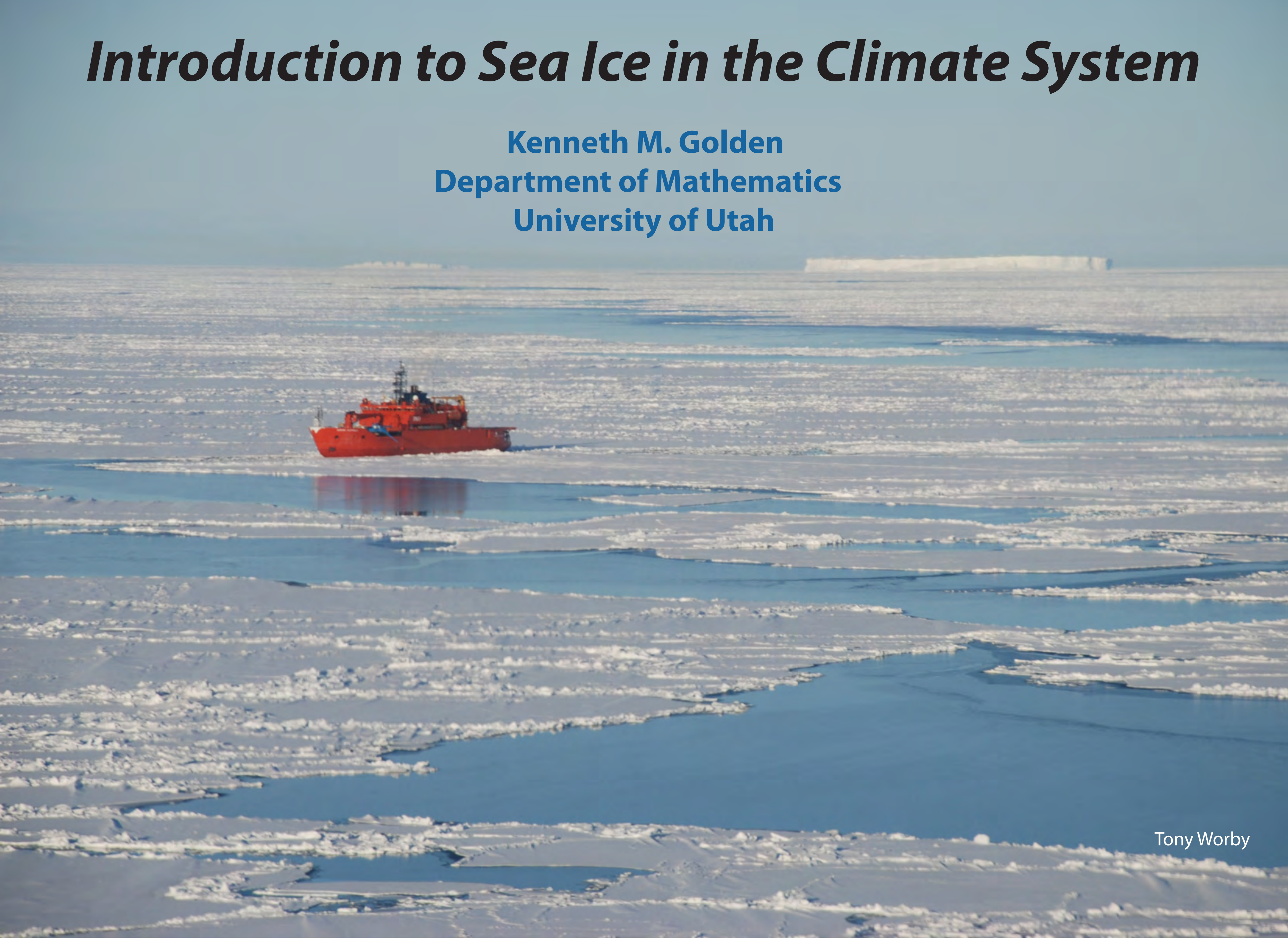
Introduction to Sea Ice in the Climate System

Kenneth M. Golden
Department of Mathematics
University of Utah



IPAM Mini-Workshop: Mathematics of Sea Ice ***May 10, 2010***

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

- boundary between ocean and atmosphere
- mediates exchange of heat, moisture, momentum
- indicator and agent of climate change

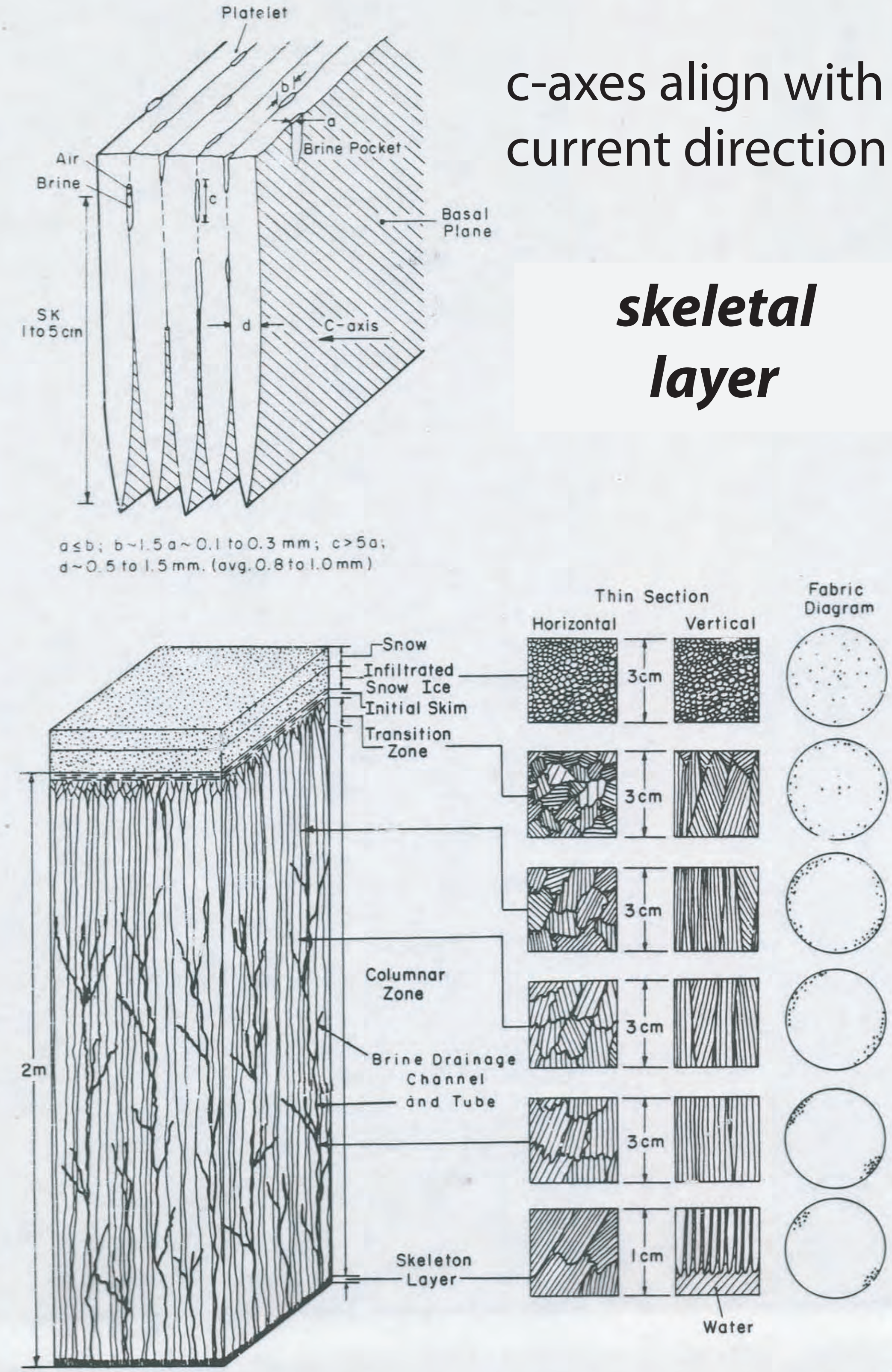
cross-sections of sea ice structure

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

crystallographic textures

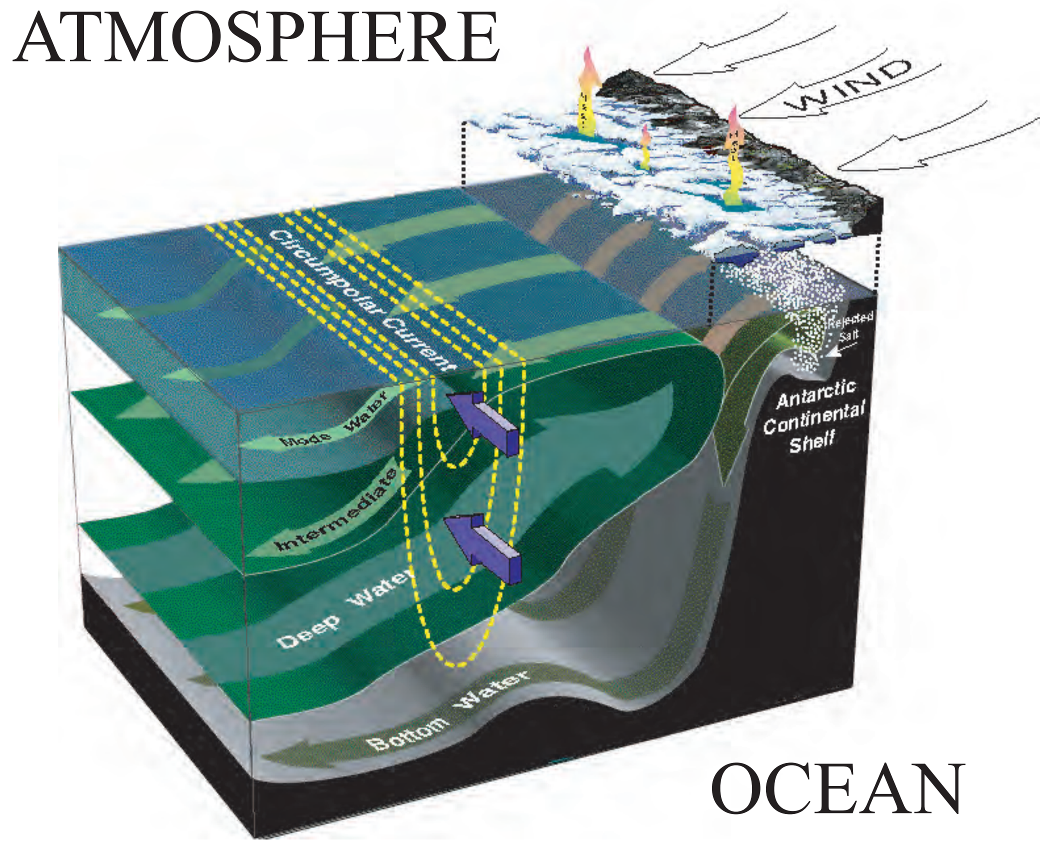
c-axes align with current direction

skeletal layer



Southern Ocean off Wilkes Land
Antarctica, September 2007

RSV *Aurora Australis*



ICE - ATMOSPHERE - OCEAN INTERACTIONS

- freezing sea ice rejects cold salty brine

→ ***deep - water formation***

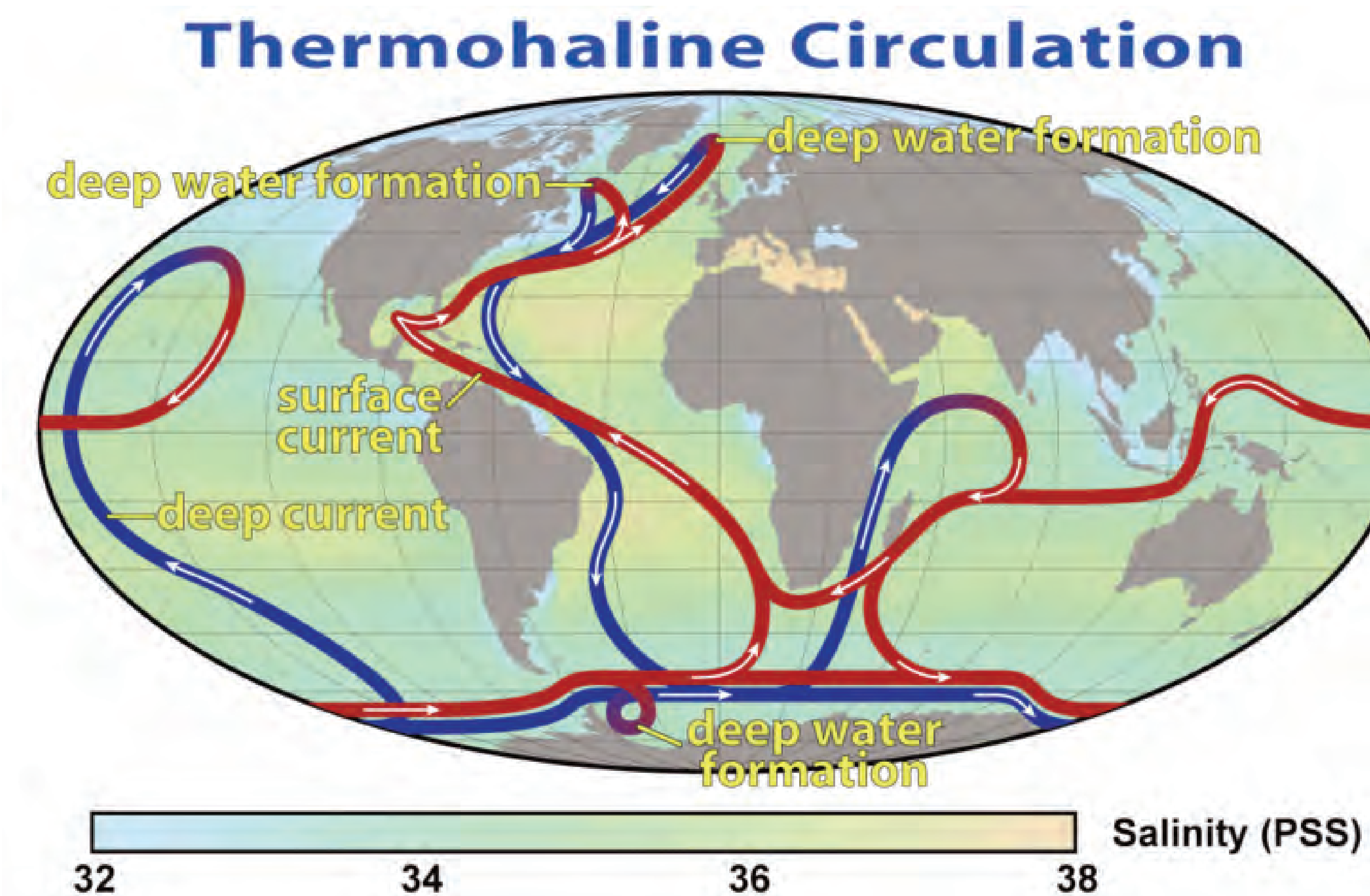
brine has lower freezing point

fluid inclusions trapped between ice platelets

- melting sea ice drains fresh water

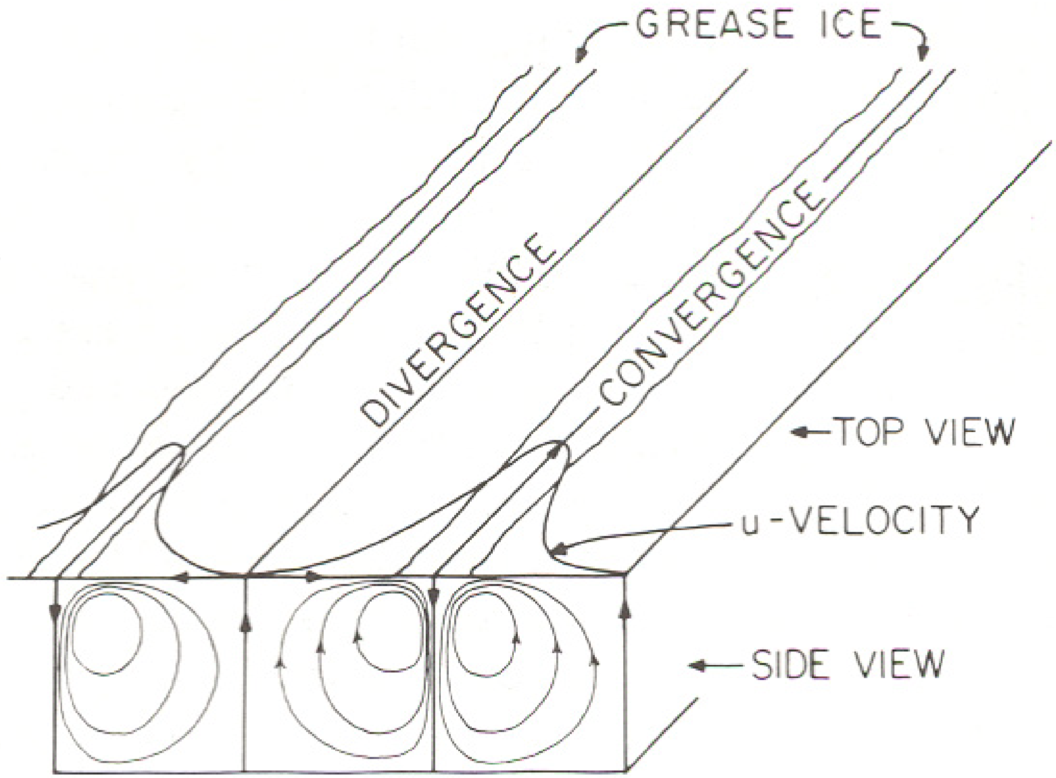
brine expulsion from sea ice formation results in water beneath the ice becoming cooler and saltier → **this denser water sinks rapidly to great depths**

