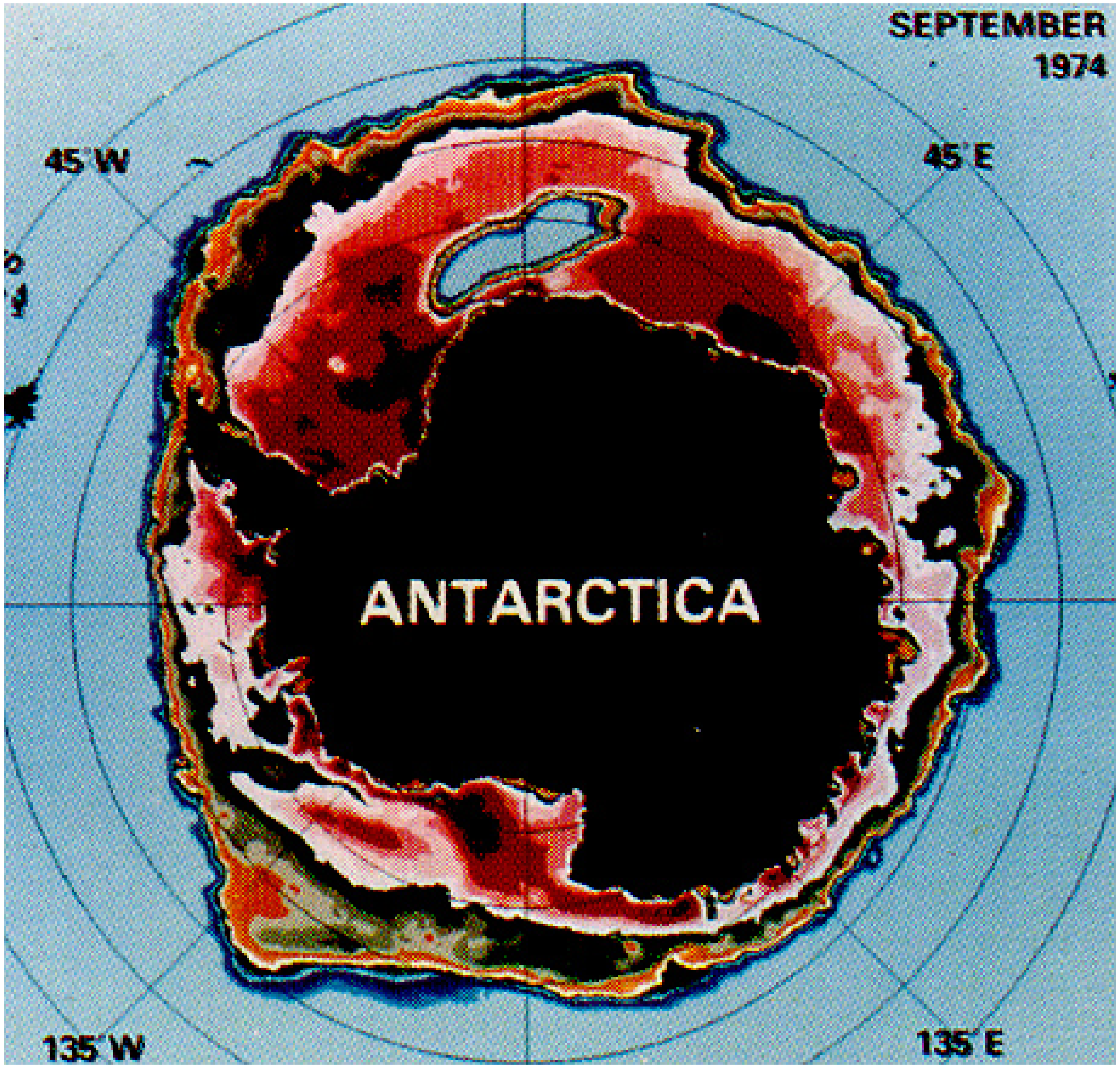

SGB1
67°S
148°E
Y
SGB2
Consolidated
Pack Ice
Polynya
B-9B
Polynya Regime 2
67°S
C-08
B-4
Consolidated
Pack Ice
MGT
Polynya
Regime 2
SGB3
144°E
WB
Buchanan
Bay
George V
Land
Adélie
Land
CB
50 km


