Sea Ice Modeling for Climate Applications

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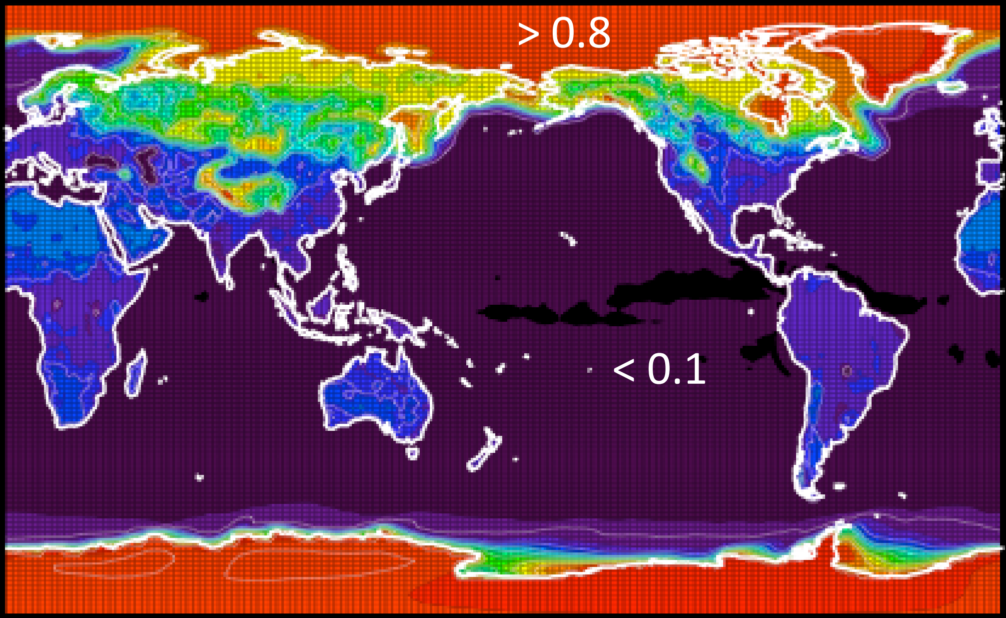
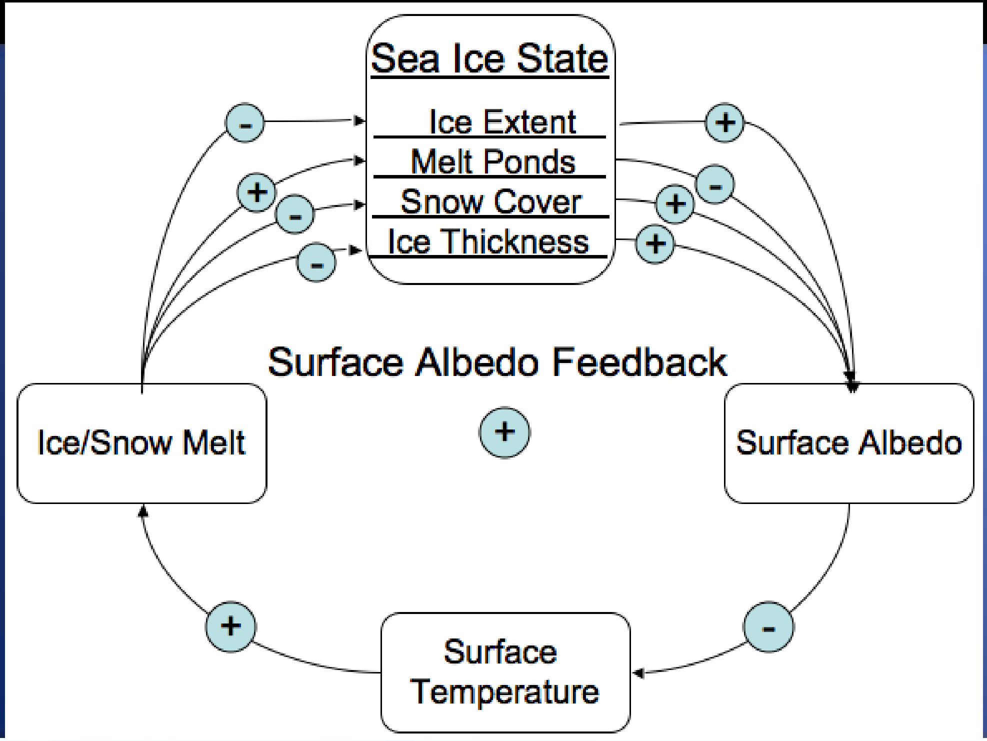
David Bailey (NCAR), Cecilia Bitz (U. Washington), Elizabeth Hunke (LANL)