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



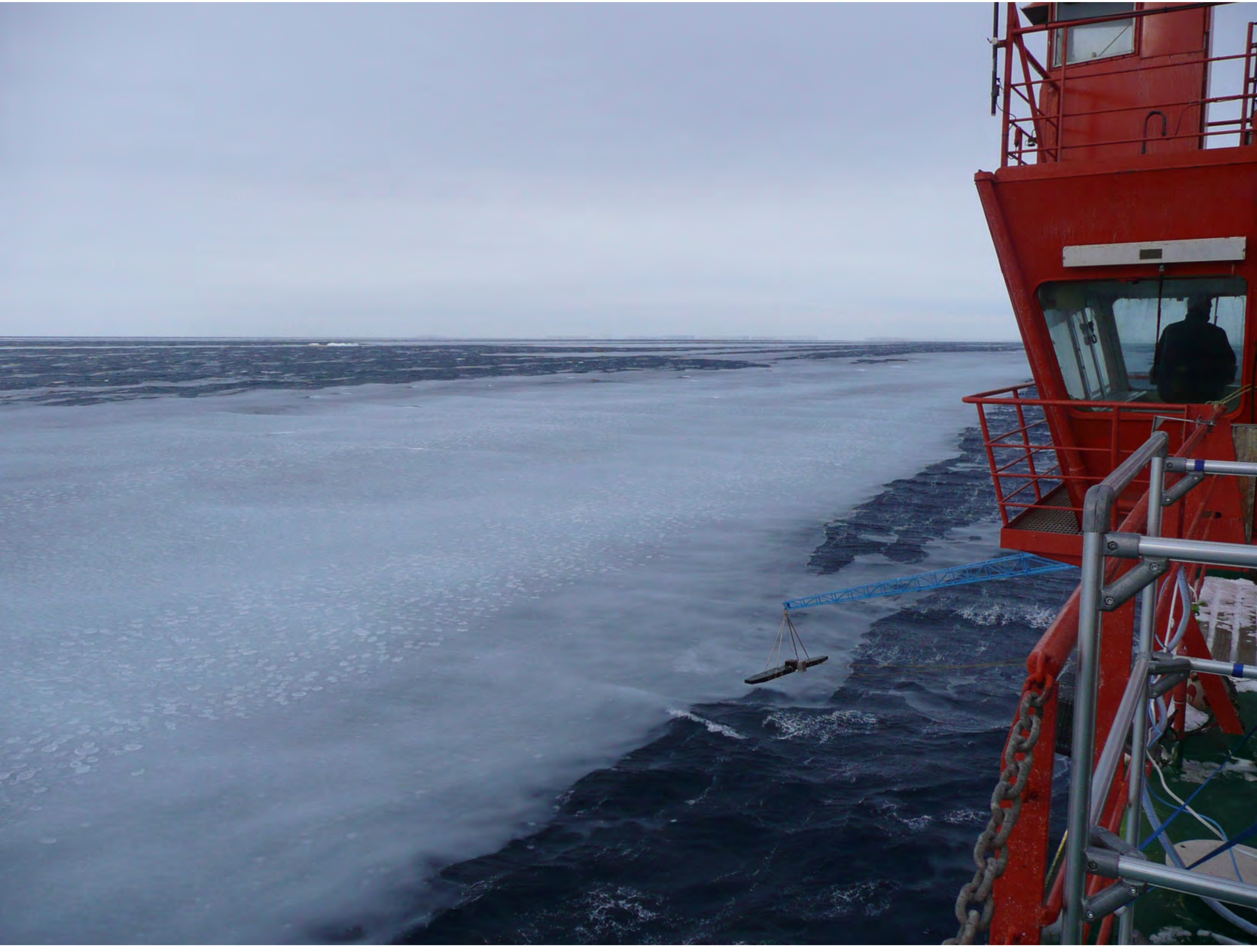
GLOBAL THERMOHALINE CONVEYOR BELT

sea ice formation



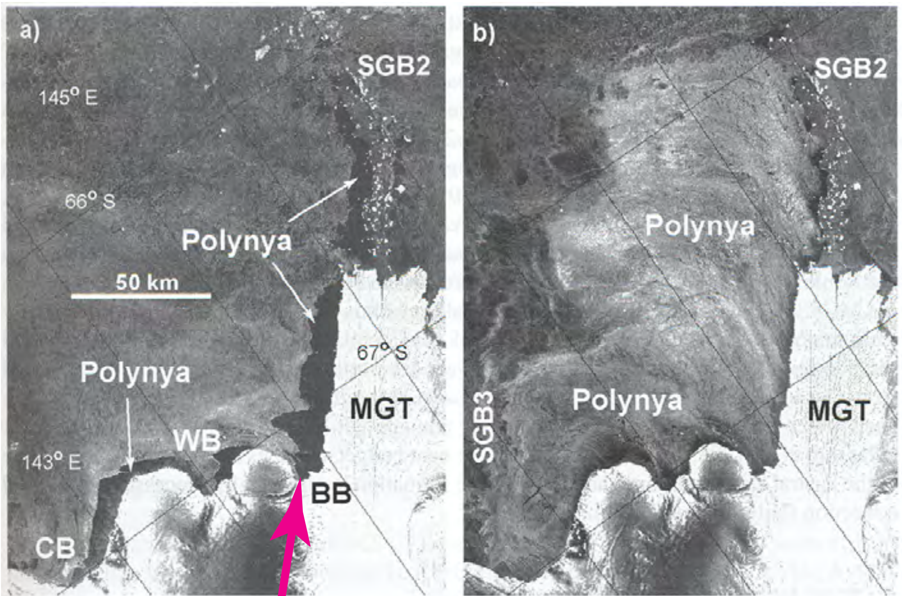
effect of Langmuir circulation
on grease and pancake ice

Martin and Kauffman, 1981



polynyas ice factories

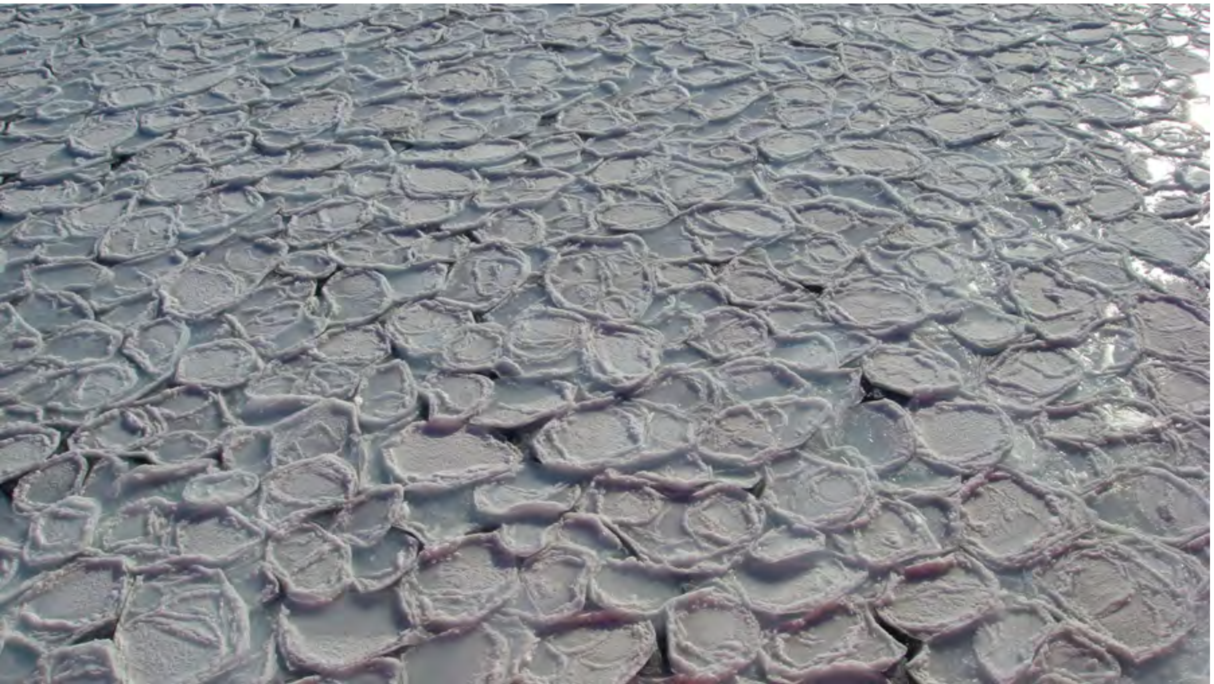
Mertz Glacier Polynya, located in East Antarctica, covers only 0.001% of the overall Antarctic sea ice zone at its maximum winter extent, but is responsible for 1% of the total sea ice production in the Southern Ocean.



Buchanan Bay

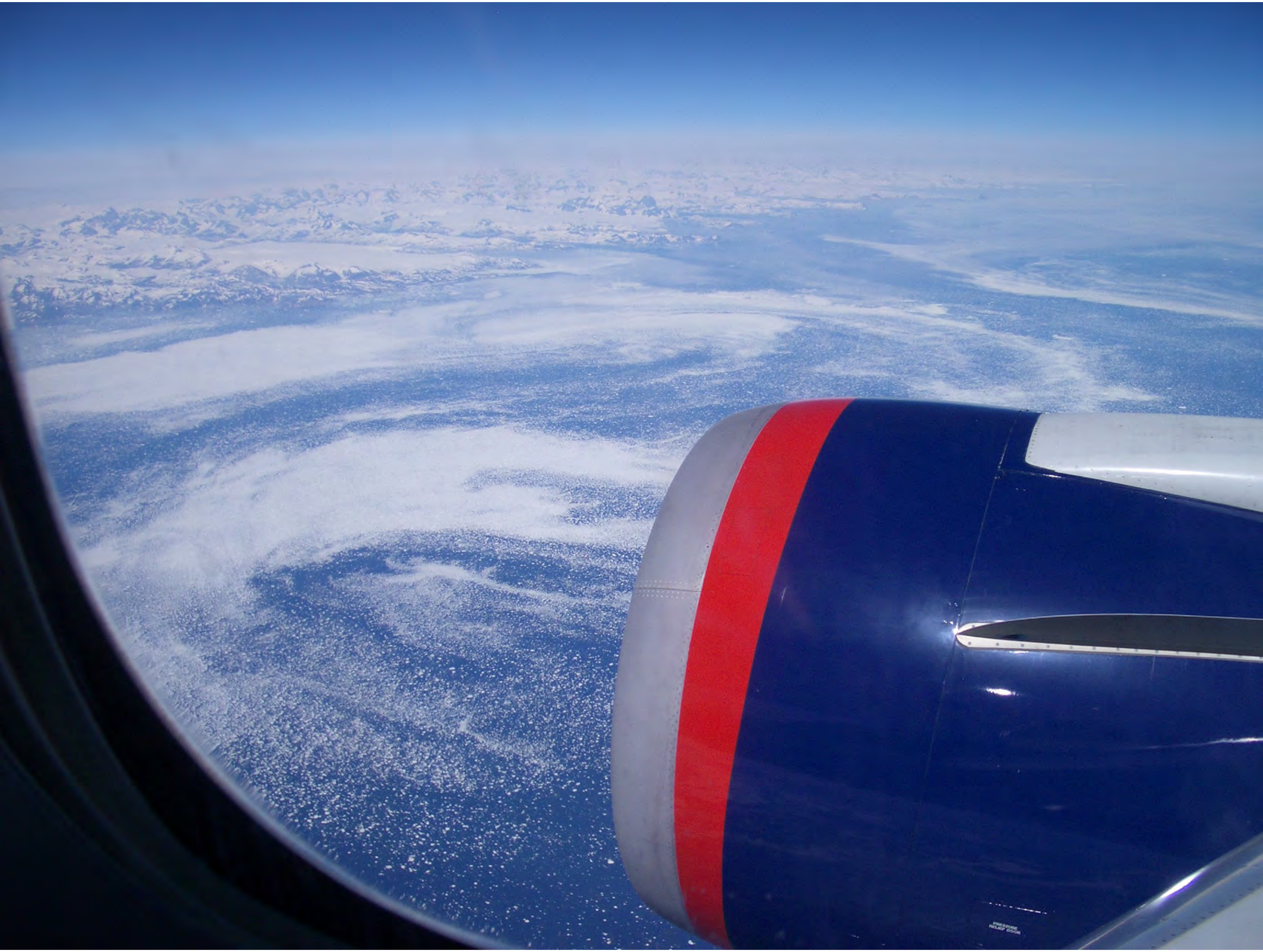
pancake ice forming in a wave field off the coast of East Antarctica

pancake ice



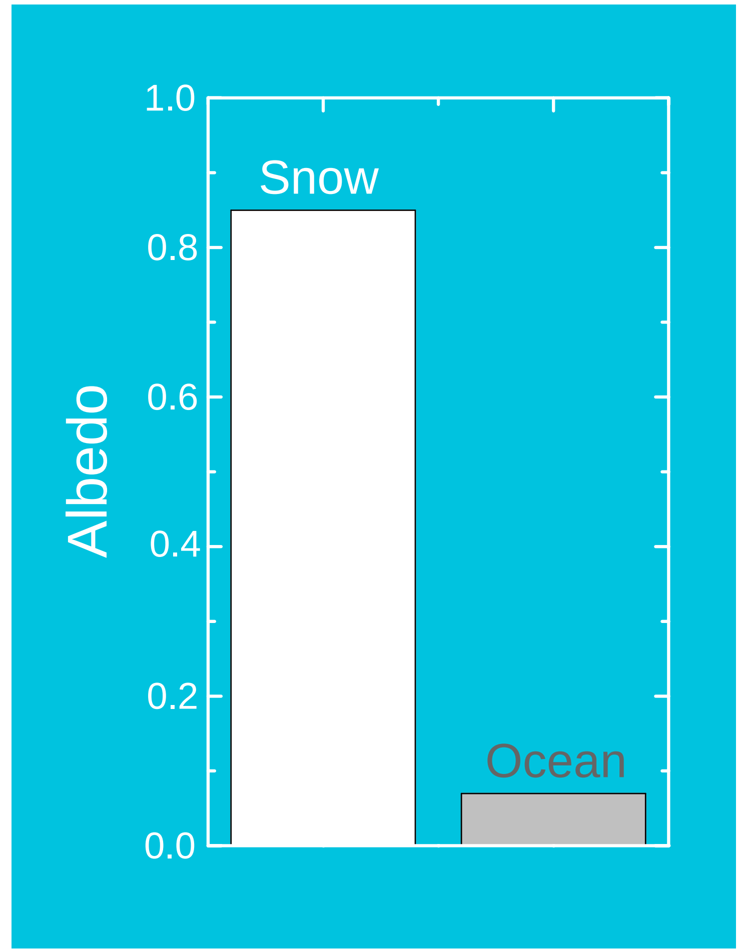
ocean swells propagating through a vast field of pancake ice