Buchanan Bay, July 1999
Mertz Glacier Polynya Experiment


iceberg collision!
breaking the Mertz Glacier Tongue, February 2010


~ 80 x 40 km
20-Feb-2010
Photo: Neal Young

Weddell Sea Polynya



Antarctic Zone Flux Experiment

ANZFLUX 1994

sea ice thickness in dynamic equilibrium

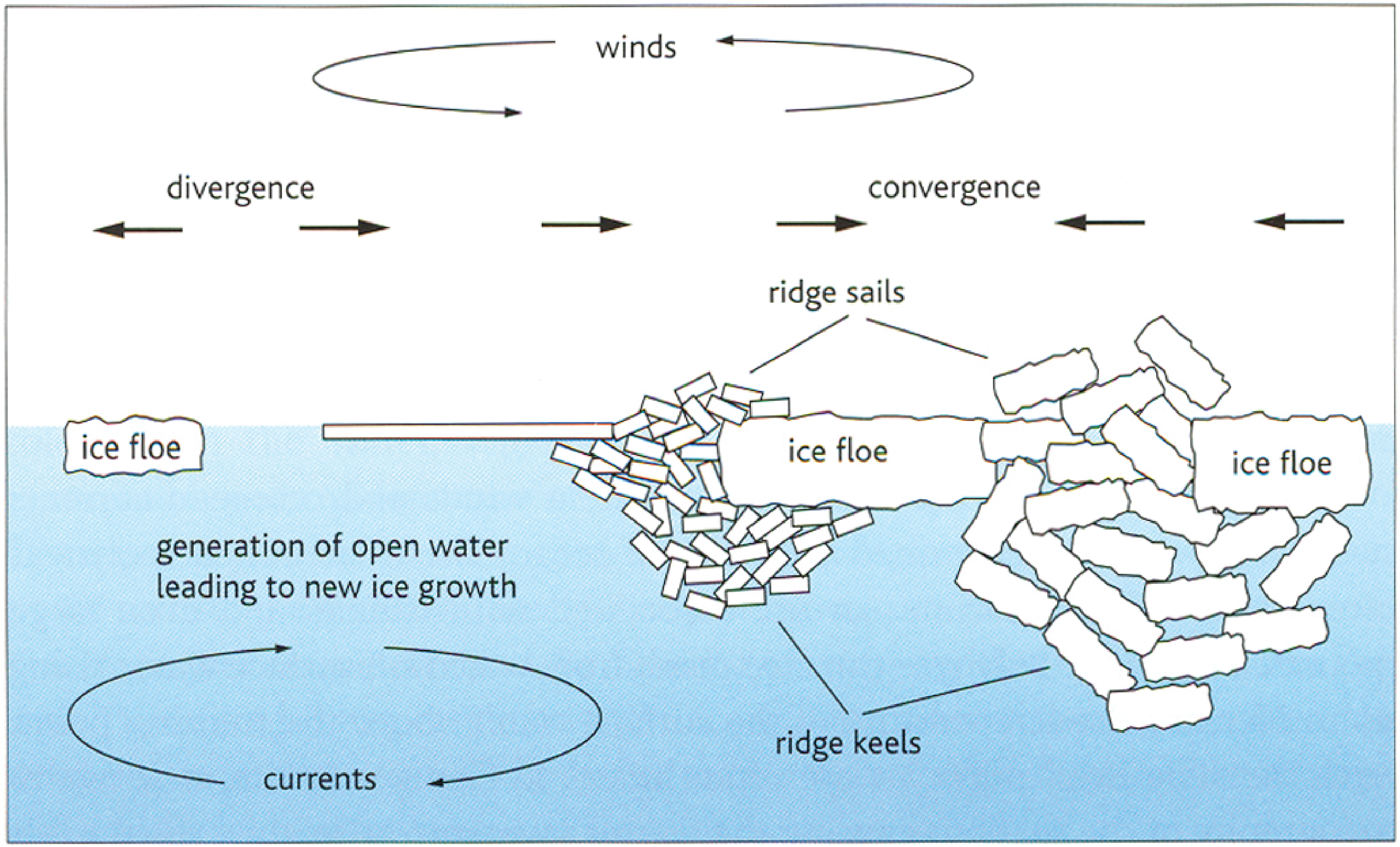
surface flooding -> snow-ice formation

controlled by ice permeability

Grow a little ice, descending brine plumes (+ storms) can help trigger deep convection, keep polynya going? Snow-ice formation shuts it down?

Doug Martinson

deeper, warmer waters deflected upwards by rise in sea floor (Maud Rise)



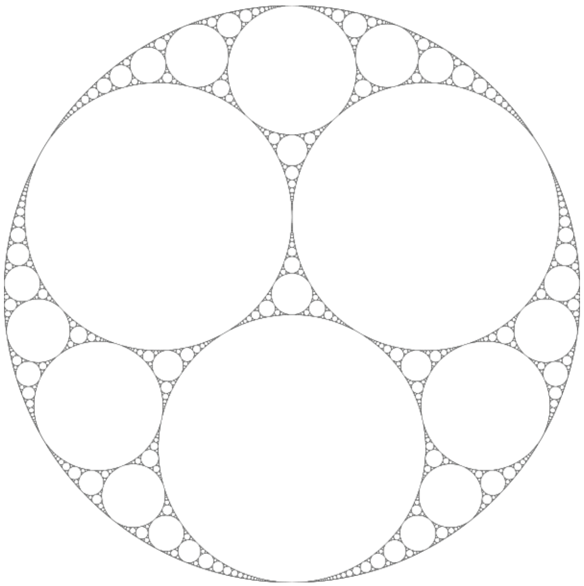
winds
divergence
convergence
ridge sails
ice floe
ice floe
ice floe
generation of open water
leading to new ice growth
ridge keels
currents

