Los Alamos NATIONAL LABORATORY

CLIMATE, OCEAN AND SEA ICE MODELING PROGRAM

Sea Ice Modeling: Characteristics and Processes Critical for the Radiation Budget

Elizabeth Hunke

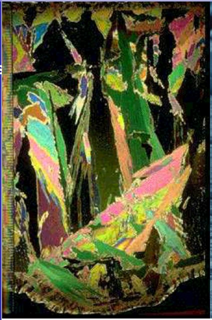
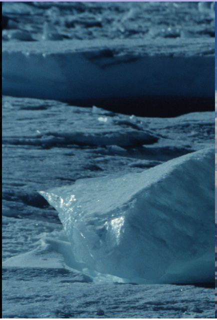
U.S. DEPARTMENT OF ENERGY
Office of Science

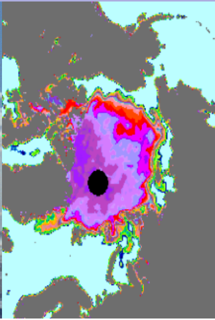
March 2015

Outline

Sea ice is frozen sea water

Sea ice scales

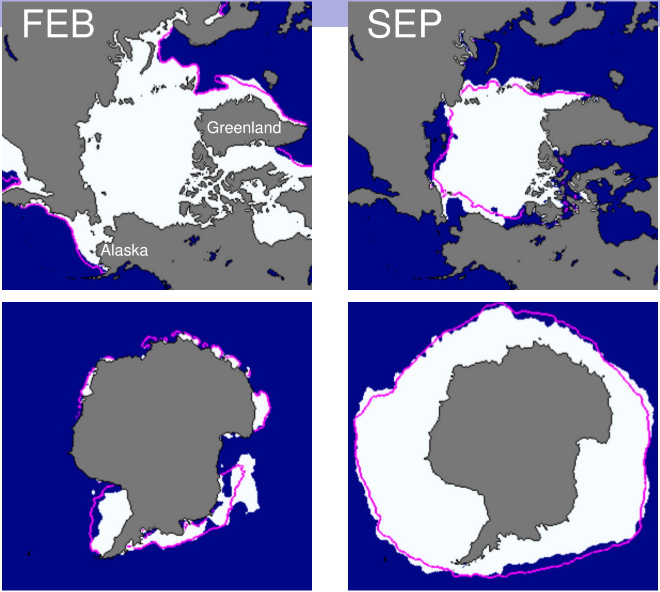


Micro	Element	Floe	Basin
< 1 cm	1 cm – 1 m	1 m – 1 km	$O(10^5$ km$)$

Sea Ice Extent

ARCTIC

ANTARCTIC



Images courtesy National Snow and Ice Data Center

Sea ice has. . .

- extent

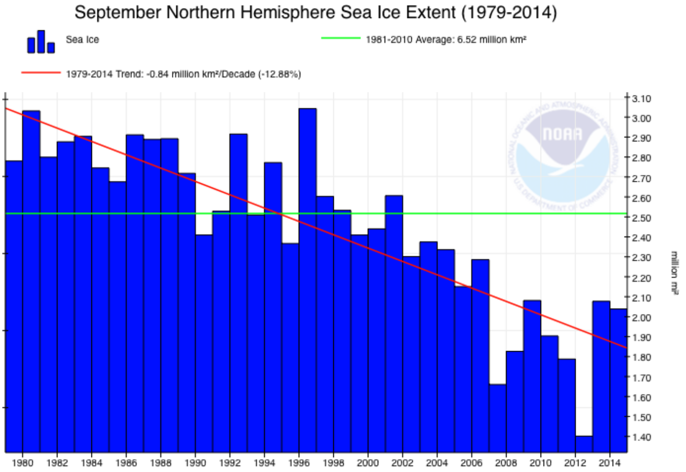


Figure courtesy NOAA National Climatic Data Center

Sea ice has. . .

- extent

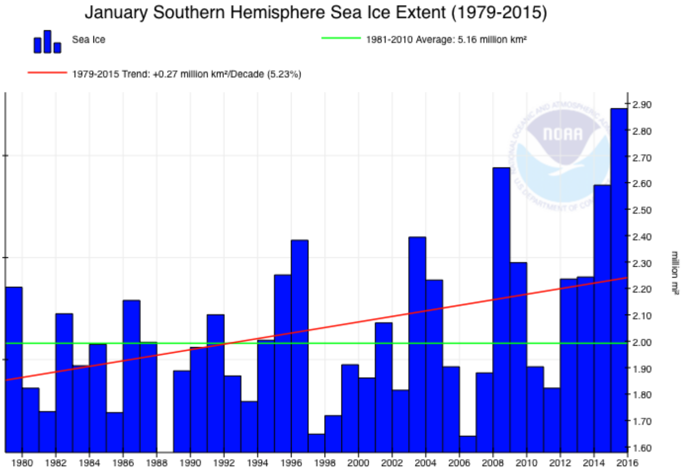


Figure courtesy NOAA National Climatic Data Center

Sea ice has. . .

- extent
- thickness

E. Hunke

Sea ice has. . .

http://youtu.be/YBTVJIH6En8

- extent
- thickness
- velocity

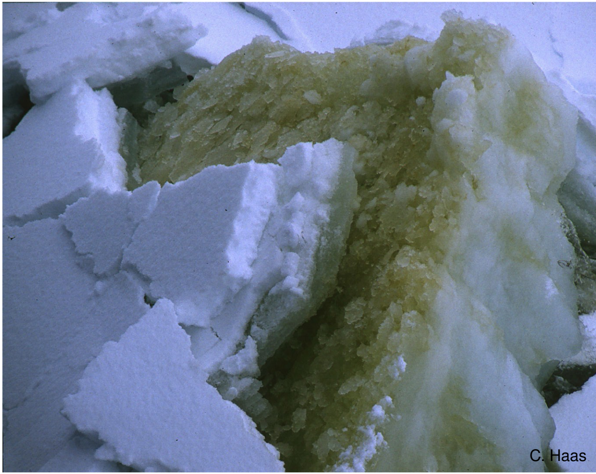
“Ice in Motion” by Kåre Holter Solhjell, near Svalbard

Sea ice has. . .