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



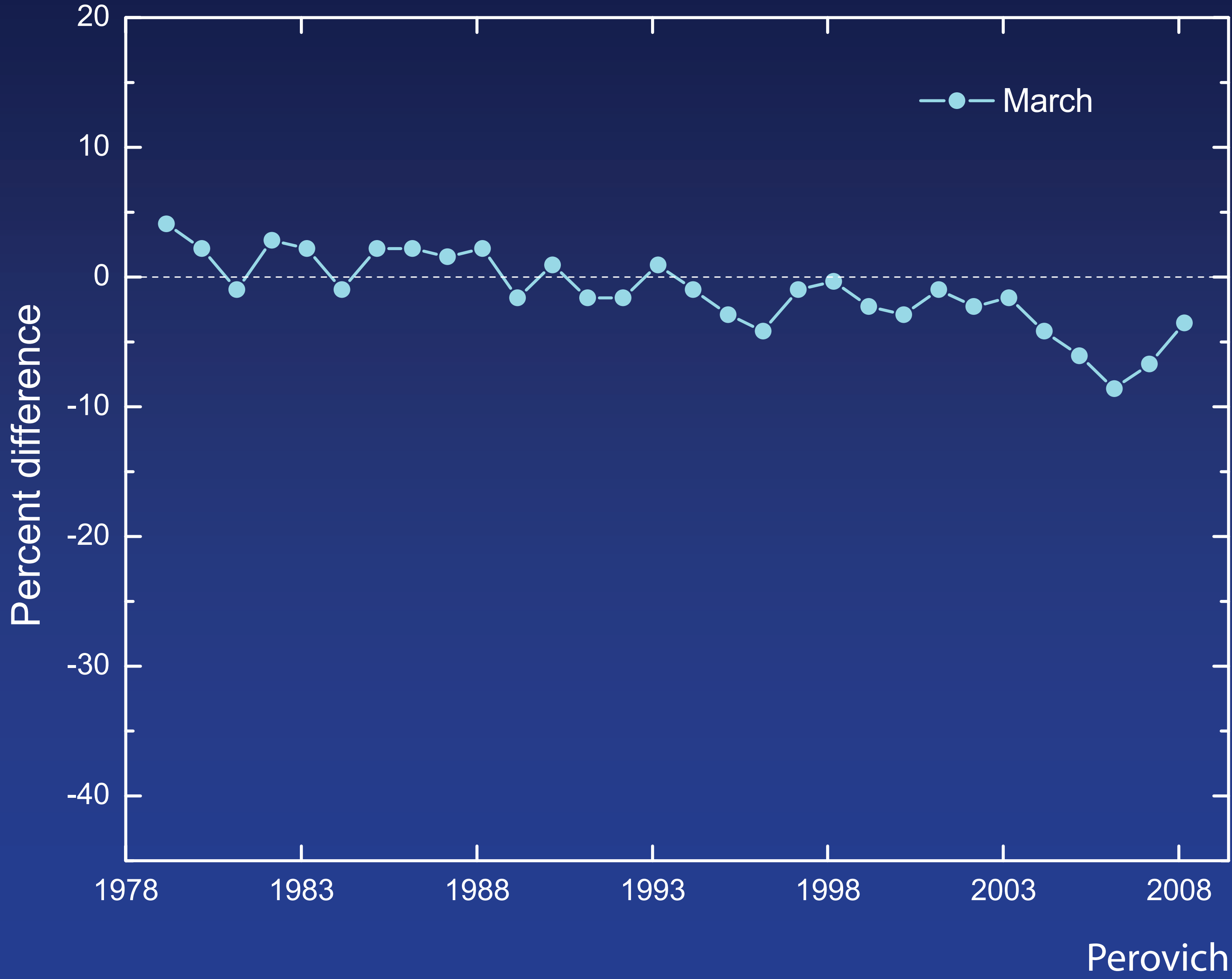
polar ice caps critical to global climate in reflecting incoming solar radiation

white snow and ice reflect

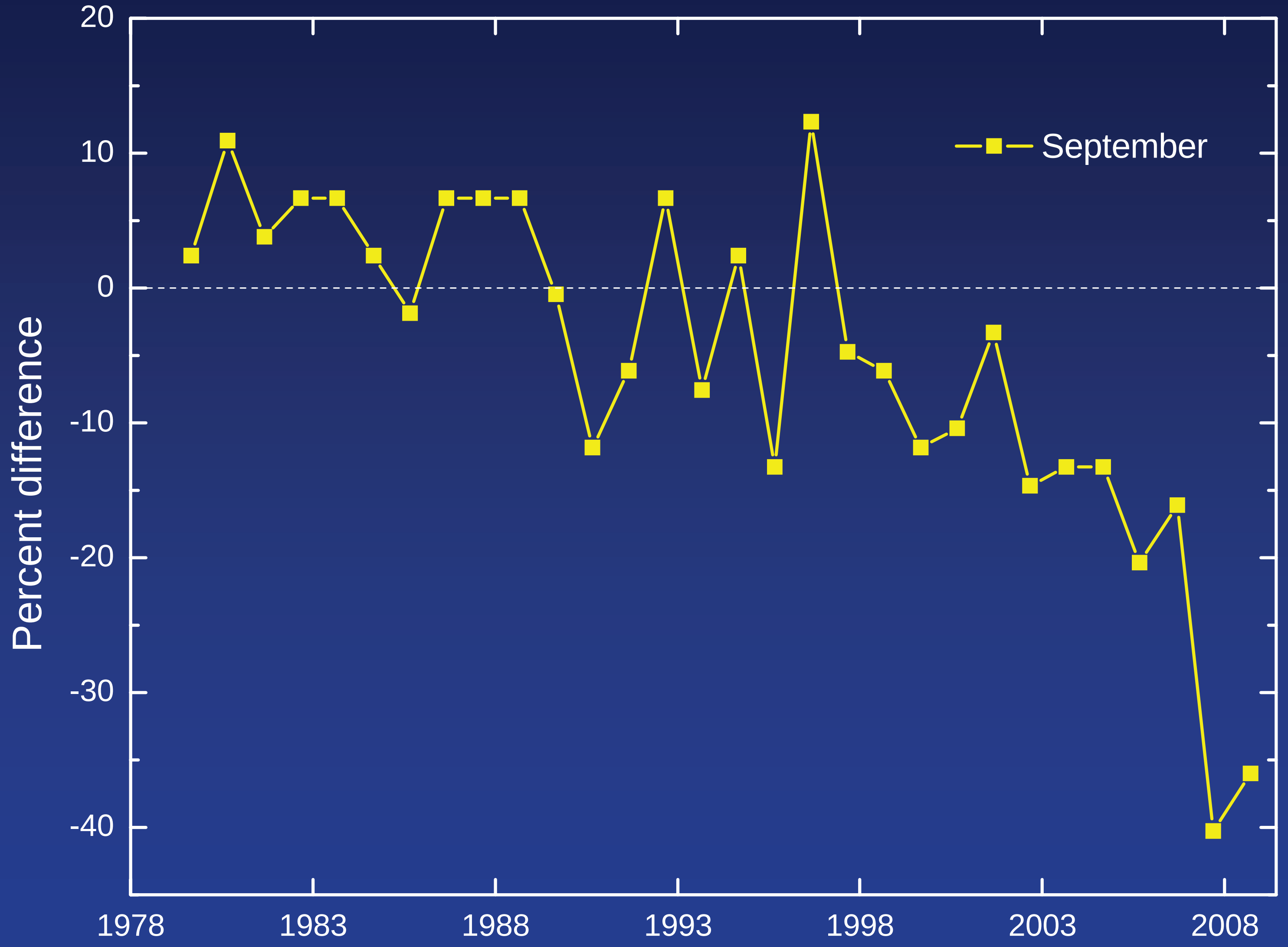


dark water and land absorb

Change in winter Arctic sea ice extent



Change in summer Arctic sea ice extent

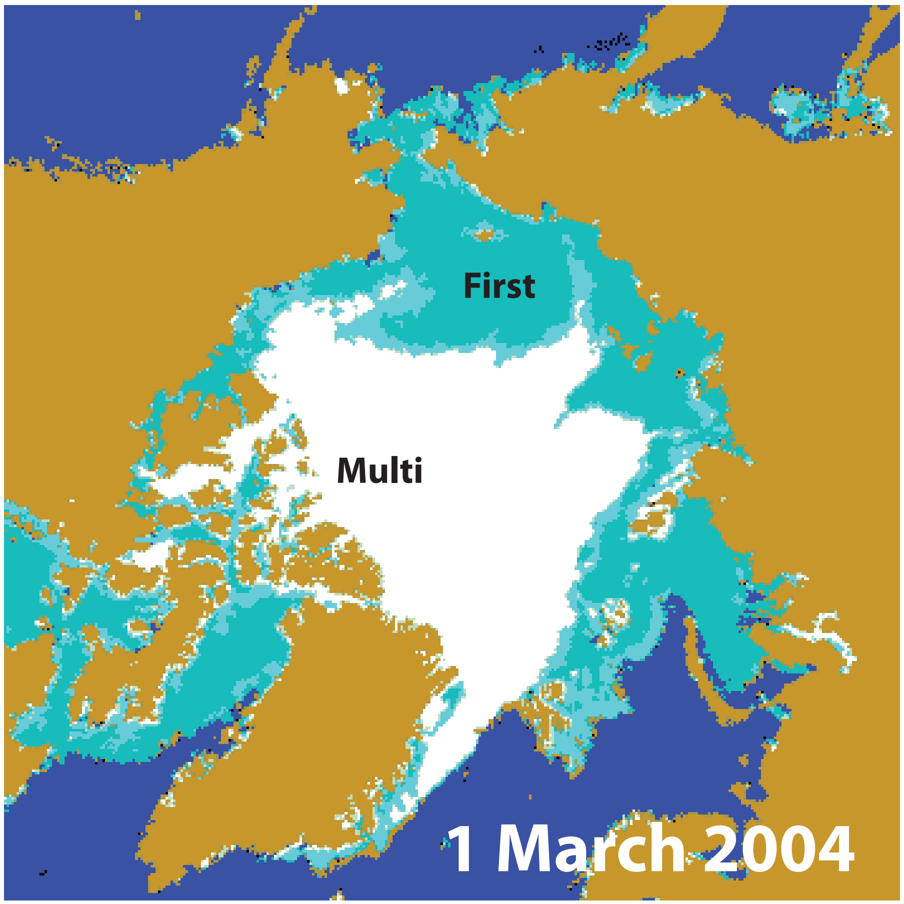


Much of the thick multiyear ice is gone.