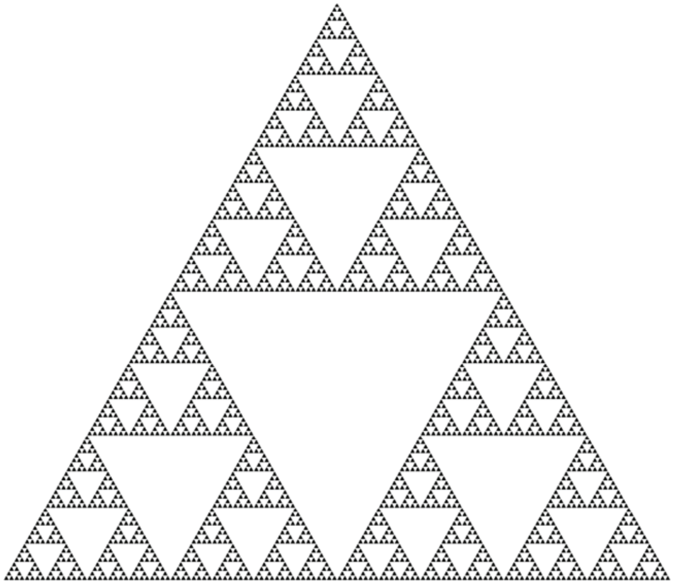
the sea ice pack is a ***fractal***

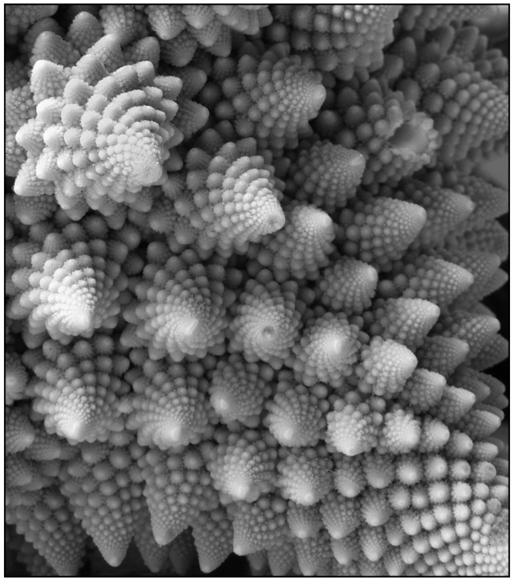
displaying self-similar structure on many scales

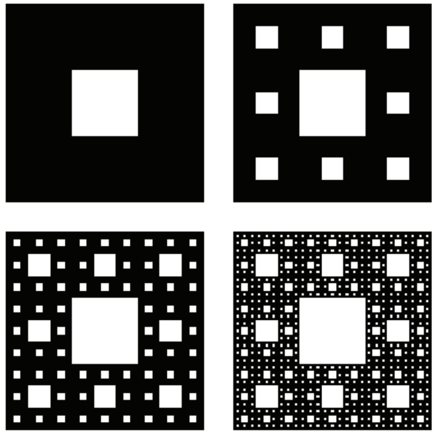
floe size distribution important in
dynamics (fracture), thermodynamics (melting)

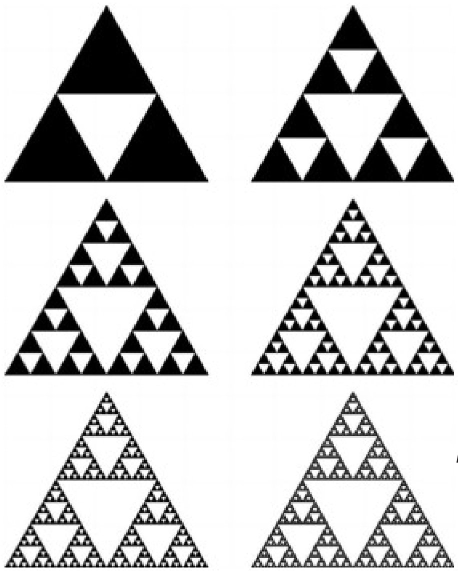
bigger floes easier to break, smaller floes easier to melt











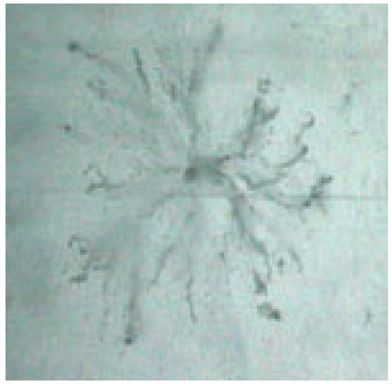
fractals

self-similar structure
non-integer dimension

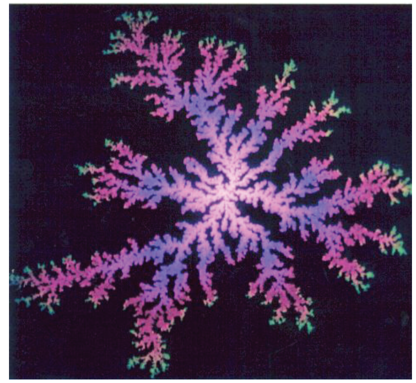
$$D = \frac{\log 3}{\log 2} = 1.585...$$