- extent
- thickness
- velocity
- stuff on it

Sea ice has. . .

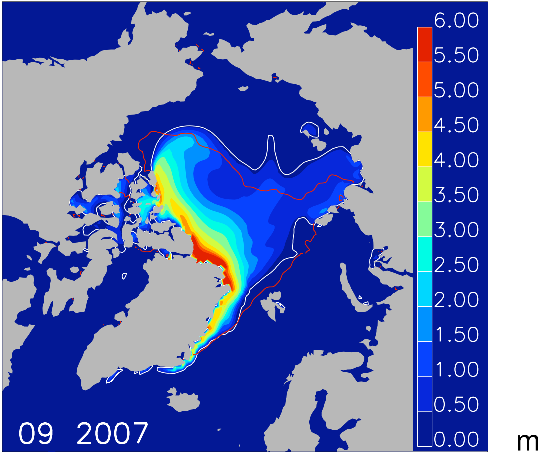
- extent
- thickness
- velocity
- stuff on it
- stuff in it



C. Haas

Monthly Sea Ice Thickness

SSM/I 15% ice concentration



1958–2007 CICE simulation

Interannual variability:

- wind
- air temperature
- humidity

Calculated/ Feedbacks:

- turbulent fluxes
- radiation
- SST
- air temperature

Thermodynamics

J. Geophys. Res. 1971

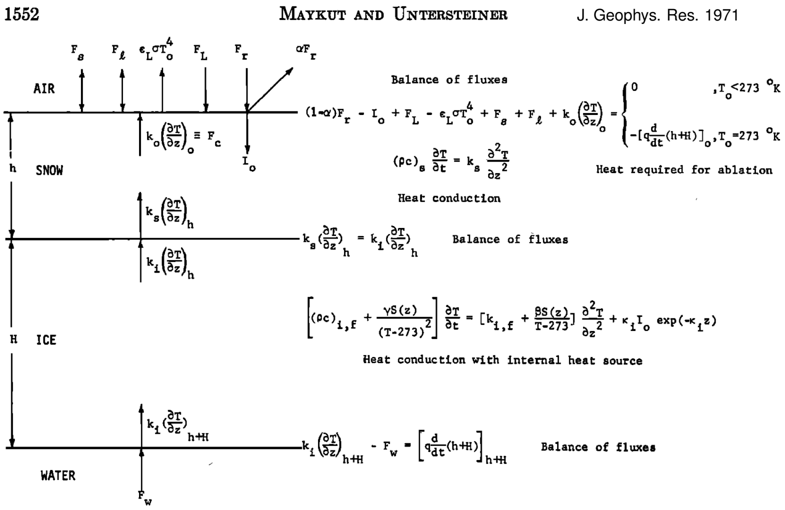
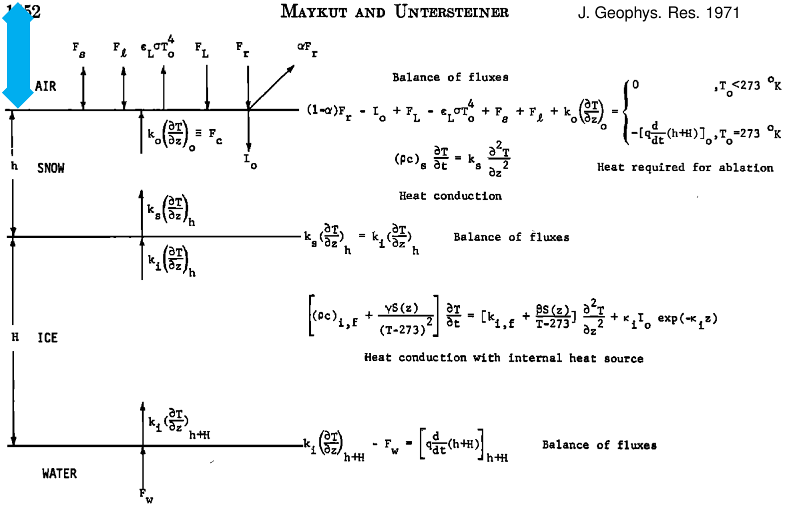


Fig. 1. Schematic illustration of the sea ice model.

Thermodynamics



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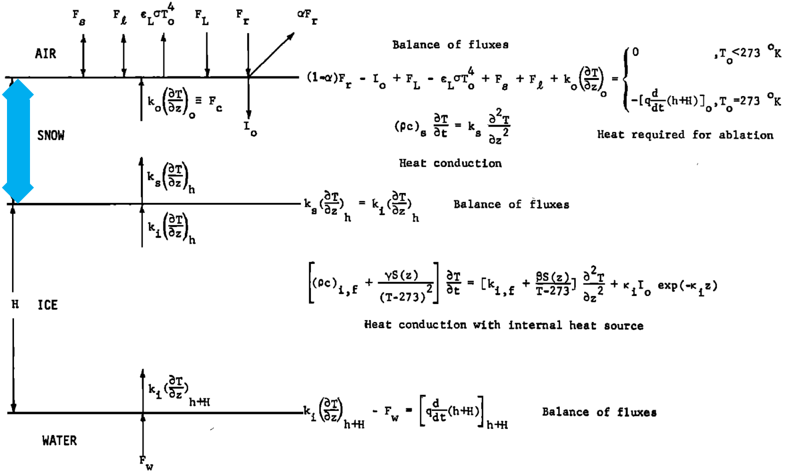
Thermodynamics