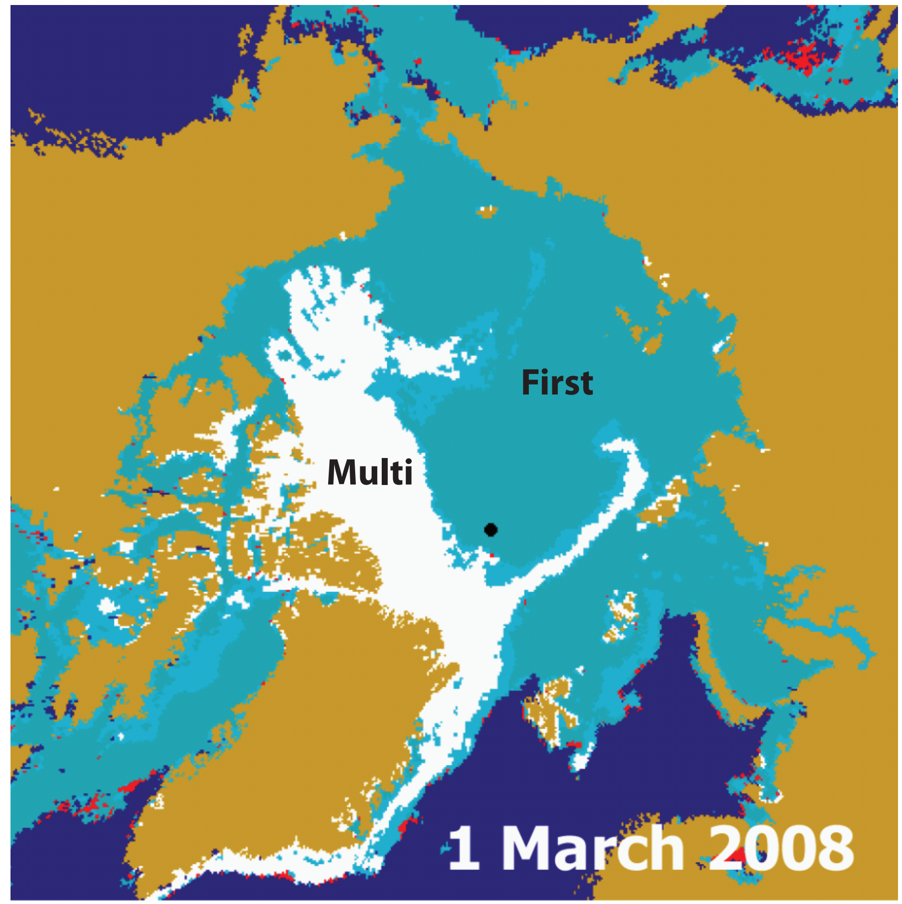
Perovich

thicker multiyear ice being replaced by thinner first year ice

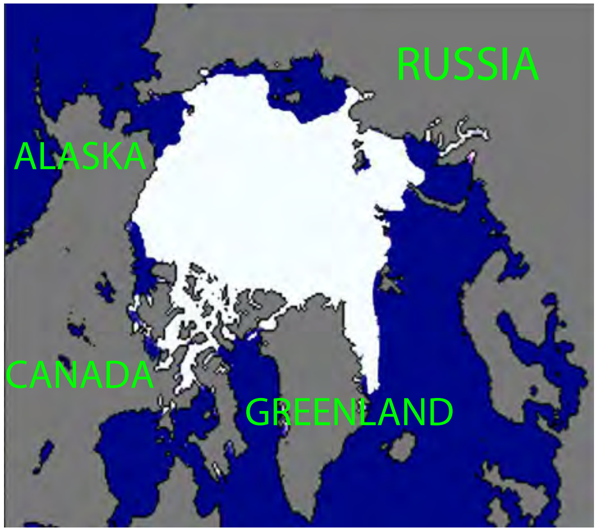
Winter 2004

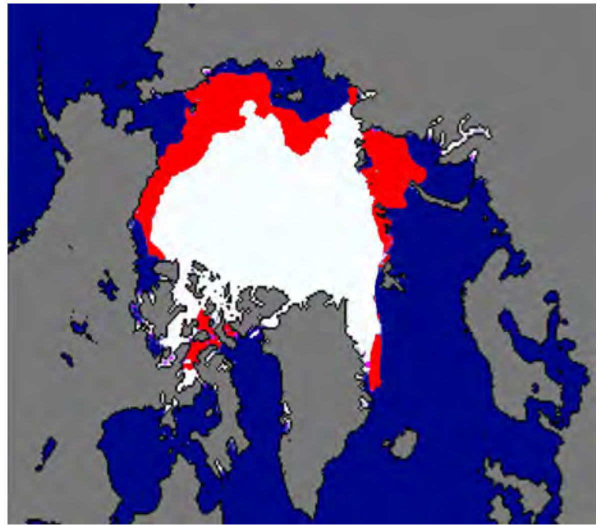


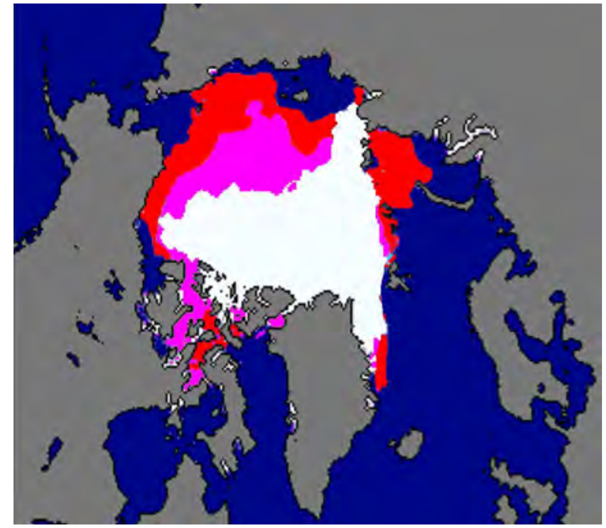
Winter 2008



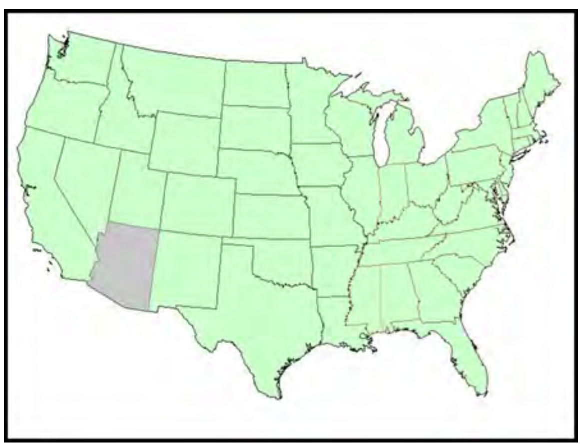
Son Nghiem

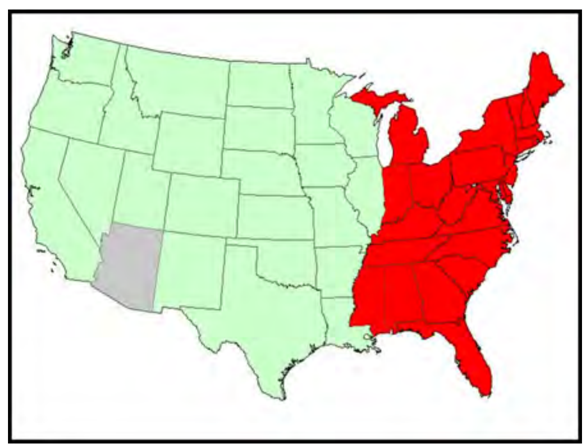


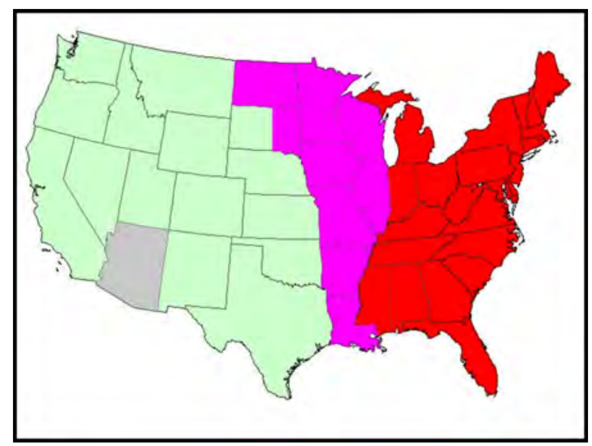




1980 2005 2007





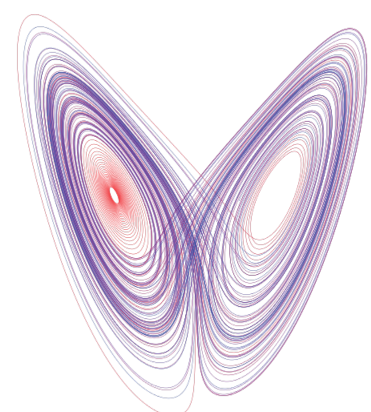


Perovich

Can Arctic sea ice rebound?

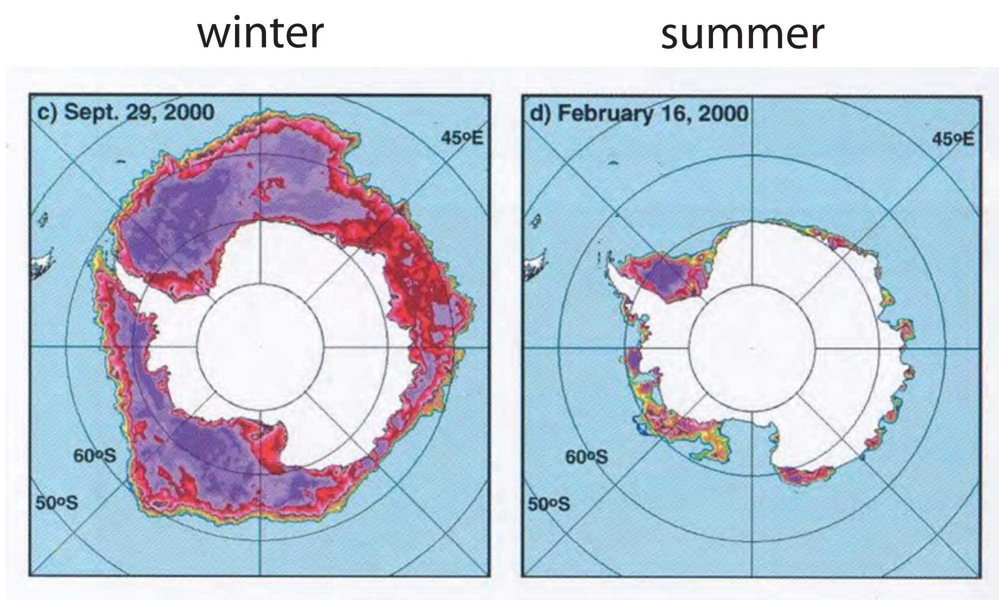
.... or have we passed a critical threshold,

a “tipping point” ?



Lorenz butterfly

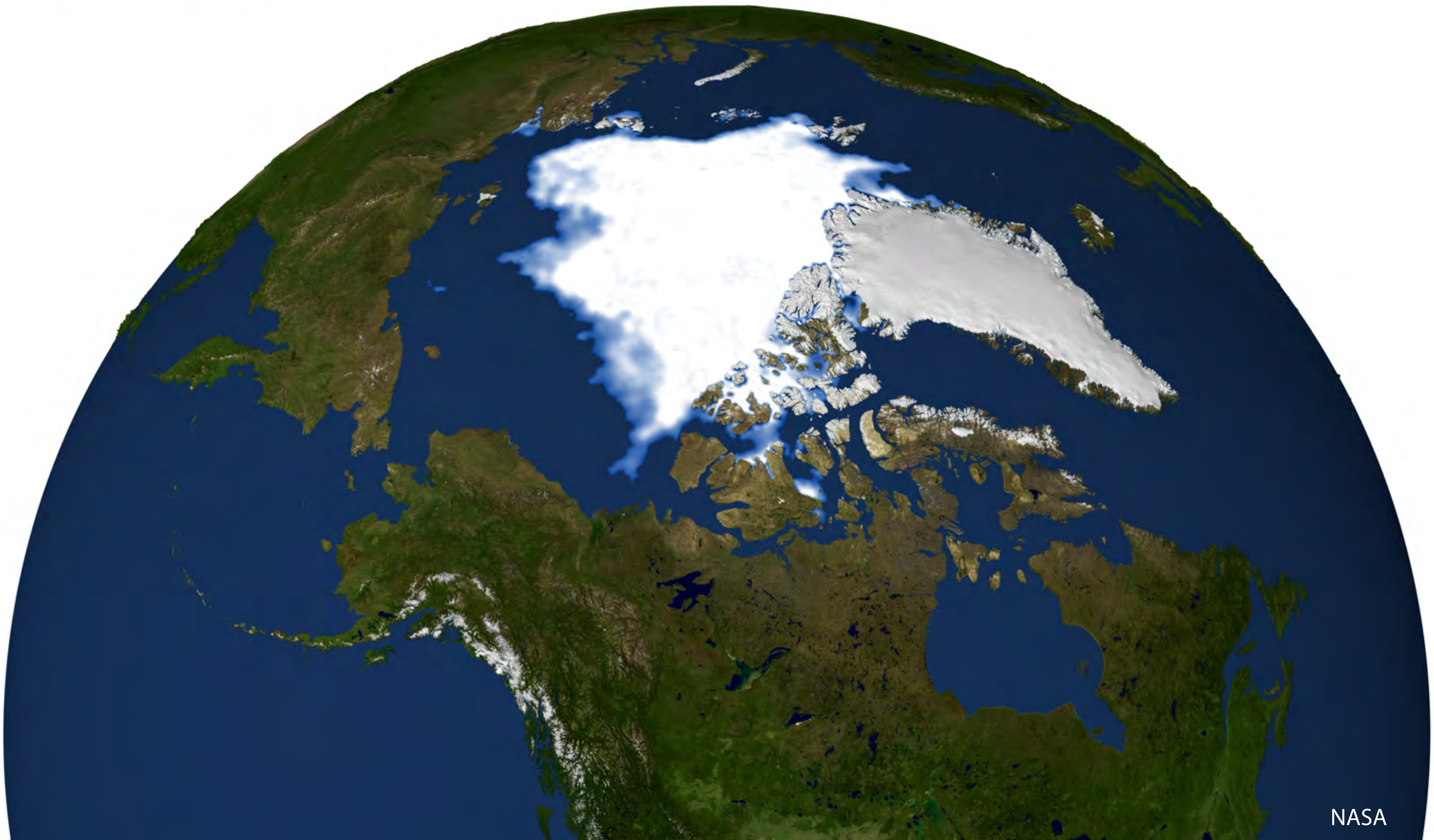
Antarctic sea ice pack is already seasonal



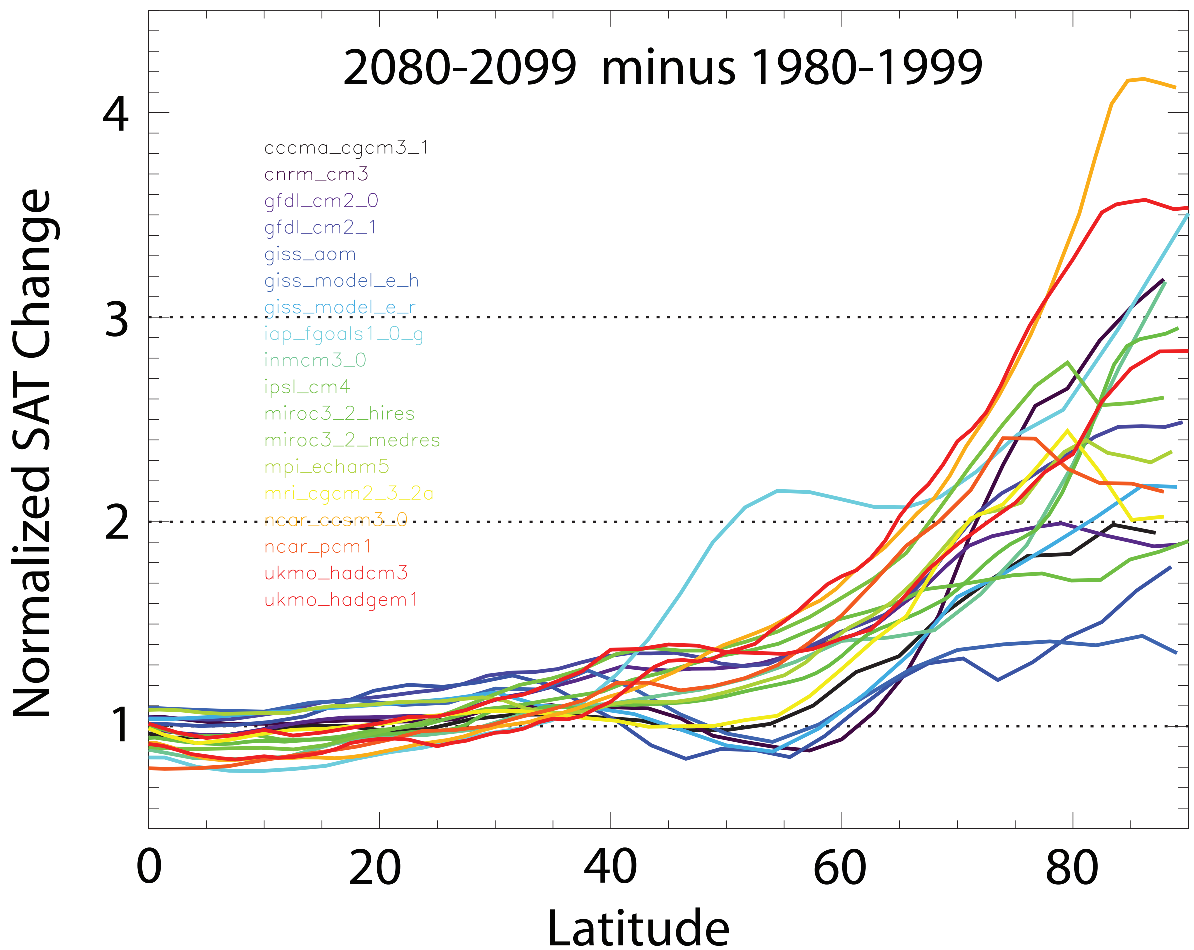
Is global warming **Antarctifying** the Arctic ?

climate change is amplified in the polar regions

14 September 2008



Polar Amplification

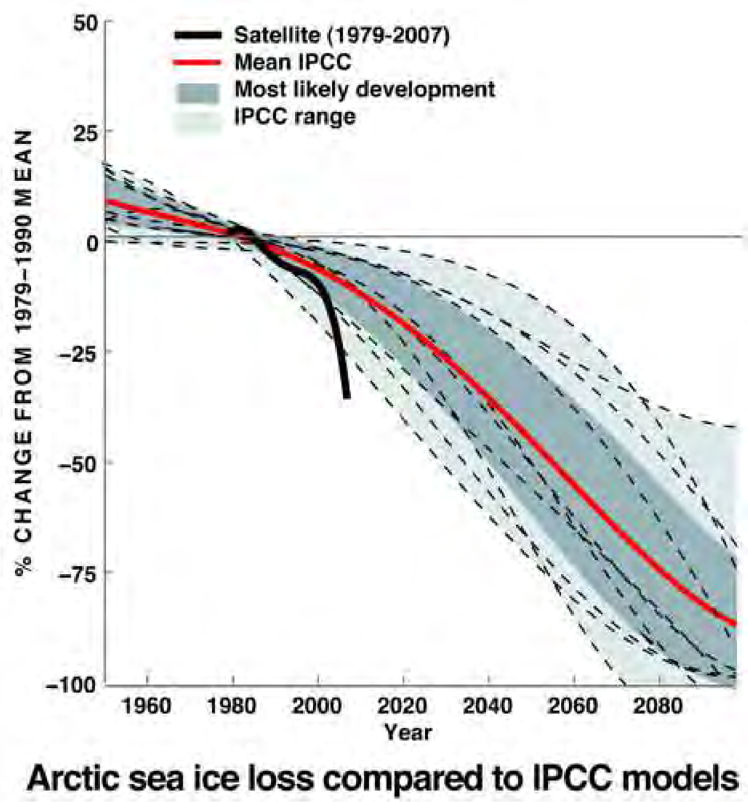


zonally averaged change in surface air temperature (SAT) normalized by the global average SAT change

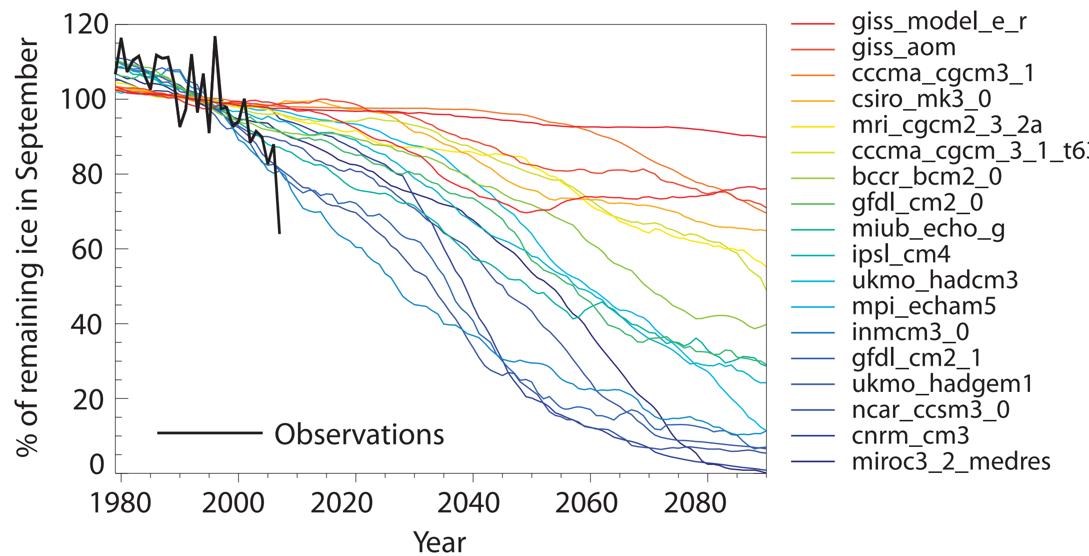
(Marika Holland, NCAR)