fractal microstructures

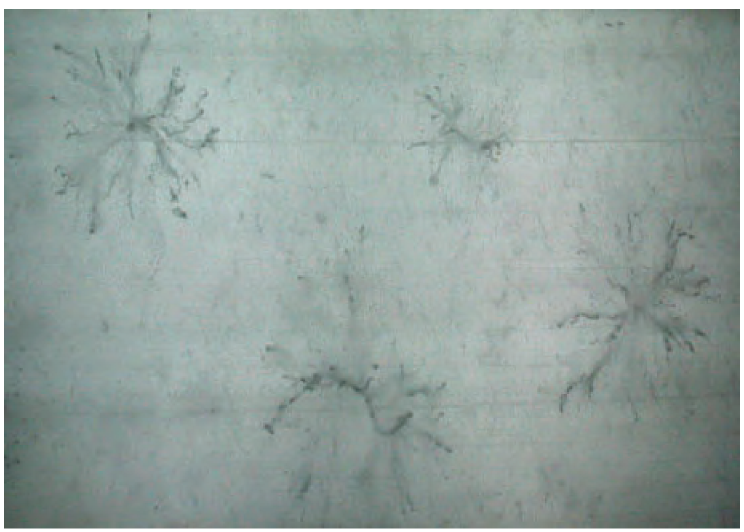
electrorheological fluid
with metal spheres