1552 MAYKUT AND UNTERSTEINER J. Geophys. Res. 1971



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Thermodynamics

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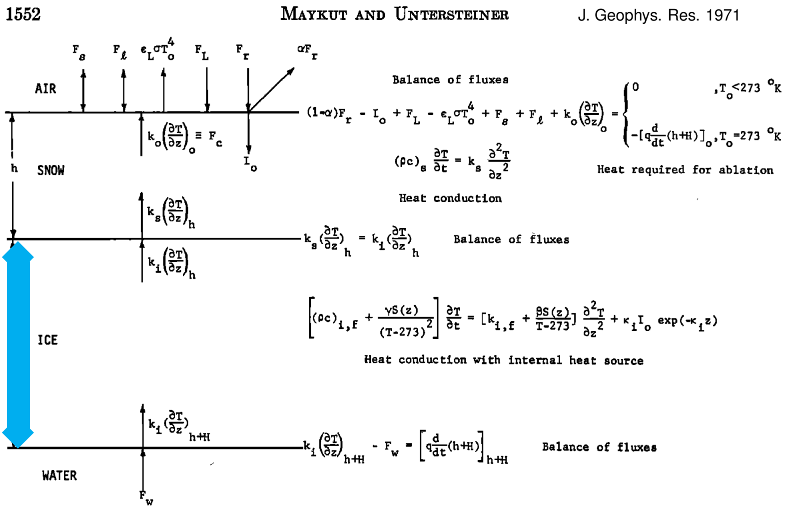
J. Geophys. Res. 1971



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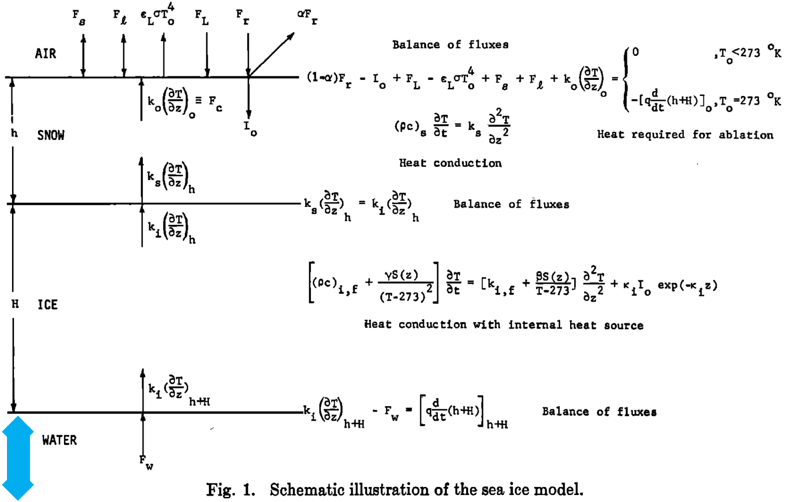

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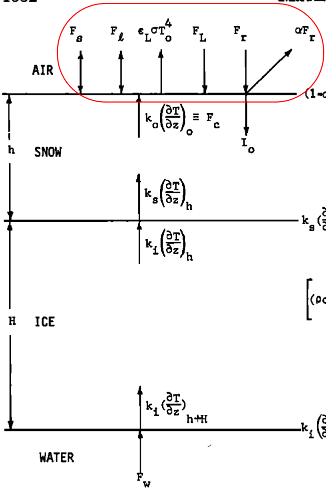

Balance of fluxes

$$(1-\alpha)F_r - I_o + F_L - \epsilon_L \sigma T_o^4 + F_s + F_\ell + k_o\left(\frac{\partial T}{\partial z}\right)_o = \begin{cases} 0 & ,T_o < 273\ ^\circ K \\ -\left[q\frac{d}{dt}(h+H)\right]_o & ,T_o = 273\ ^\circ K \end{cases}$$

Heat required for ablation

$$(\rho c)_s \frac{\partial T}{\partial t} = k_s \frac{\partial^2 T}{\partial z^2}$$

Heat conduction

$$k_s\left(\frac{\partial T}{\partial z}\right)_h = k_i\left(\frac{\partial T}{\partial z}\right)_h$$

Balance of fluxes

$$\left[(\rho c)_{i,f} + \frac{\gamma S(z)}{(T-273)^2}\right]\frac{\partial T}{\partial t} = \left[k_{i,f} + \frac{\beta S(z)}{T-273}\right]\frac{\partial^2 T}{\partial z^2} + \kappa_i I_o \exp(-\kappa_i z)$$

Heat conduction with internal heat source

$$k_i\left(\frac{\partial T}{\partial z}\right)_{h+H} - F_w = \left[q\frac{d}{dt}(h+H)\right]_{h+H}$$

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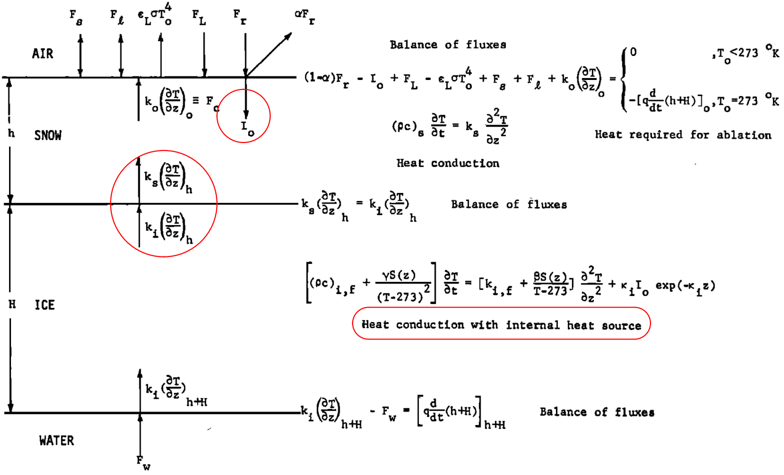