IPCC (Intergovernmental Panel on Climate Change) projections

global climate models ***underestimate*** observed decline in summer Arctic sea ice extent



September 2007

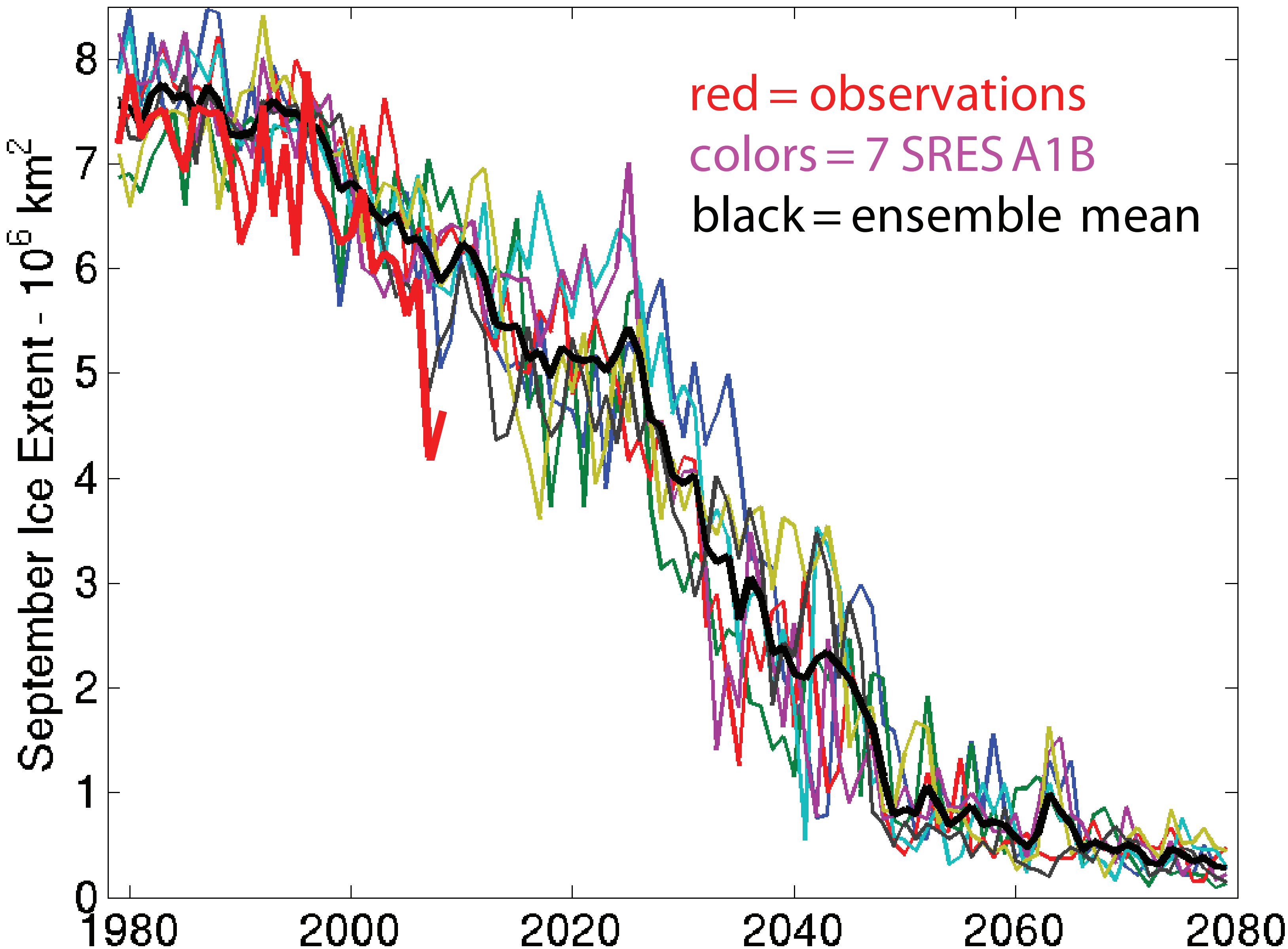


March 2009

Boé, Hall, Qu 2009

CCSM3 September Sea Ice Projections

(Community Climate System Model 3)

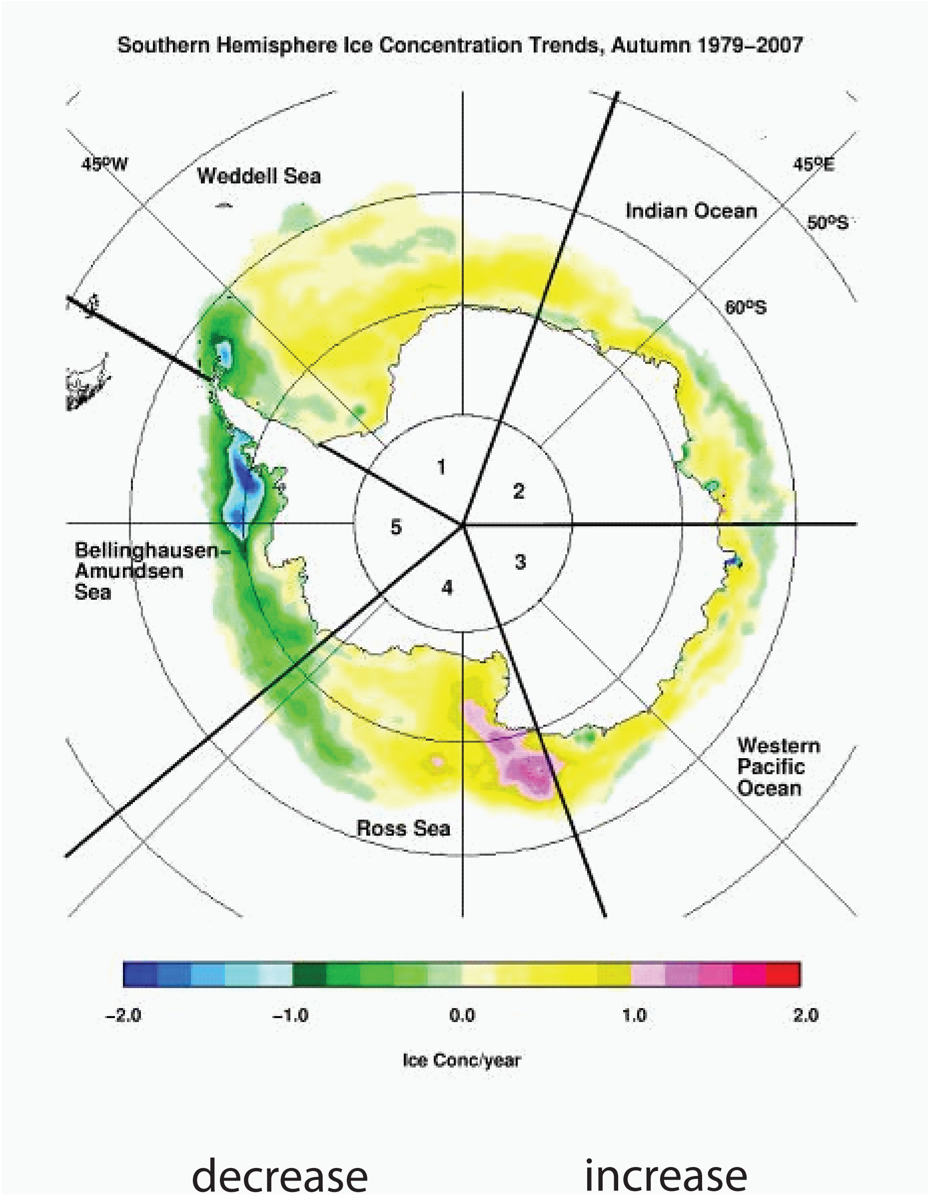


models with better physics can exhibit observed variability

Cecilia Bitz

Antarctic sea ice

climate models predict declines in annual average ice area and volume, ***however ...***



Southern Hemisphere Sea Ice Concentration Trends for Autumn 1979 – 2007

John Turner
(Tony Worby)

What is essential in a numerical sea ice model for climate studies?

Simulate the climatological mean annual cycle of the ice and snow

Represent the sensitivity to perturbations - must have the key feedbacks

Physics appropriate to the model's spatial scale, parameterizations for sub-scale behaviors

Cecilia Bitz

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

1. Ice thickness distribution evolution equation (Thorndike et al. 1975) — dynamics + thermodynamics

2. Conservation of momentum (Hibler 1979) — dynamics

3. Heat equation of sea ice and snow (Maykut and Untersteiner 1971) — thermodynamics

Sea Ice Dynamics Constitutive Law -- stress *vs.* strain relation (sea ice is treated as a continuum that is plastic at normal strain rates and viscous at very small strain rates, Hibler 1979)

sea ice flows when stress exceeds certain level

Cecilia Bitz

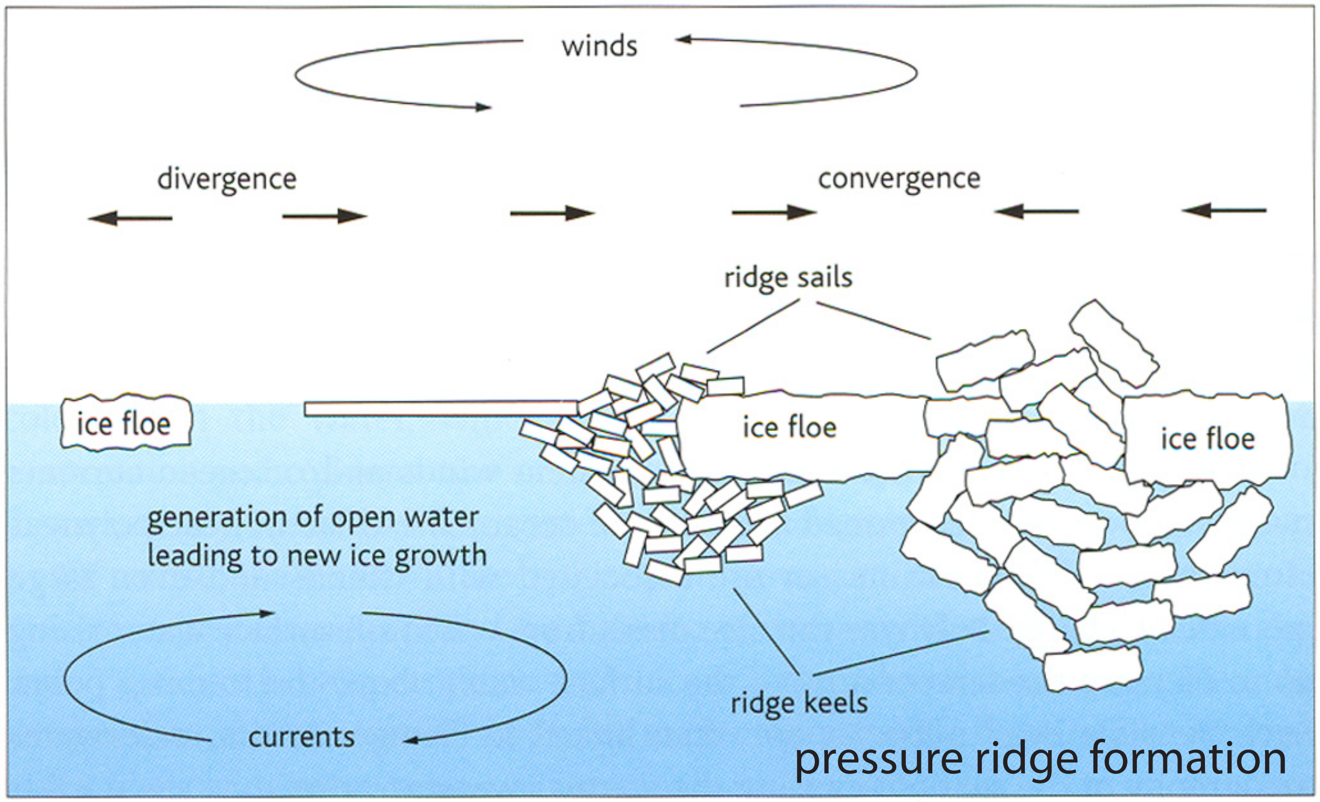
ice thickness distribution $g(x, y, h, t)$ evolution equation

$$\frac{Dg}{Dt} = -g\nabla \cdot \mathbf{u} + \Psi(g) - \frac{\partial}{\partial h}(fg) + \mathcal{L}$$

$\frac{Dg}{Dt} = \frac{\partial g}{\partial t} + \mathbf{u} \cdot \nabla g$	Lagrangian or convective derivative
$\mathbf{u}$	ice velocity field
h	ice thickness
$-g\nabla \cdot \mathbf{u}$	flux divergence
Ψ	mechanical redistribution opening and ridging
f	thermodynamic growth rate
$\frac{\partial}{\partial h}(fg)$	ice growth/melt results in *thickness advection*
$\mathcal{L}$	lateral melting

depend on g (Ψ, f, $\frac{\partial}{\partial h}(fg)$, $\mathcal{L}$)

dynamically modifying the ice thickness distribution



thinning

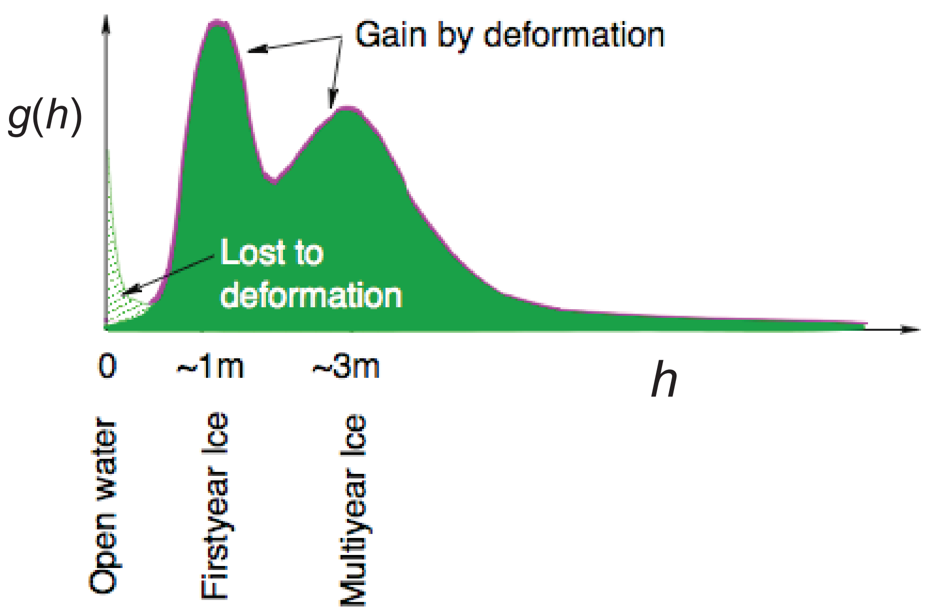
thickening

David Thomas 2004

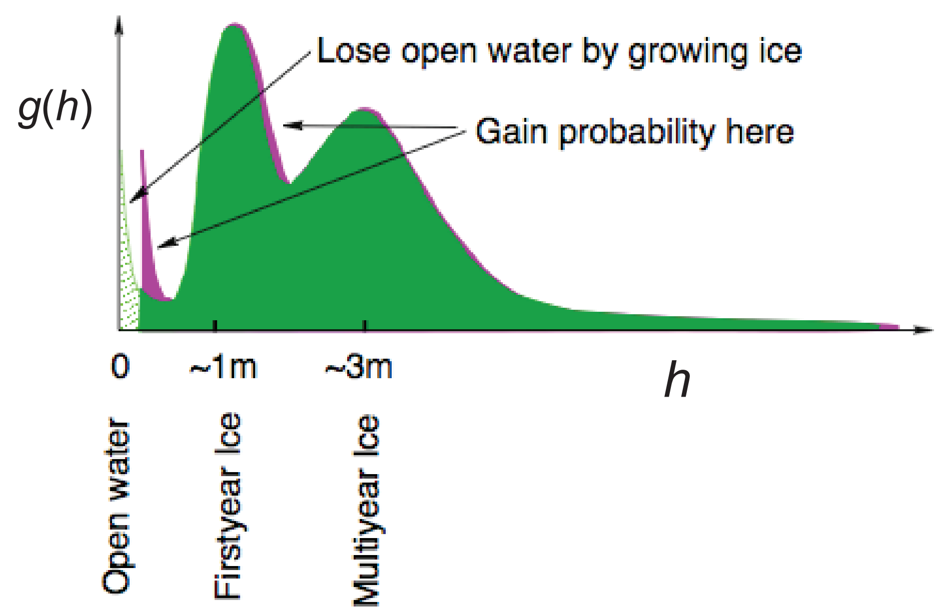
ice thickness distribution function $g(x,y,h,t)$