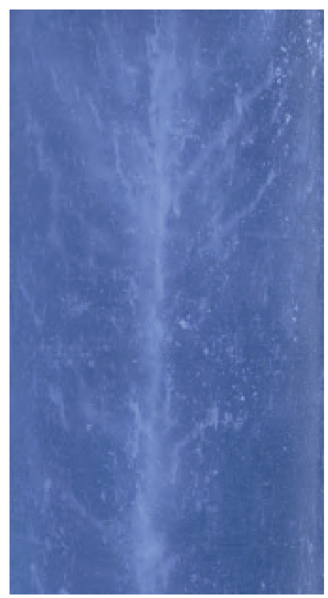


brine channel
in sea ice



diffusion limited
aggregation



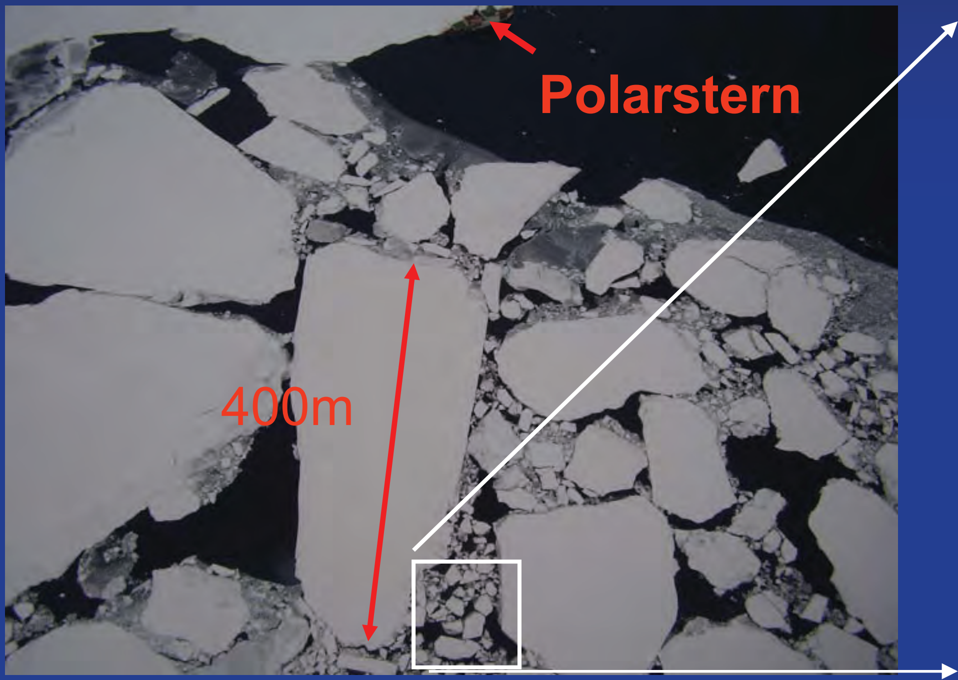


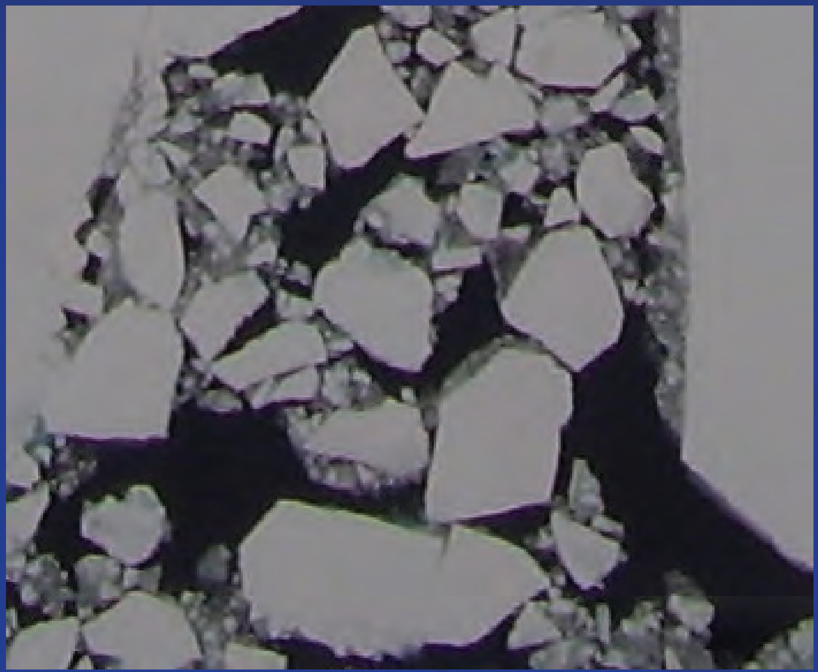
brine channels

The sea ice pack has fractal structure.

Self-similarity of sea ice floes

Weddell Sea, Antarctica



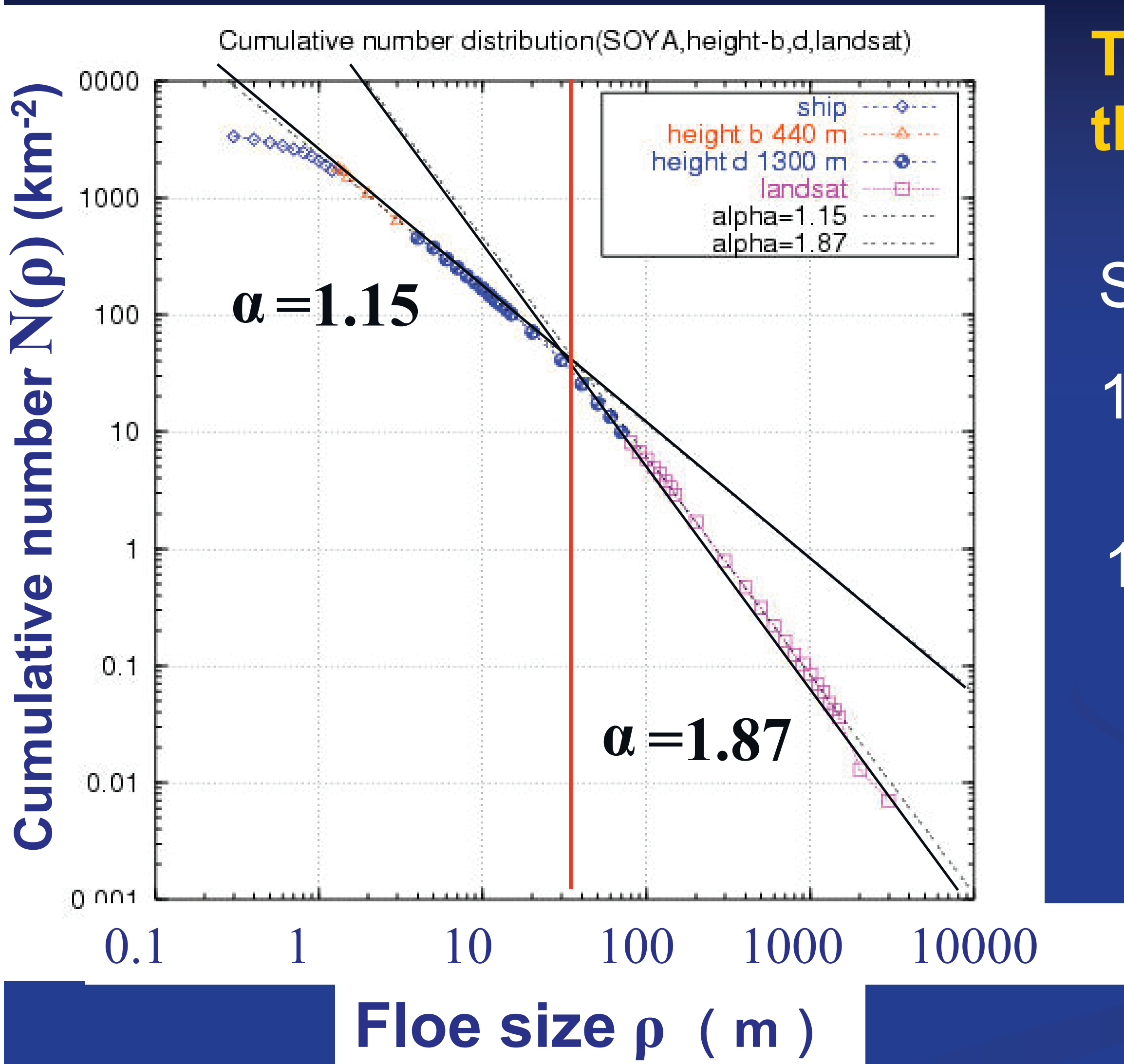


fractal dimensions of Okhotsk Sea ice pack
smaller scales D~1.2, larger scales D~1.9

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

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

Results from Okhotsk Sea ice



There are two regimes in the ice floe distribution.