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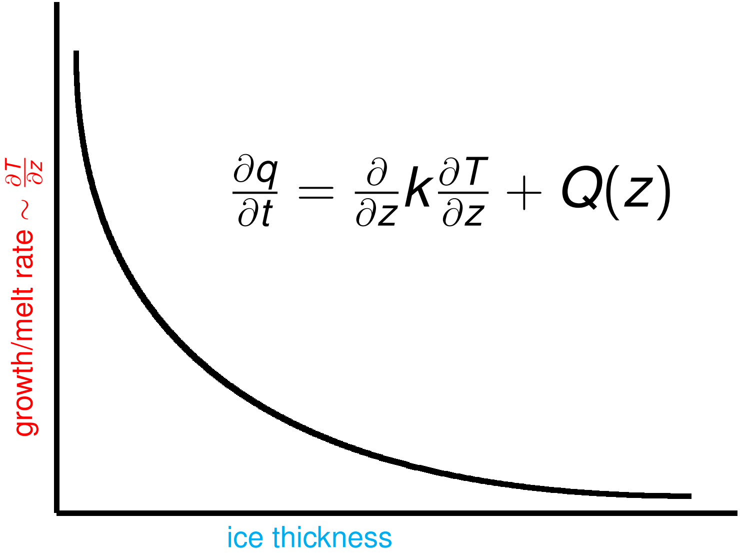
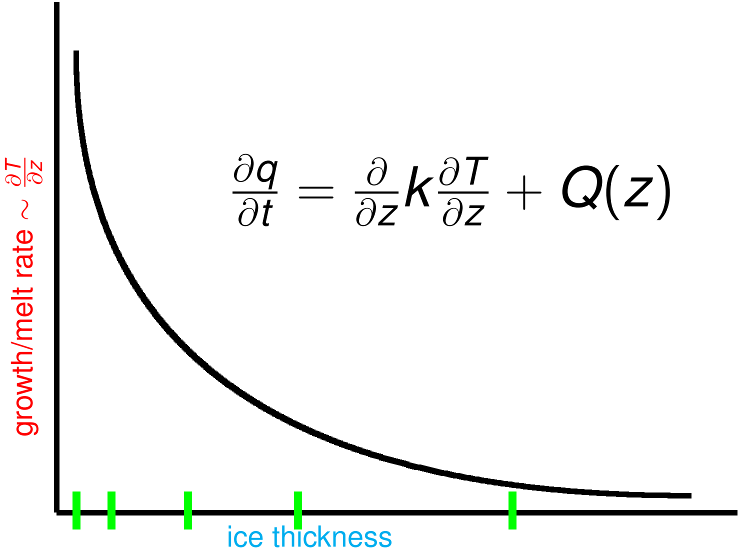
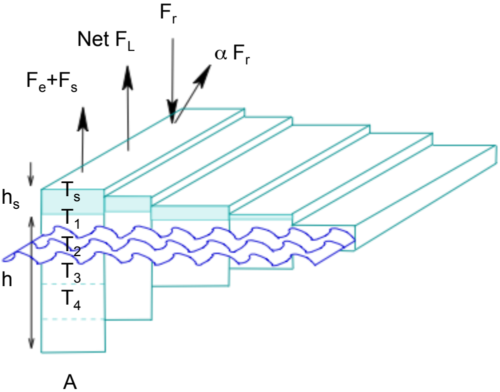

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z} + Q(z)$$
growth/melt rate $\sim \frac{\partial T}{\partial z}$
ice thickness

Ice Thickness Distribution



Ice Thickness Distribution g

Schematic of model representation of g(H) in five ice "categories"



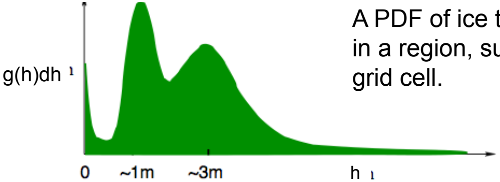
A=fractional coverage of a category

Slide courtesy Dave Bailey, NCAR

Ice Thickness Distribution g

$g(\mathbf{x}, h, t)\, dh =$ the fractional area covered by ice in the thickness range $(h, h + dh)$ at a given time t and location $\mathbf{x}$

$$\frac{\partial g}{\partial t} = -\nabla \cdot (g\mathbf{u}) + \psi - \frac{\partial}{\partial h}(fg) + L,$$



A PDF of ice thickness h in a region, such as a grid cell.

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$\nabla = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y})$

$\mathbf{u}$ = horizontal ice velocity

ψ = mechanical redistribution function

f = rate of thermodynamic ice growth

L = lateral melting

What's important?

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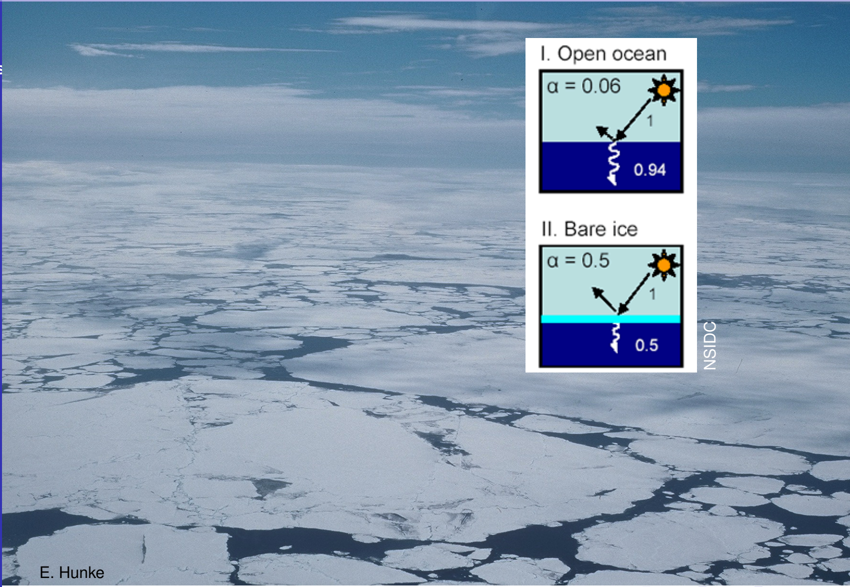
What's important? ALBEDO



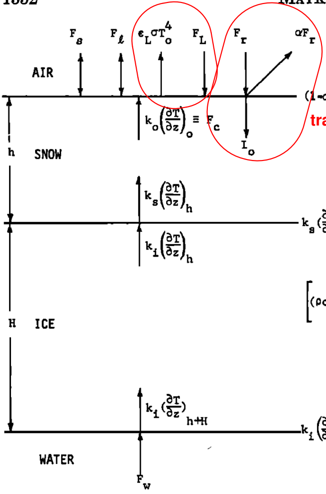
The Radiation Budget

(June) net longwave = 291 - 321 = -30 W/m^2

 J. Geophys. Res. 1971

net shortwave = 310 - 239 = 71 W/m^2

transmitted shortwave = 1.6 W/m^2



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Balance of fluxes

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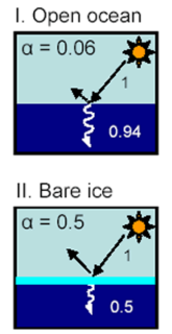
Surface characteristics