h = ice thickness

mechanical redistribution



advection in thickness space from growth



Cecilia Bitz

sea ice dynamics

plate tectonics on a fast time scale

measuring ice depth in ridges off Barrow, AK

dynamic sea ice

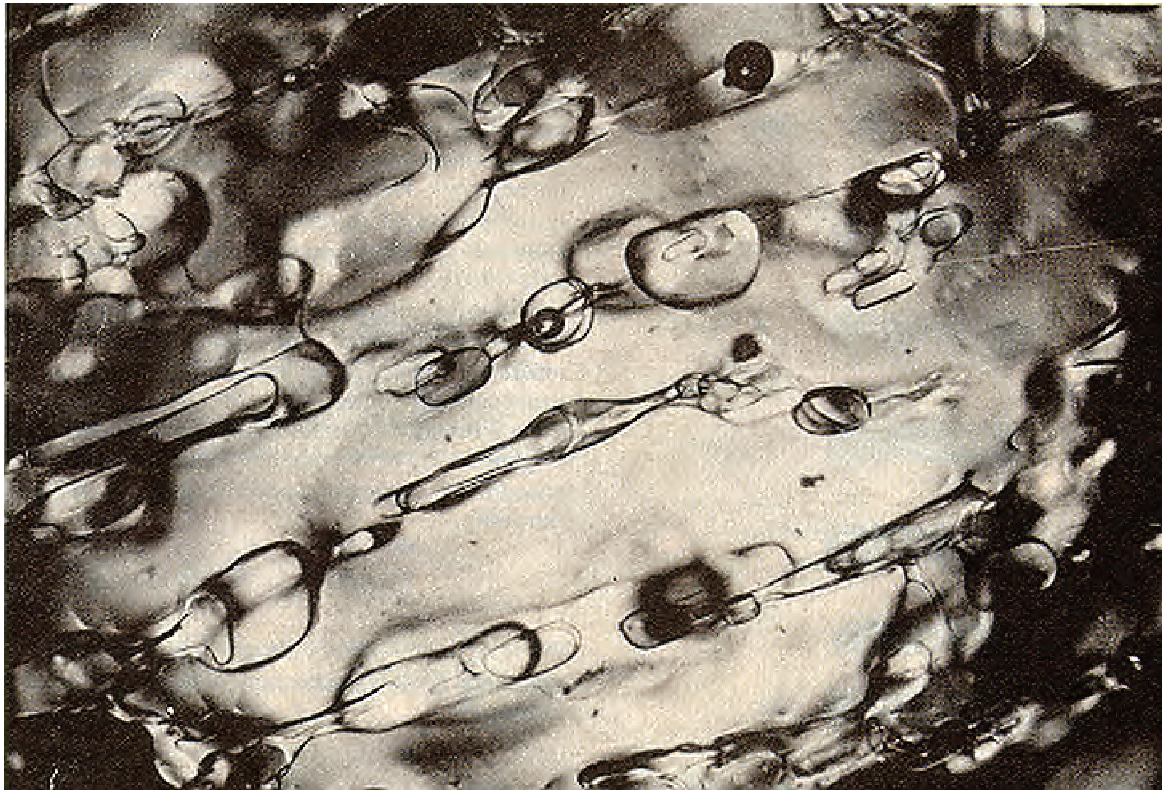
Thermodynamics: 4 ways to melt

Top, bottom, lateral, internal

Perovich

some sea ice properties and processes relevant to climate modeling

sea ice — ***composite material***

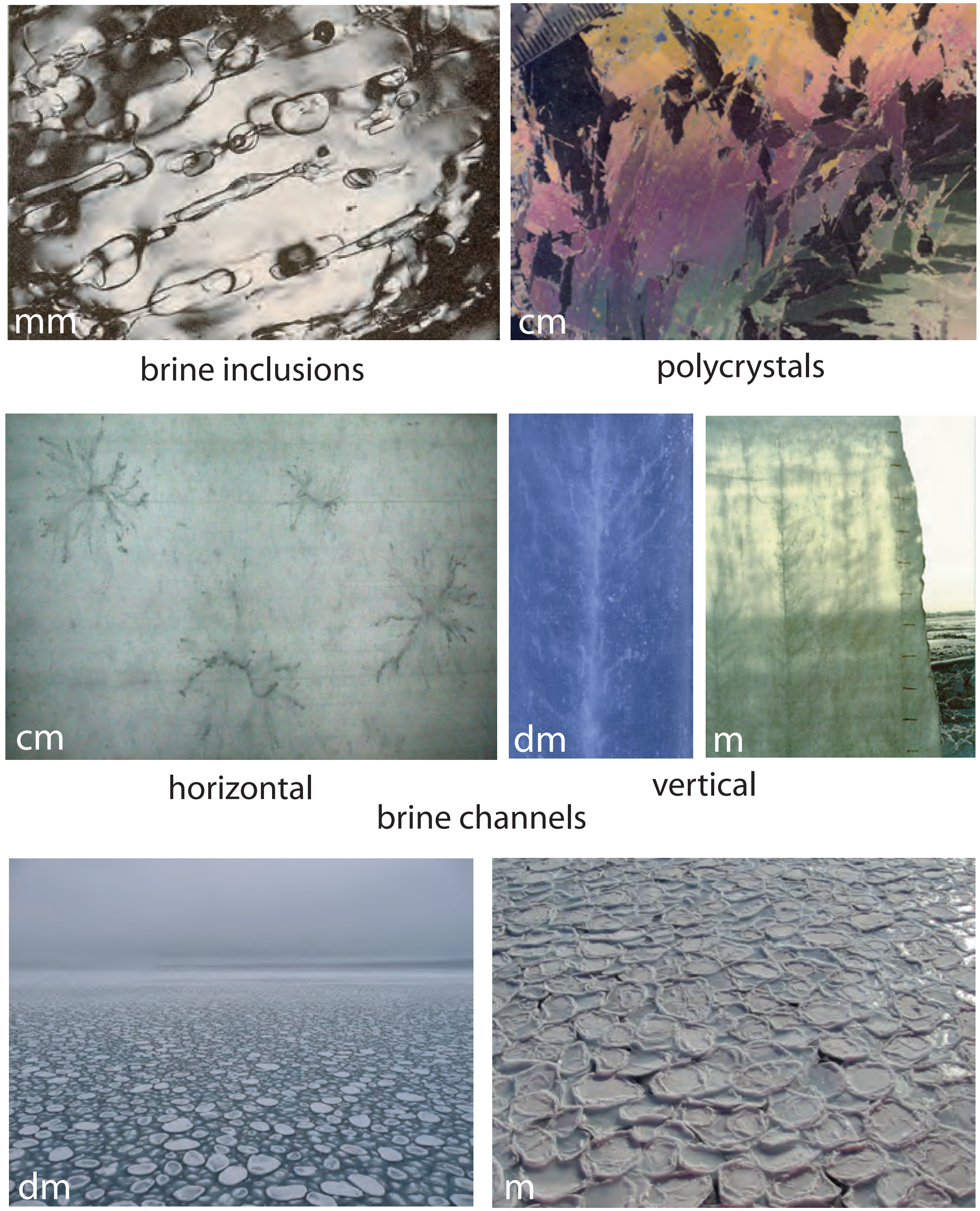


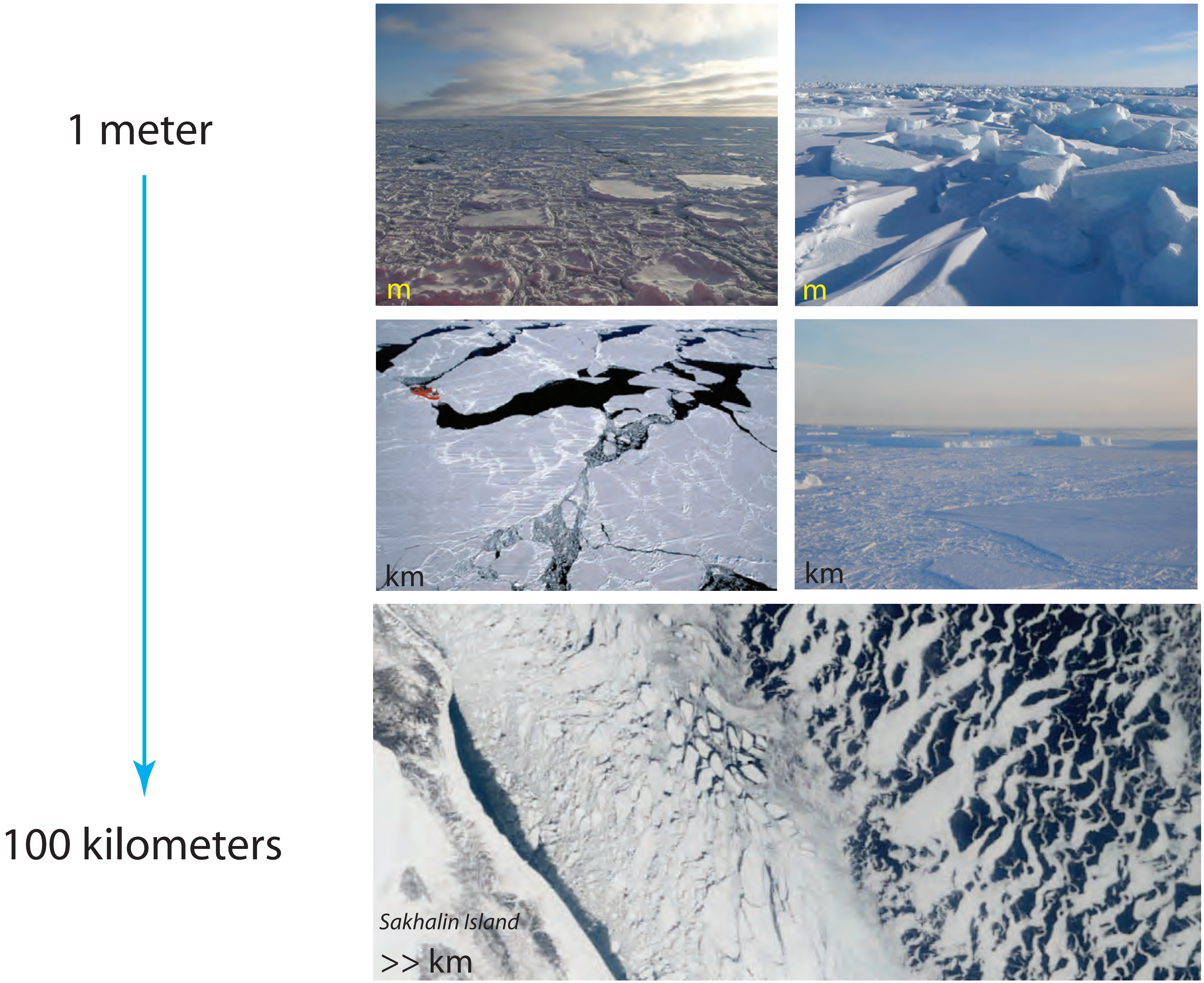
pure ice with ***brine***, air, and salt inclusions

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

0.1 millimeter

1 meter



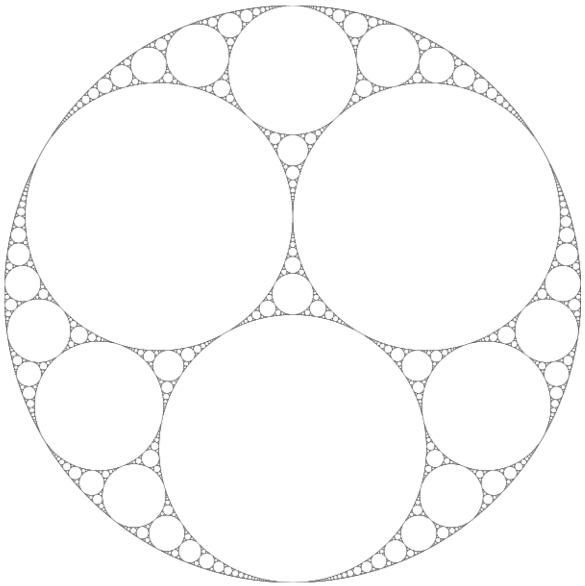

1 meter
100 kilometers
m
m
km
km
Sakhalin Island
>> km

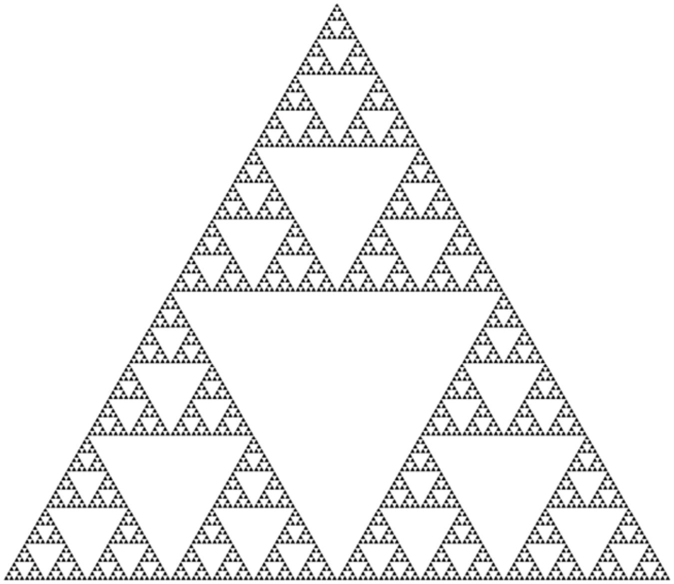
the sea ice pack is a ***fractal***

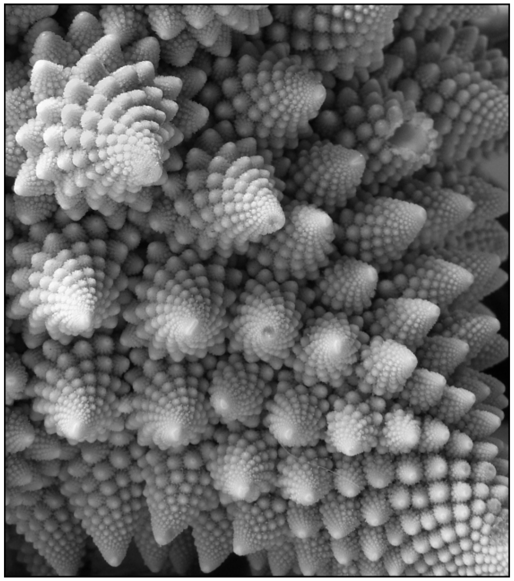
displaying self-similar structure on many scales