Size

1 ~ 20 m : α = 1.15 ± 0.02

100 ~ 1500 m :

α = 1.87 ± 0.02

(Toyota, Takatsuji et al., 2006)

melt pond formation and albedo evolution:

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

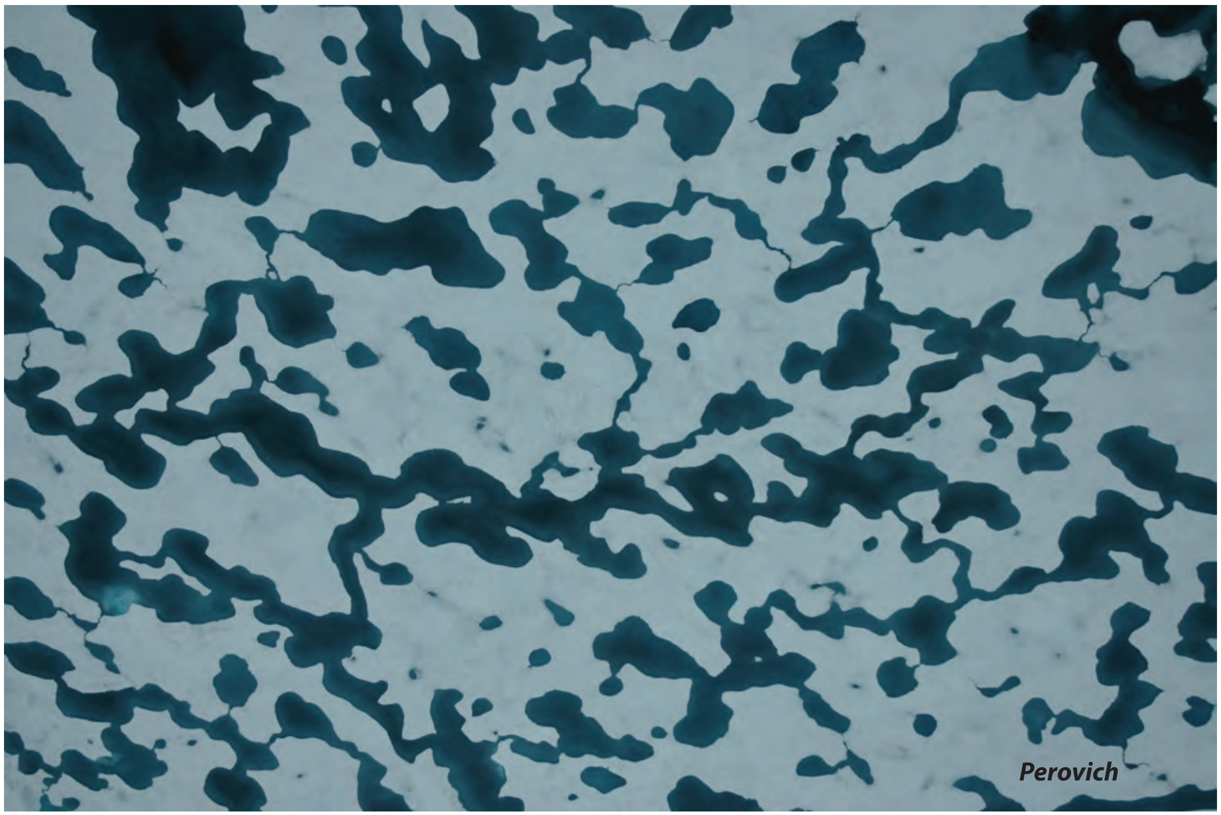
numerical models of melt pond evolution, including topography, drainage (permeability), etc.