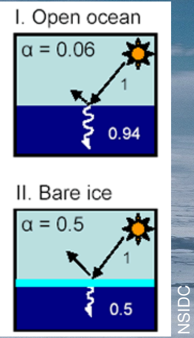
Ice area



NSIDC

- lateral growth and melt
- ice motion
  - rheology
    - elastic-viscous-plastic
    - elastic-anisotropic-plastic
  - momentum
    - wind, currents, Coriolis, tilt, internal stress
    - Monin-Obukhov similarity for turbulent fluxes
    - form drag (ridges, keels, floe and pond edges)
  - transport equations

Surface characteristics



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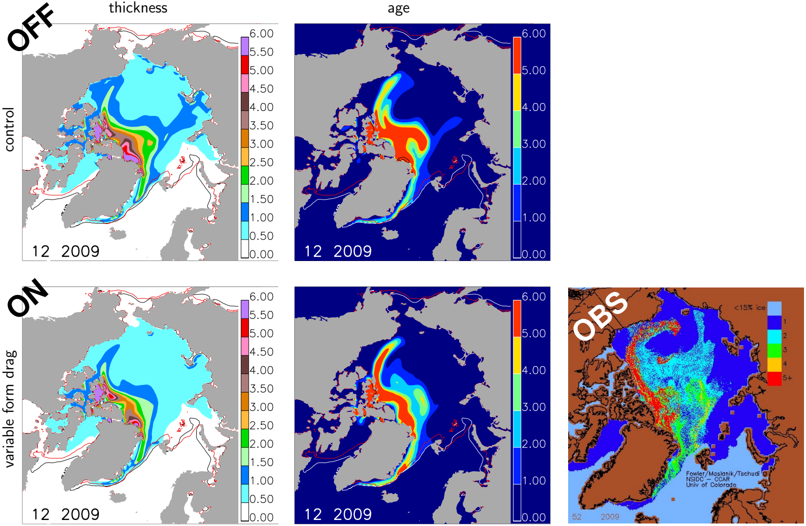
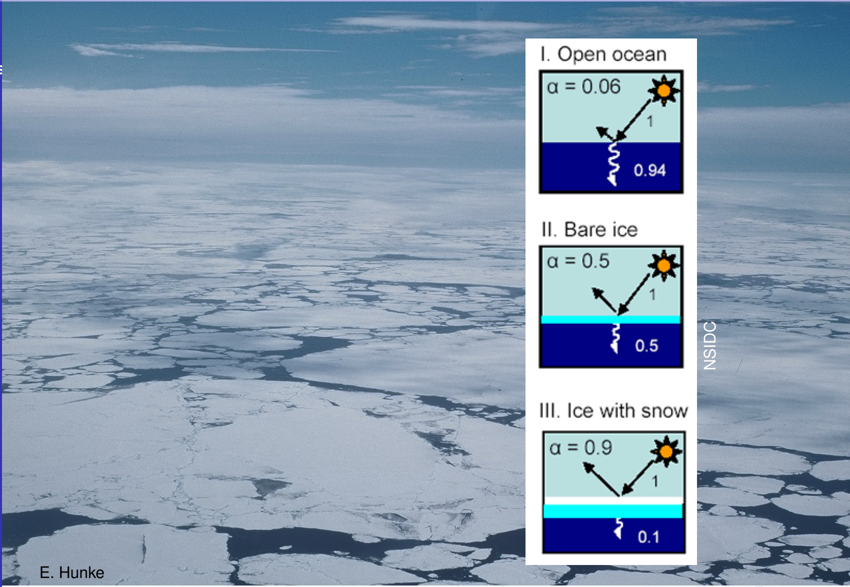
Variable form drag



Surface characteristics

Snow



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Surface characteristics

Snow

vertical conductive, radiative, turbulent fluxes

assumed density profile (constant!)

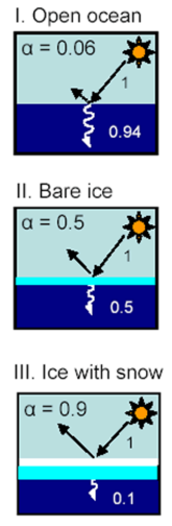
effective thermal conductivity

salinity = 0

mass changes due to
- snow-ice formation
- snowfall
- sublimation/deposition
- melt
- loss during ridging

transported on top of sea ice

interacts with melt ponds



NSIDC

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- mass changes due to
  - snow-ice formation
  - snowfall
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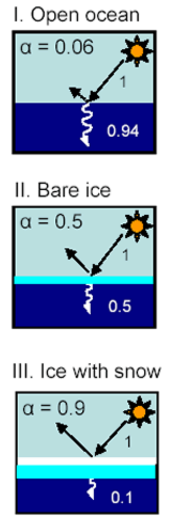
  - melt
  - loss during ridging
- transported on top of sea ice
- interacts with melt ponds

Coming Soon:

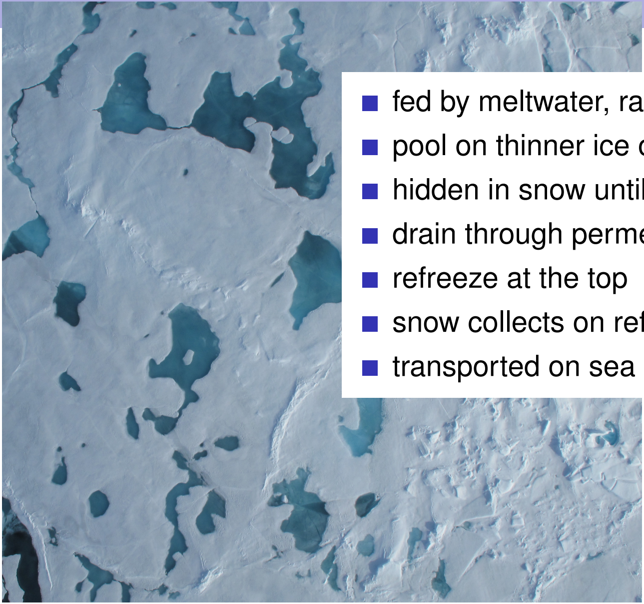
- *snow redistribution by wind*
- *depth hoar (variable crystal size)*
- *variable density*