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

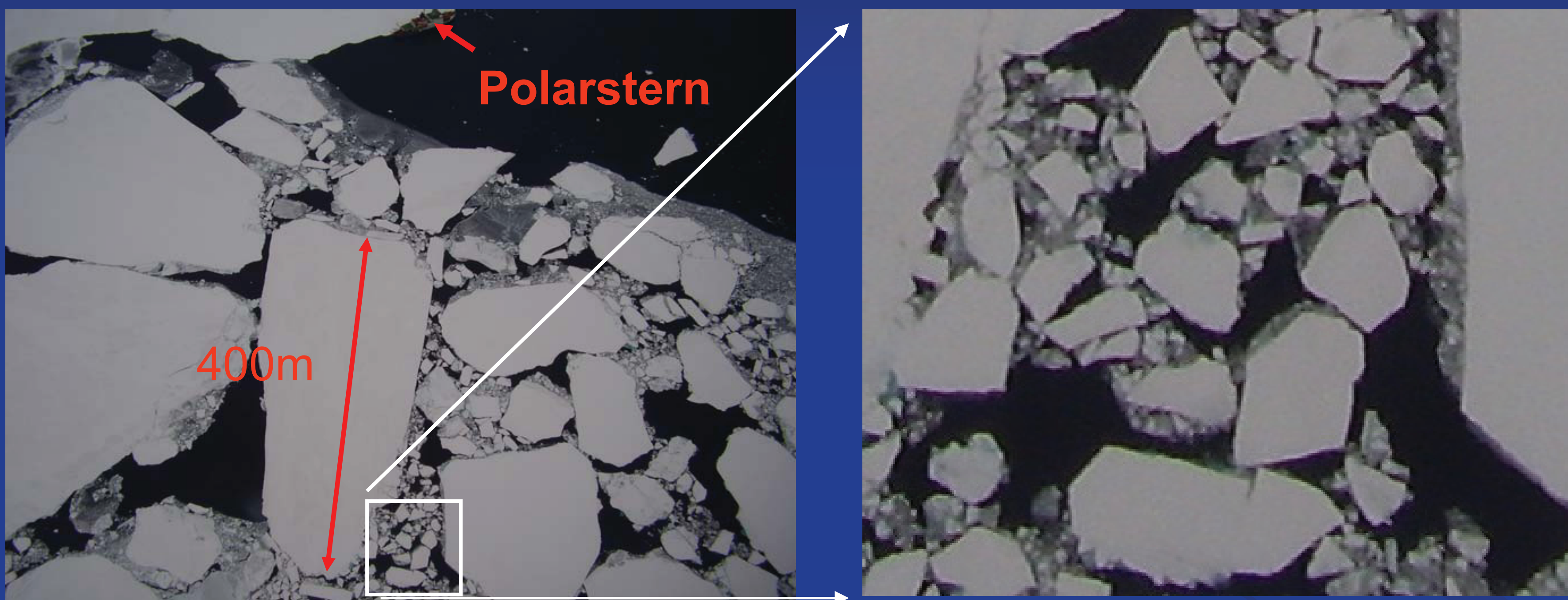
bigger floes easier to break, smaller floes easier to melt







Self-similarity of sea ice floes



Weddell Sea, Antarctica 2006

two regimes for fractal dimension
floe sizes 1 - 20 m; 100 - 1500 m

Takenobu Toyota

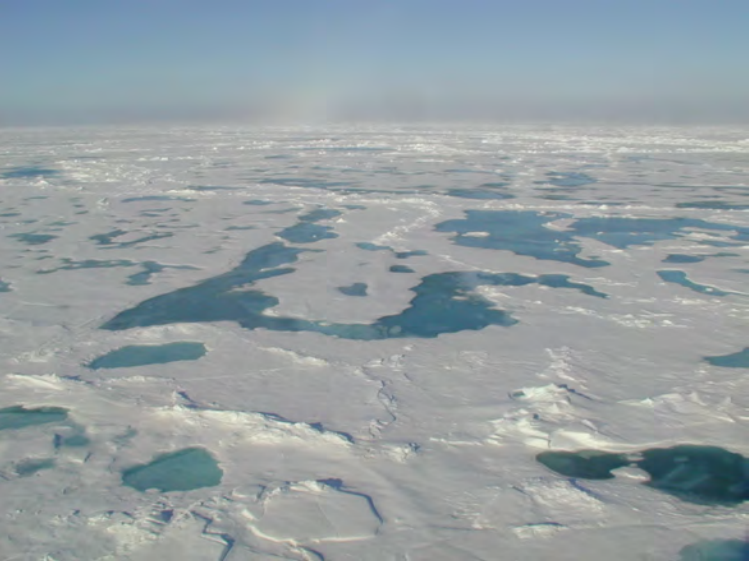
leads

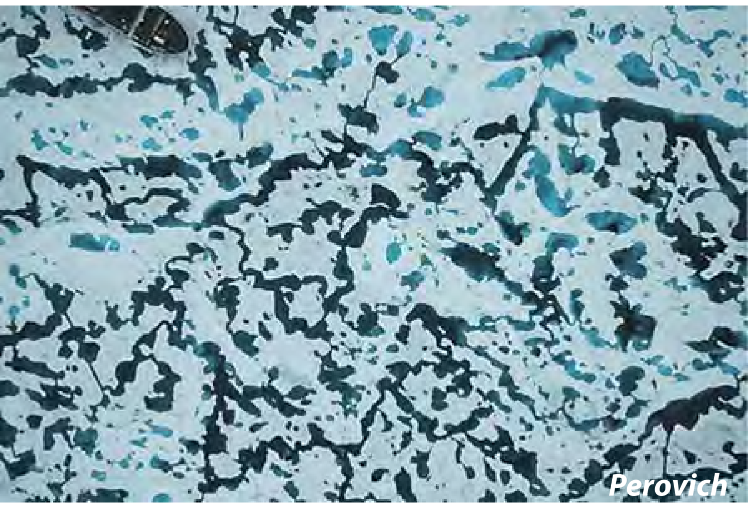
heat flows directly from ocean to atmosphere

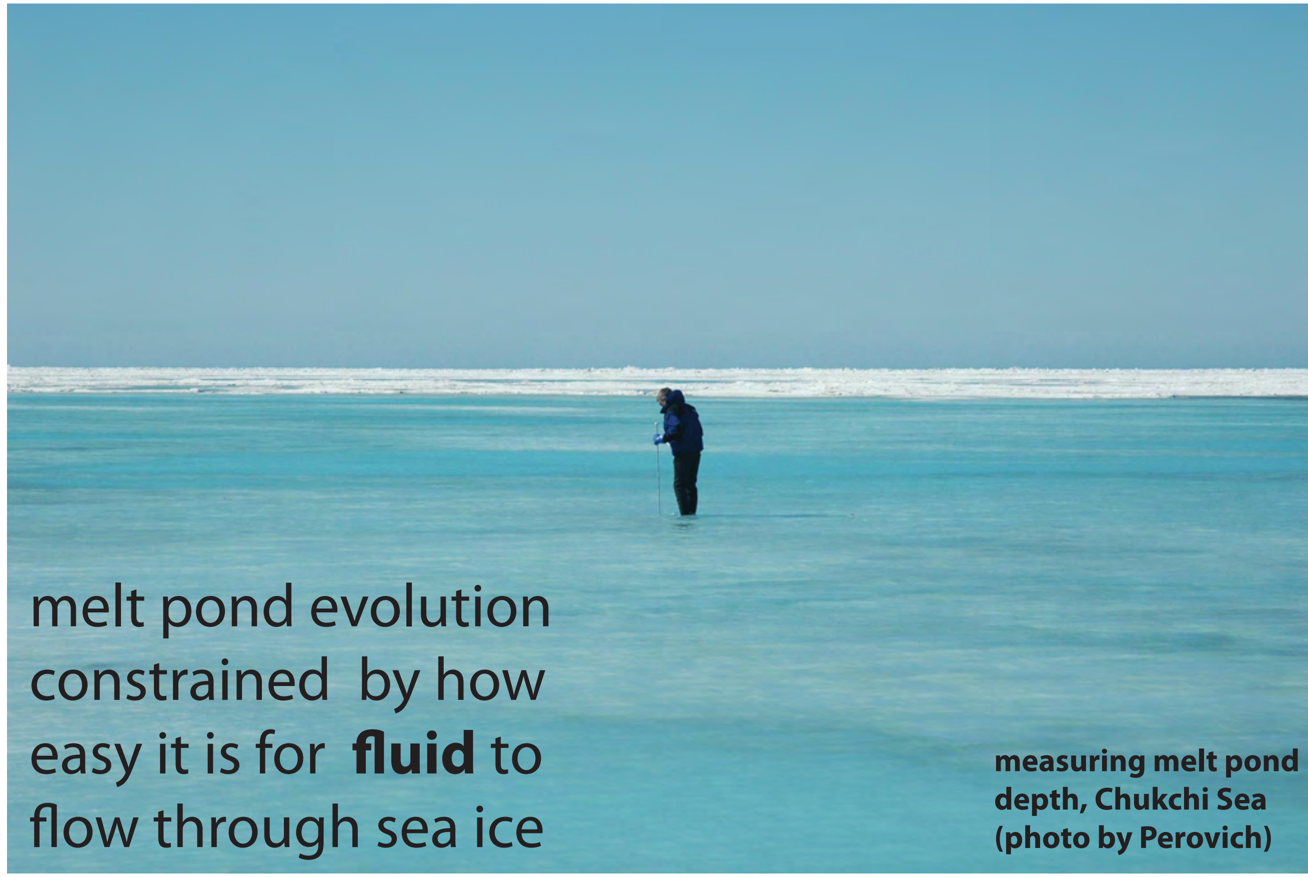
Ice albedo feedback

Perovich

sea ice albedo determined by melt ponds







melt pond evolution constrained by how easy it is for **fluid** to flow through sea ice

measuring melt pond depth, Chukchi Sea (photo by Perovich)

fluid permeability

depends on microstructure

melt pond evolution depends also on large-scale "pores" in ice cover

photos courtesy of C. Polashenski and D. Perovich

Was the Arctic ice pack ***preconditioned*** for dramatic declines?

1. Anomalous export of sea ice through Fram Strait during 1990’s

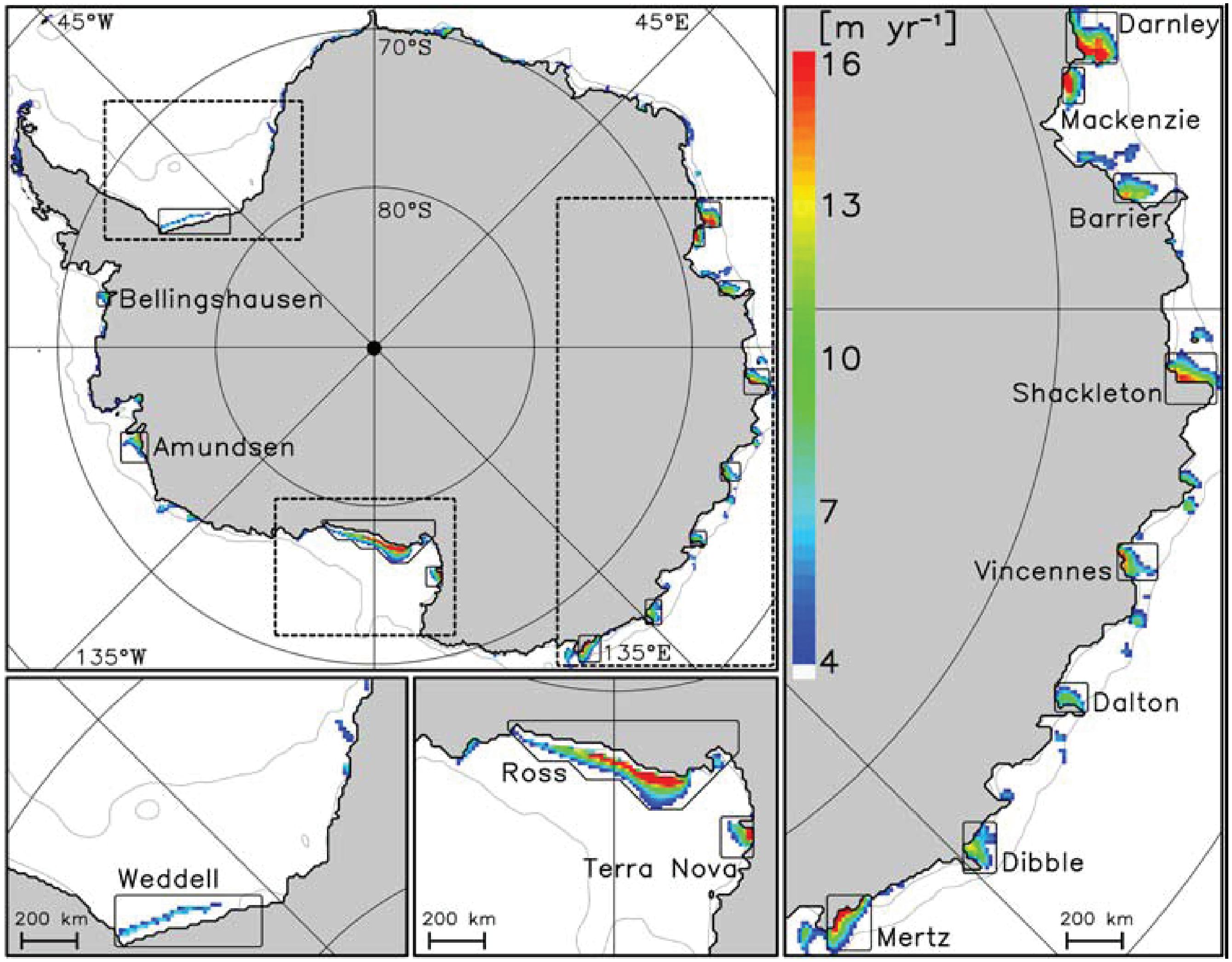
2. Oceanic heat accumulation in Western Arctic via advection from Pacific and Atlantic perhaps critical factor in thinning the ice pack

(need higher resolution Arctic Ocean models and better ice thickness data)