Lüthje, Feltham, Taylor, Worster 2006

Flocco, Feltham 2007

Skyllingstad, Paulson, Perovich 2009

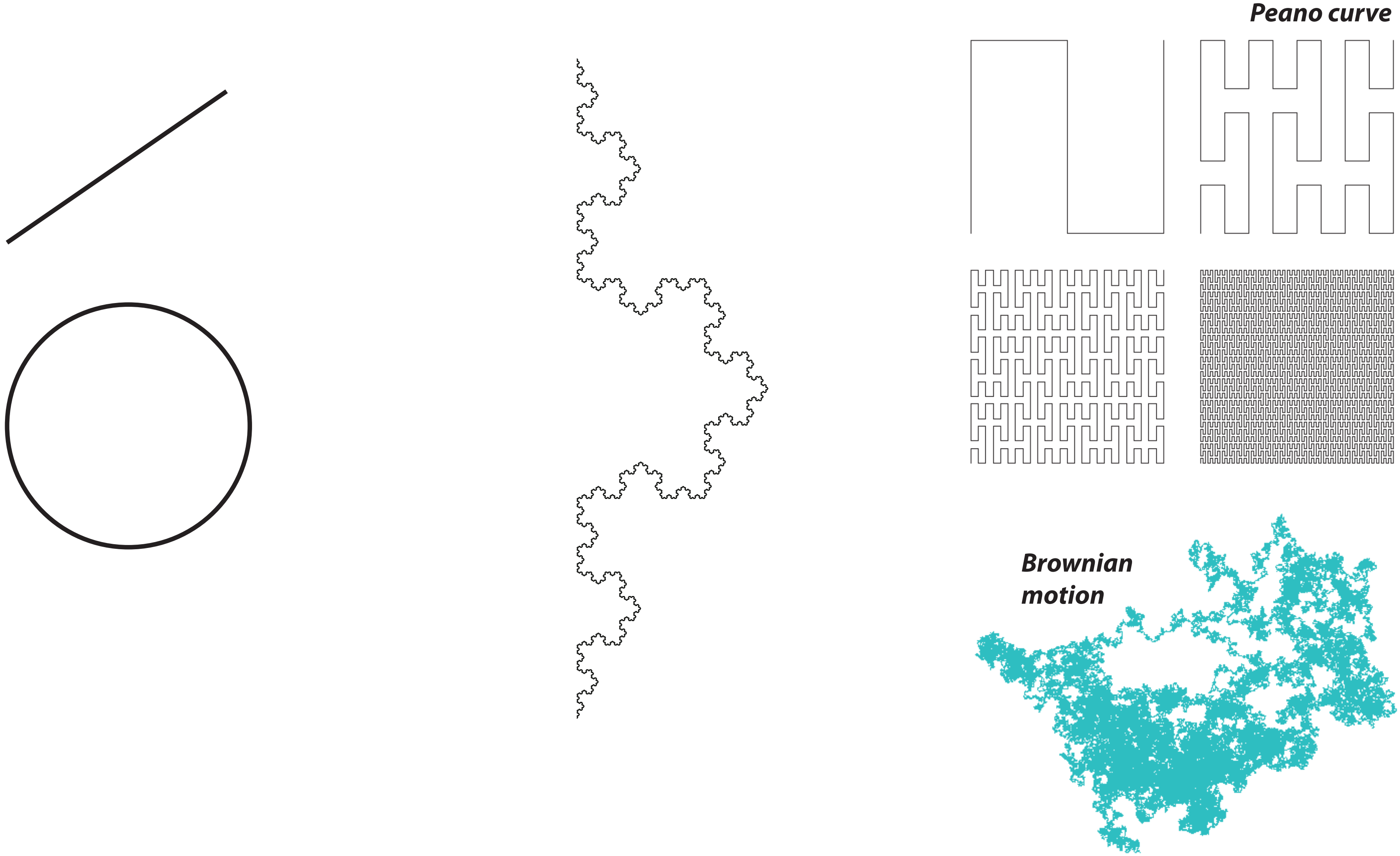
Flocco, Feltham, Hunke 2012



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	***Koch snowflake***	***space filling curves***
D = 1	***D = 1.26***	***D = 2***

clouds exhibit fractal behavior from 1 to 1000 km

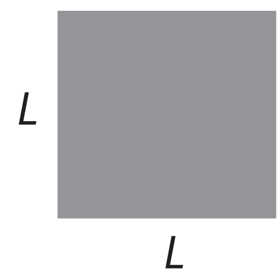
use ***perimeter-area*** data to find that cloud and rain boundaries are fractals