NSIDC

Surface characteristics

Melt ponds



U. Herzfeld/CASIE

- fed by meltwater, rain
- pool on thinner ice or level ice
- hidden in snow until saturation
- drain through permeable ice
- refreeze at the top
- snow collects on refrozen ponds
- transported on sea ice

Surface characteristics

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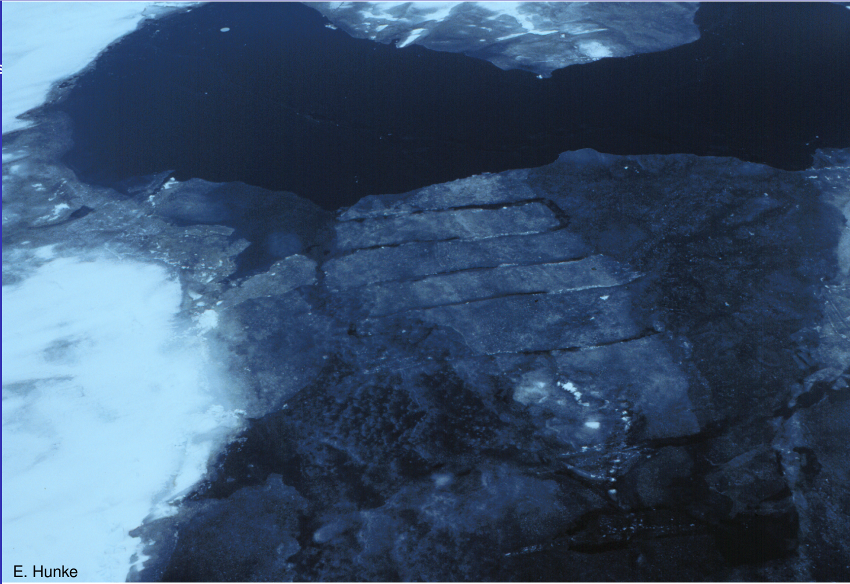
Ice thickness



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Ice thickness

- mechanical redistribution (ridging)
- thermodynamic growth/melt
    - top and bottom ablation
    - bottom accretion (congelation)
    - frazil growth
    - snow-ice formation
    - “mushy layer” with prognostic salinity

Ice thickness

mechanical redistribution (ridging)

thermodynamic growth/melt

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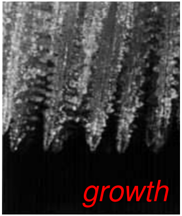
- "mushy layer" with prognostic salinity

“Mushy Layer” Thermodynamics



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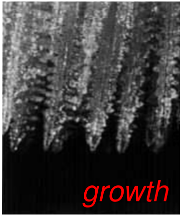

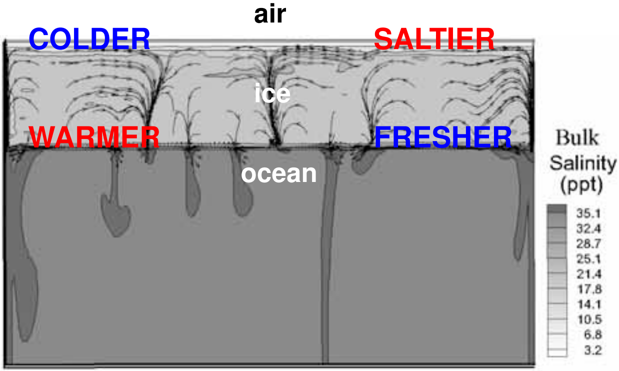

Oertling & Watts JGR 2004

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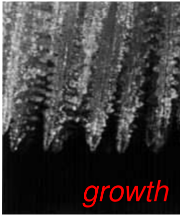

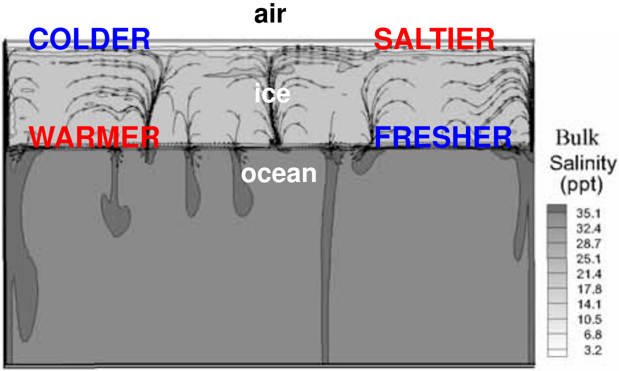

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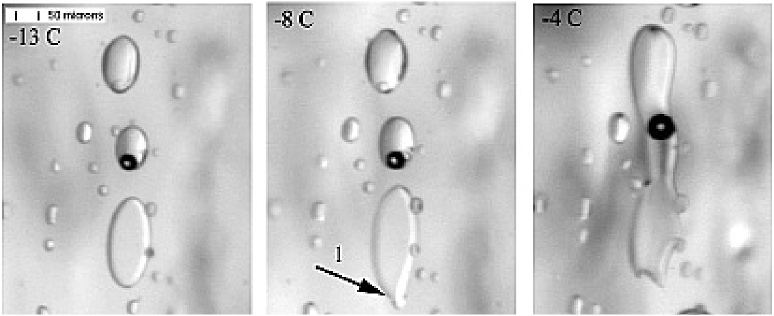
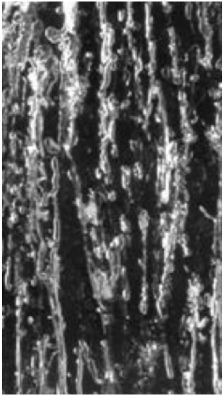