making the pack more susceptible to ice-albedo feedback

Wieslaw Maslowski

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

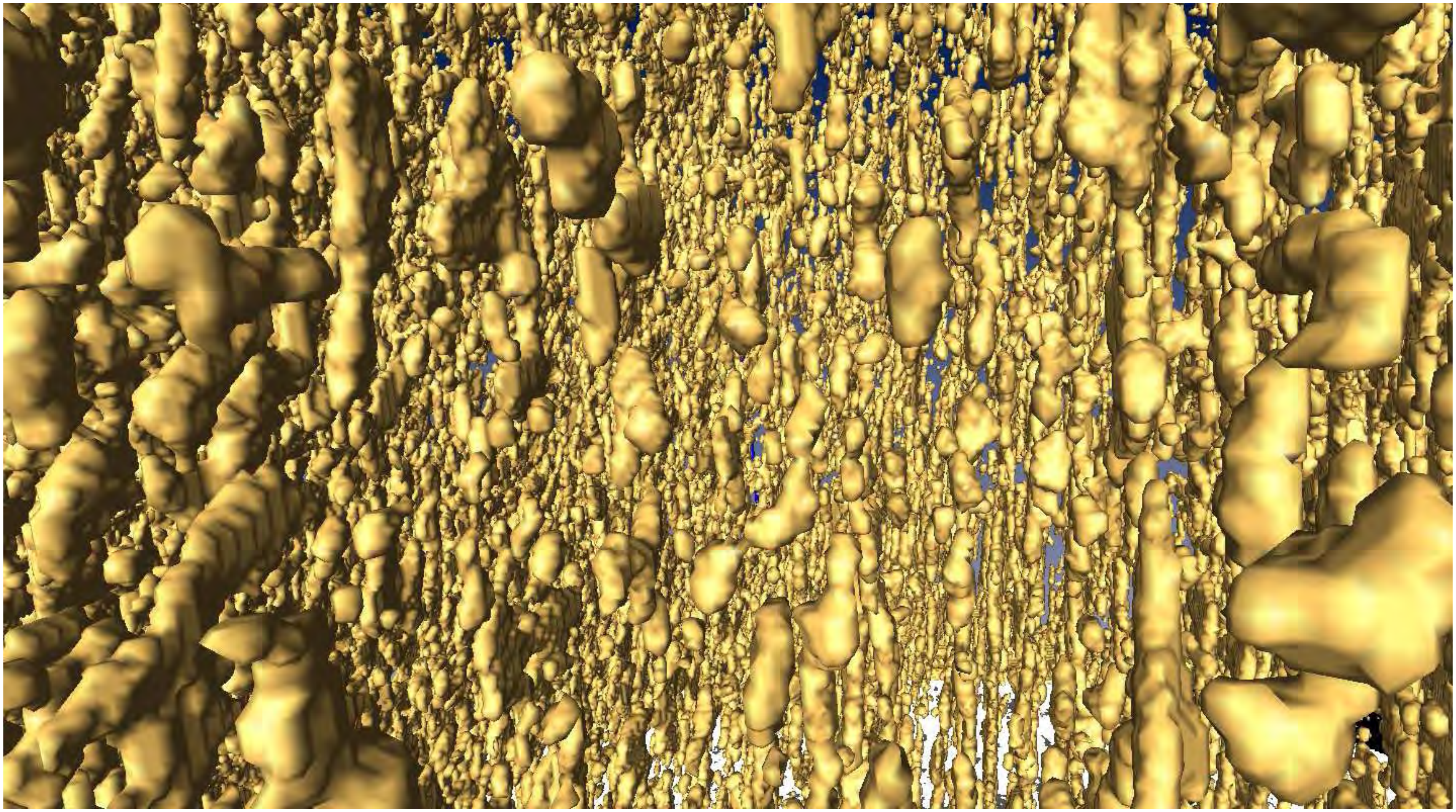
Tamura, Ohshima, Nihashi, GRL 2008

sea ice microphysics

fluid transport

X-ray computed tomography of brine inclusions in sea ice

~ 1 cm across



brine volume fraction $\phi = 5.7\ \%$ $T = -8^{\circ}C$

Golden, Eicken, Heaton, Miner, Pringle, Zhu, *Geophys. Res. Lett.* 2007

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

averaged fluid velocity

pressure gradient

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

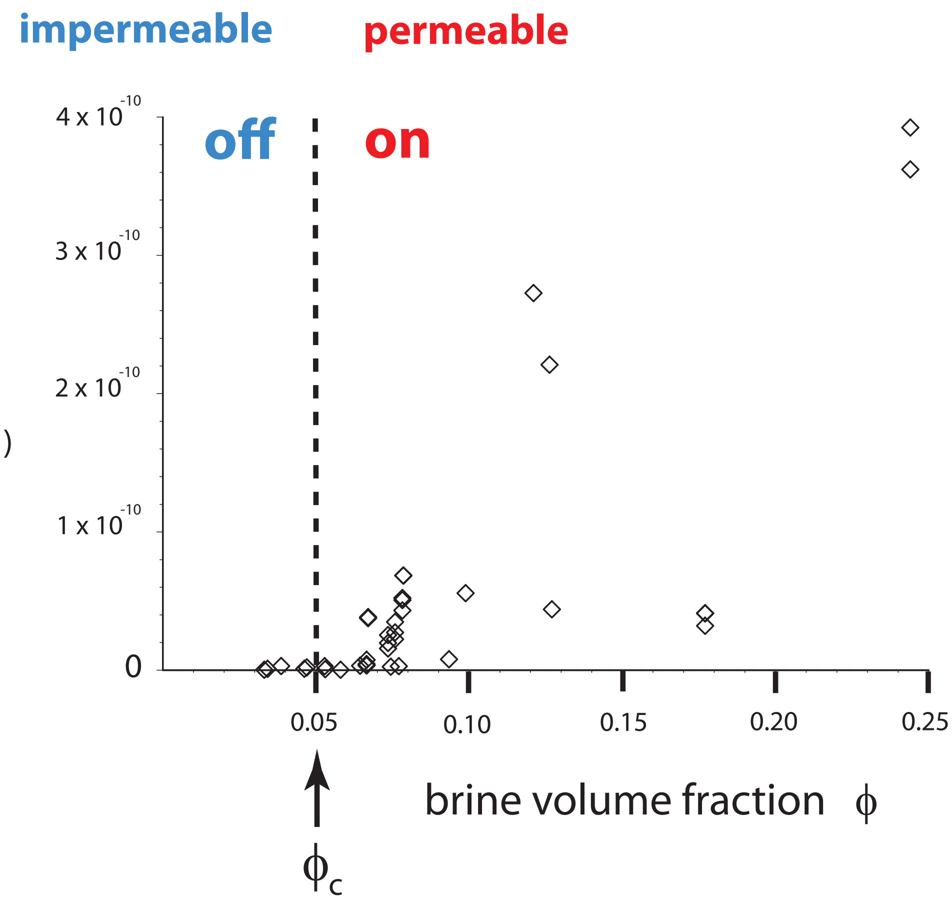
viscosity

$\mathbf{k}$ = fluid permeability tensor

example of *homogenization*

mathematics for analyzing effective behavior of heterogeneous systems

Critical behavior of fluid transport in sea ice



Arctic field data

vertical fluid permeability k (m ^{2})

on - off switch for fluid flow

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

RULE OF FIVES

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

The ***on-off*** switch constrains a broad range of proceses:

1. evolution of melt ponds and ice albedo

2. surface flooding and snow-ice formation

3. evolution of salinity profiles and brine drainage

4. transport of heat and gases (CO_2)

5. microbial activity, nutrient replenishment

6. electromagnetic signatures, remote sensing

What must we understand better about

sea ice processes & air-ice-ocean interactions

to improve climate projections?

What must be represented more realistically in models?

linkage of scales

e.g. microstructure → permeability → melt pond evolution

→ ice pack albedo → sea ice trajectory → global climate

IPAM Mini-Workshop on Mathematics of Sea Ice

MONDAY

Elizabeth Hunke	Sea ice in global climate models
Kara Peterson	Leads in sea ice models
Dimitris Menemenlis	Data assimilation and large scale models
Donald Perovich	Ice-albedo feedback and melt pond evolution
Cecilia Bitz	Sea ice microphysics and brine transport

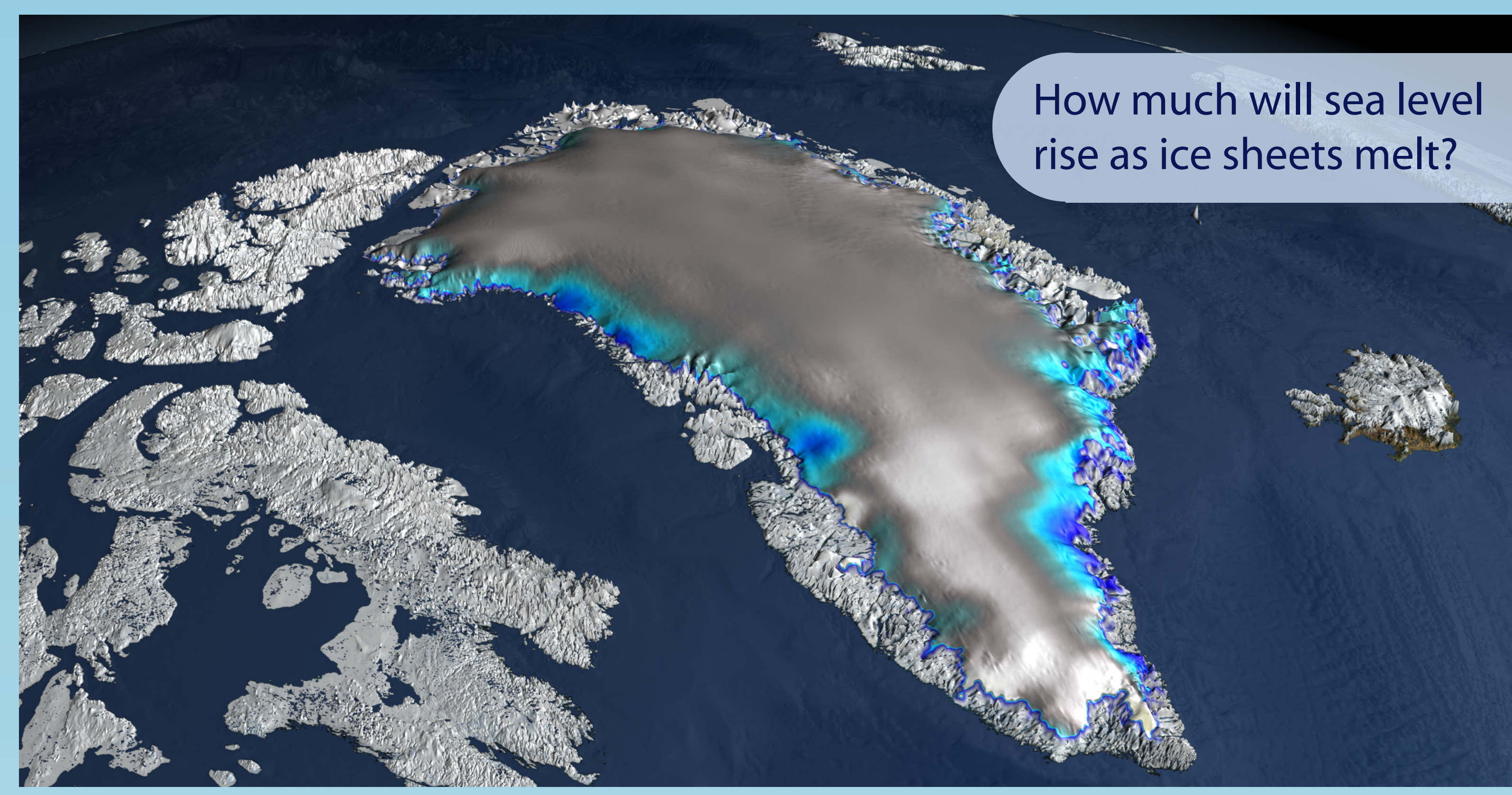
TUESDAY

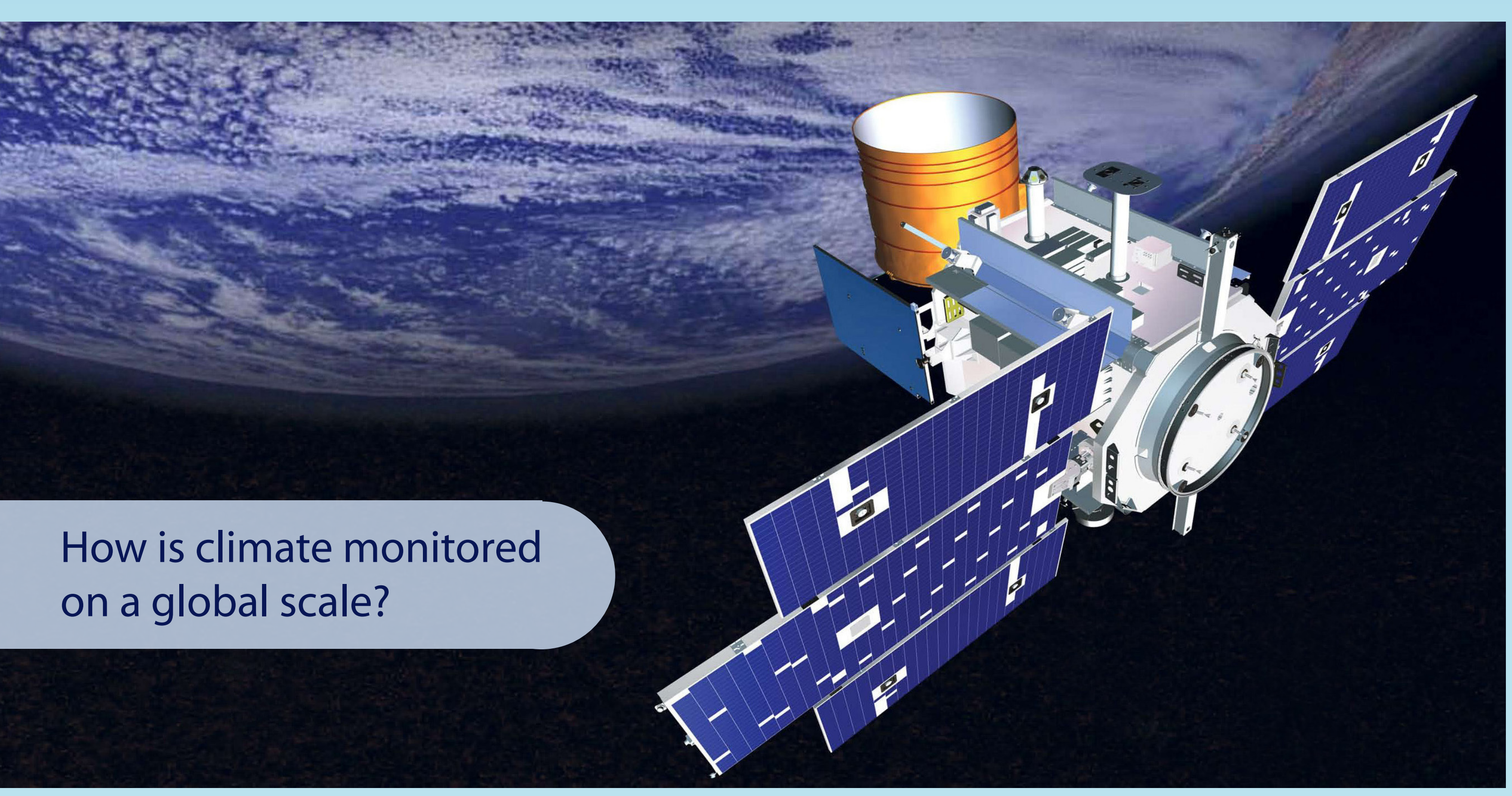
Ken Golden	Critical behavior of fluid transport in sea ice
Ted Maksym	Role of snow in the evolution of Antarctic sea ice
Ian Eisenman	Critical threshold for summer Arctic sea ice

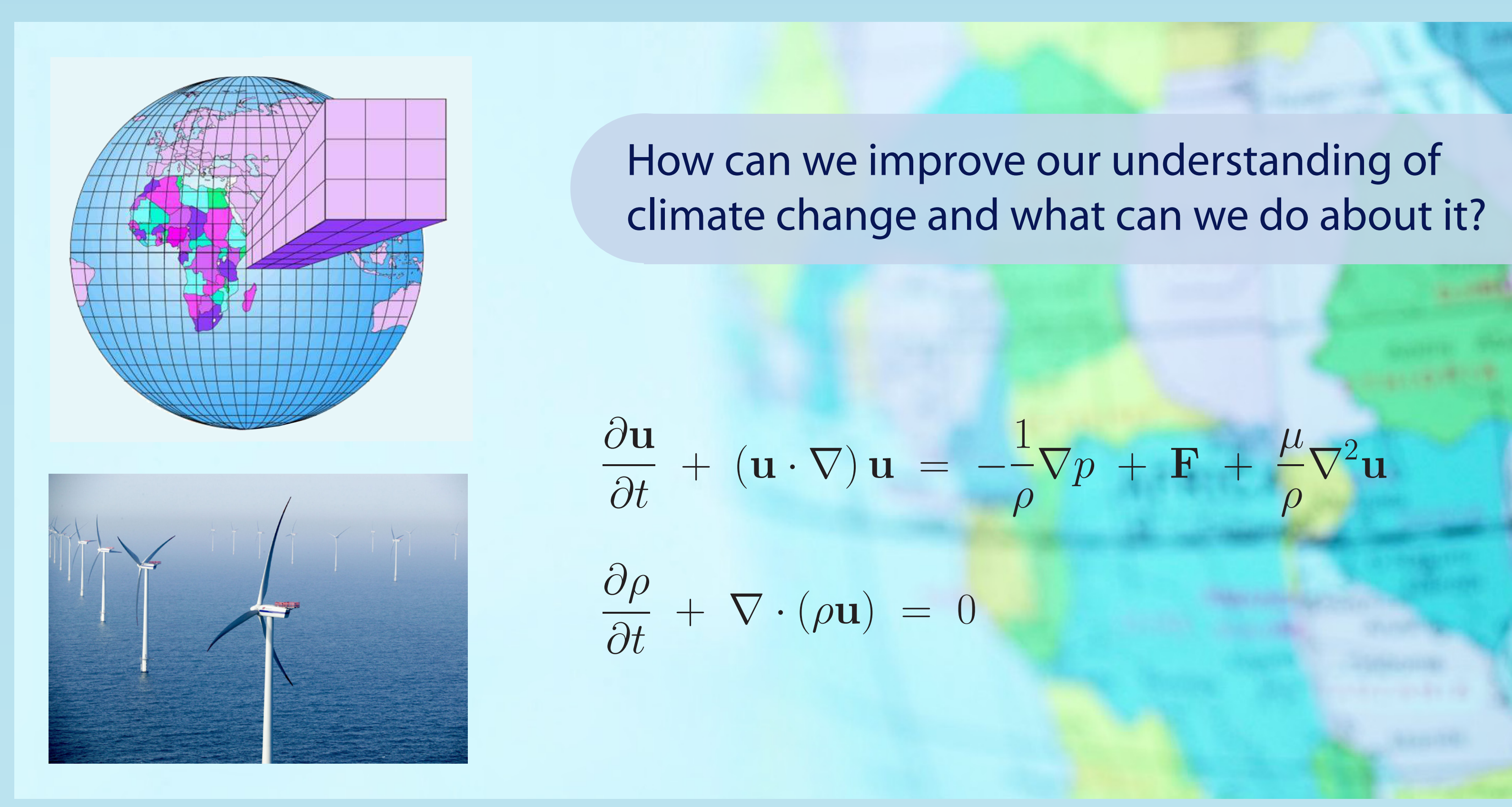
Mathematics Awareness Month - April 2009

Mathematics and Climate

Discover how math and science are used to address questions of climate change:







www.mathaware.org

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David Neelin (UCLA)
Jay Zwally (NASA)

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