$$D \approx 1.35$$

S. Lovejoy, Science, 1982

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

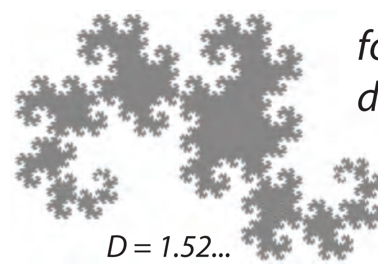
simple shapes



$A = L^2$

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

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



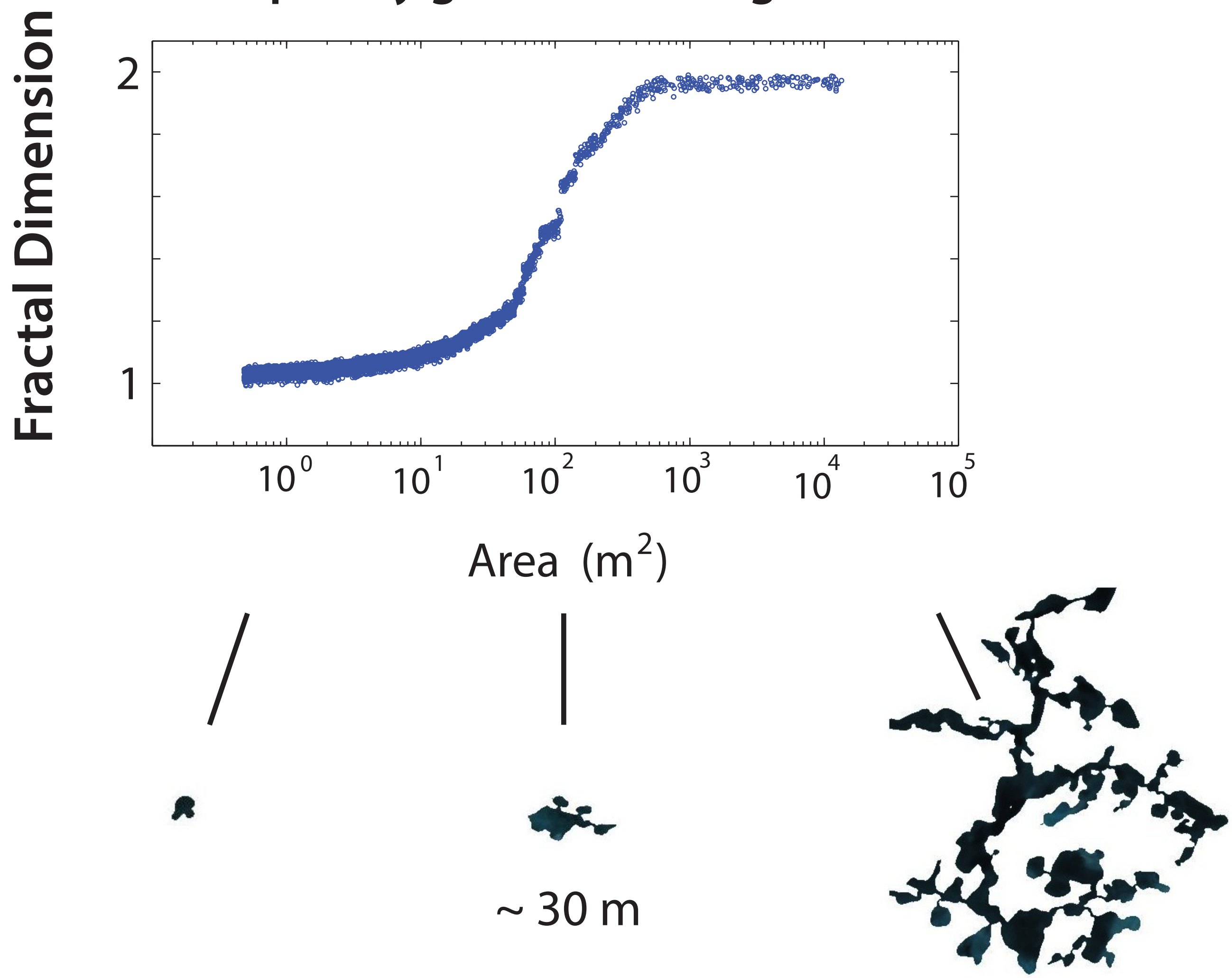
for fractals with dimension D

Transition in the fractal geometry of Arctic melt ponds

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

The Cryosphere, 2012

complexity grows with length scale

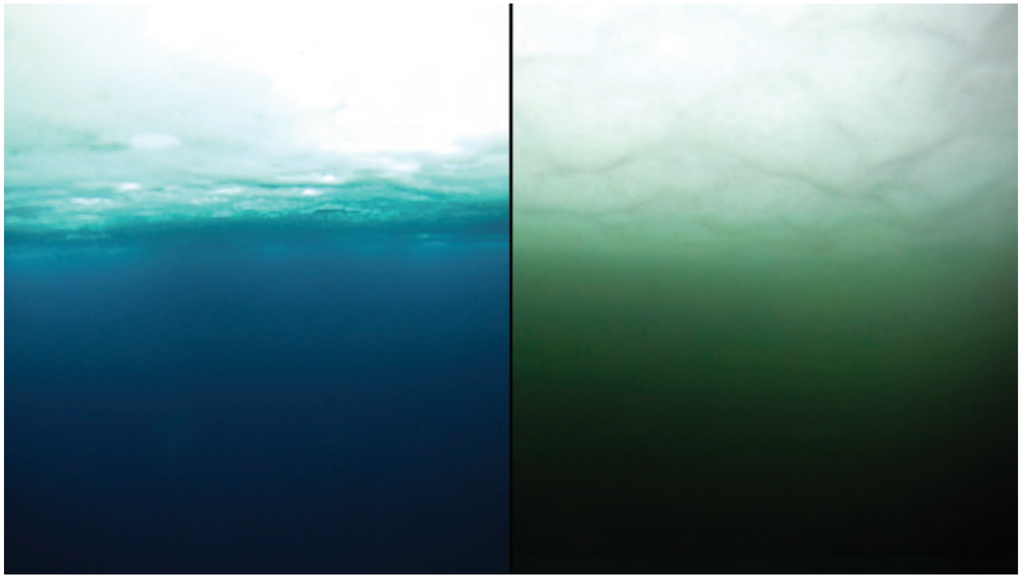


simple pond ***transitional pond*** ***complex pond***

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

(2015 AMS MRC, Snowbird)