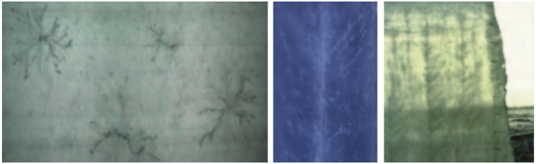
warmer →

courtesy B. Light, JGR 2003

"Mushy Layer" Thermodynamics



brine channels



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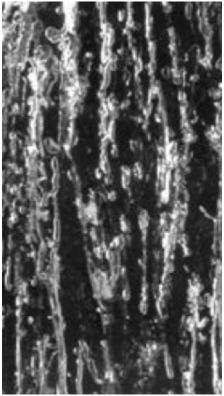
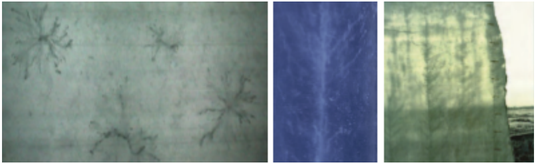


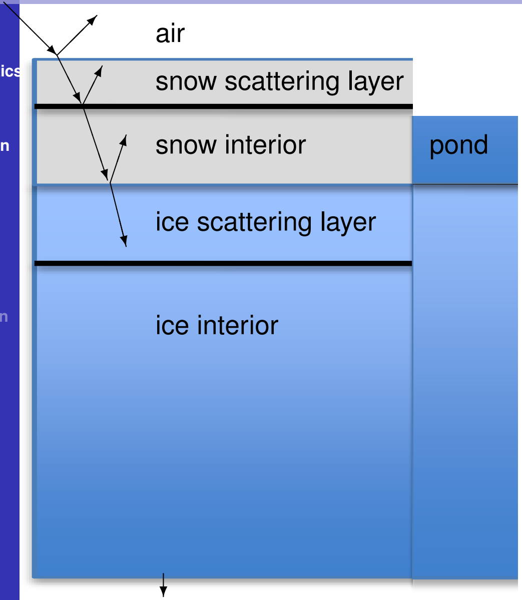
Equations	Variables
Conservation of energy	Enthalpy
Conservation of salt	Bulk salinity
Ice-brine liquidus relation	Liquid fraction
Darcy flow through a porous medium	Vertical velocity

brine channels



Delta Eddington

Multiple Scattering Parameterization for Solar Radiation



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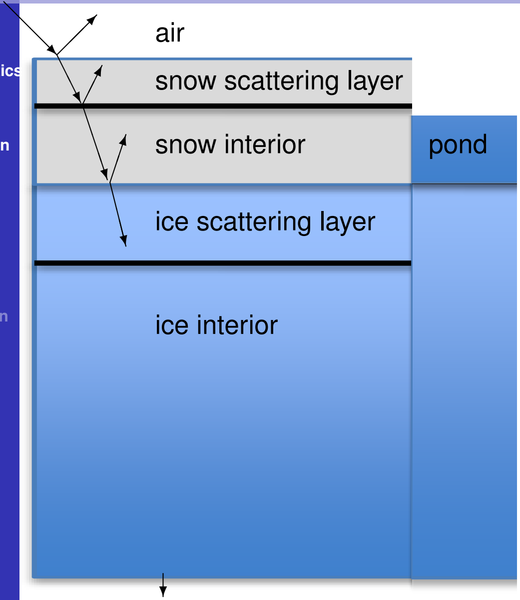


Thin snow is patchy

Inherent optical properties:
- extinction coefficient
- single scattering albedo
- scattering asymmetry

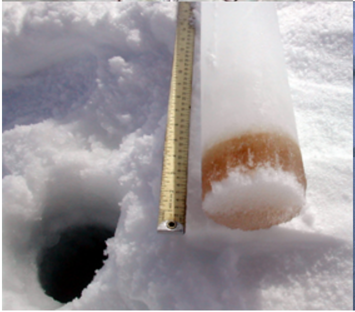
Apparent optical properties:
- albedo
- internal absorption
- transmission to ocean

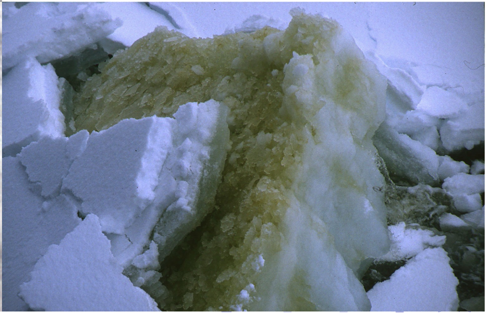
Tuning parameters:
- snow grain radii

  fresh, melting, nonmelting
  standard deviation

Sea Ice Ecosystem

- physical, hydrological system
- chemistry and biology
  - in the ice column
  - at the bottom





Algae in the Bottom Ice, 1992

IARC/UAF

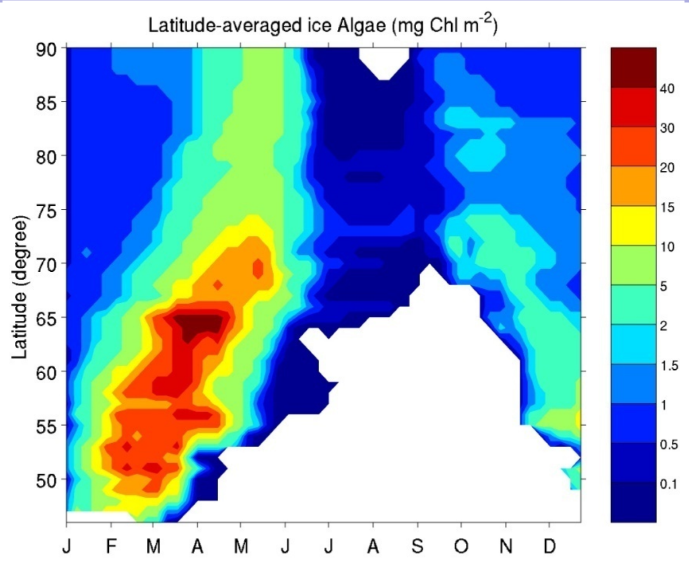


Figure courtesy Clara Deal, IARC

Aerosol Enhanced Ice Shortwave Absorption

CICE4
CESM

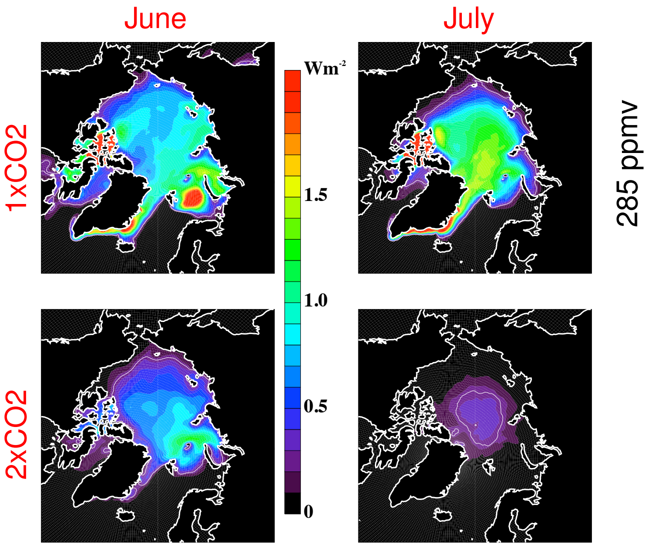


Figure courtesy Marika Holland, NCAR

Vertically Resolved Sea Ice Biogeochemistry

- algal types: diatoms, flagellates, *Phaeocystis*
- DON/DOC: proteins, polysaccharides, lipids
- nutrients: nitrate/nitrite, silicate, ammonium, DMS(P)(d)
- aerosols & chlorophyll absorption alter ice growth, under-ice PAR via Delta-Eddington

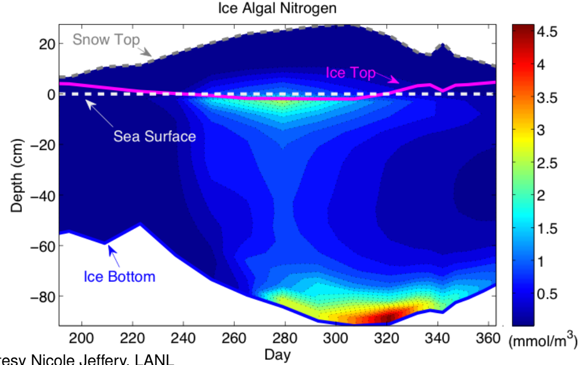
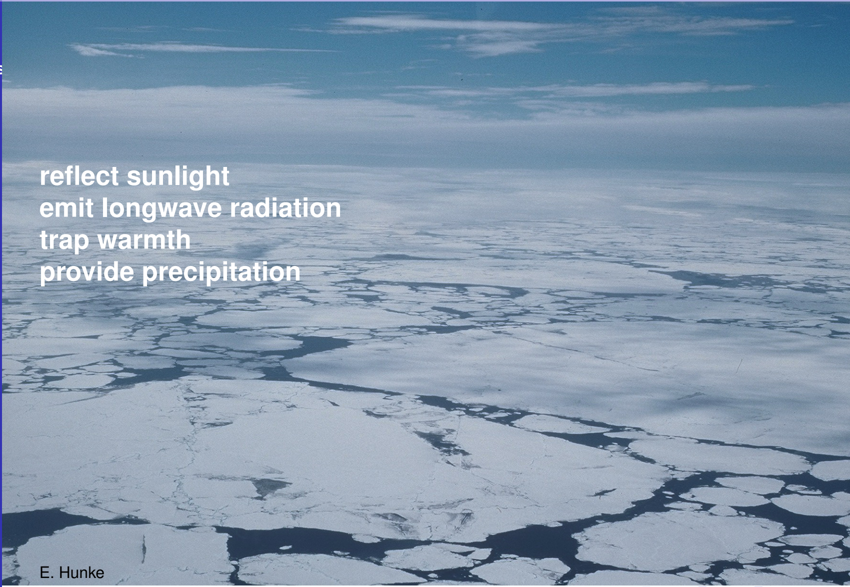


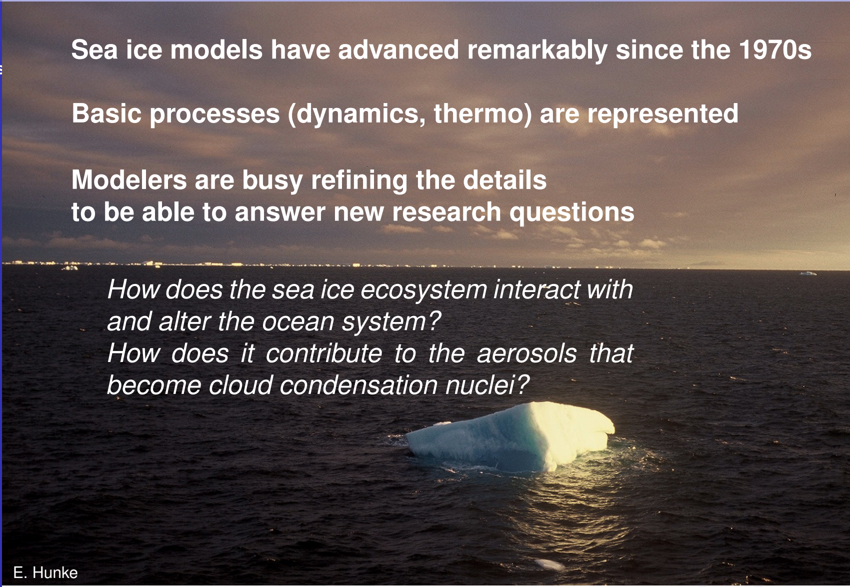
Figure courtesy Nicole Jeffery, LANL

Clouds ... in the atmosphere (model)



reflect sunlight
emit longwave radiation
trap warmth
provide precipitation

Summary



Sea ice models have advanced remarkably since the 1970s

Basic processes (dynamics, thermo) are represented

Modelers are busy refining the details
to be able to answer new research questions

How does the sea ice ecosystem interact with and alter the ocean system?
How does it contribute to the aerosols that become cloud condensation nuclei?