Surface albedo

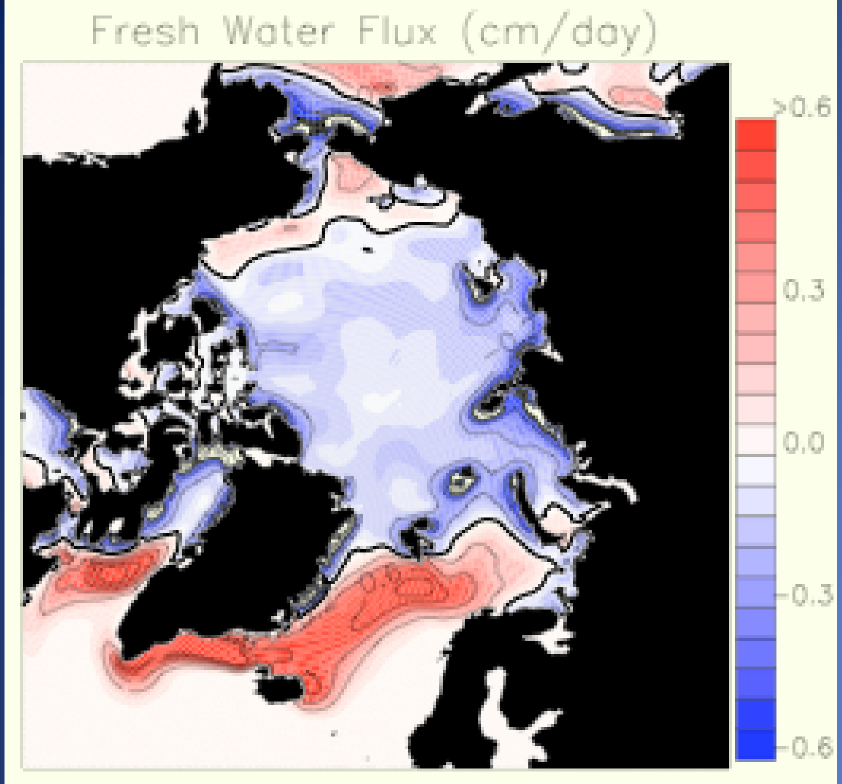




Why do we care about sea ice? Surface energy (heat) budget

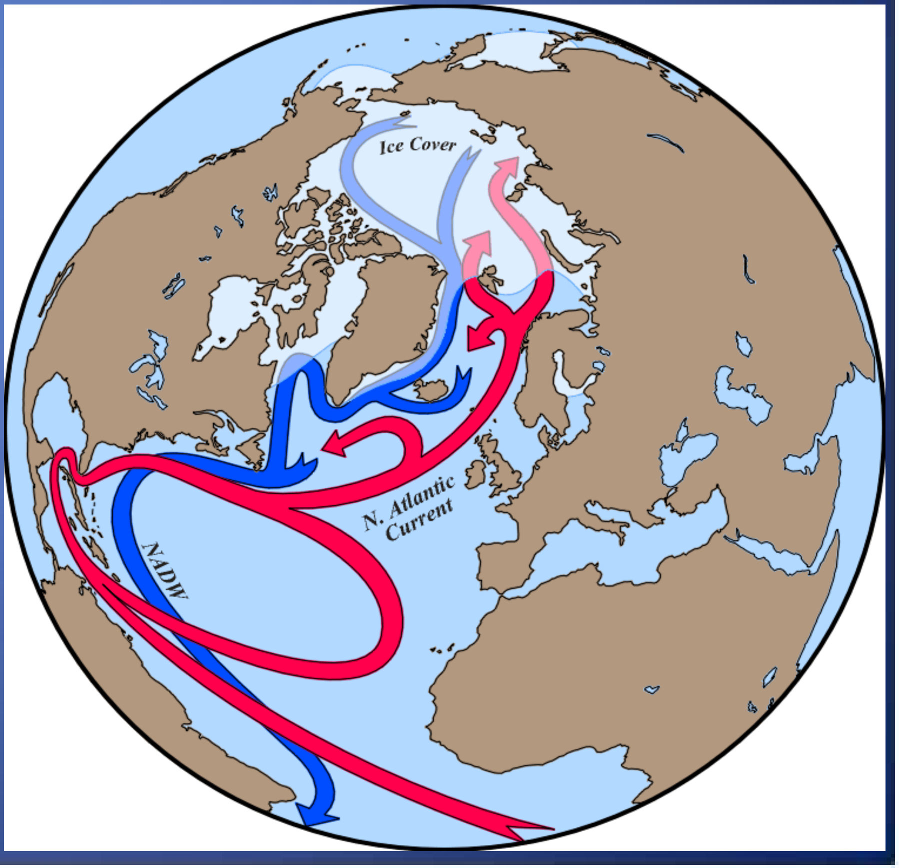
- High albedo of sea ice modifies radiative fluxes
- Sea ice insulates ocean from atmosphere influencing turbulent heat & moisture exchange

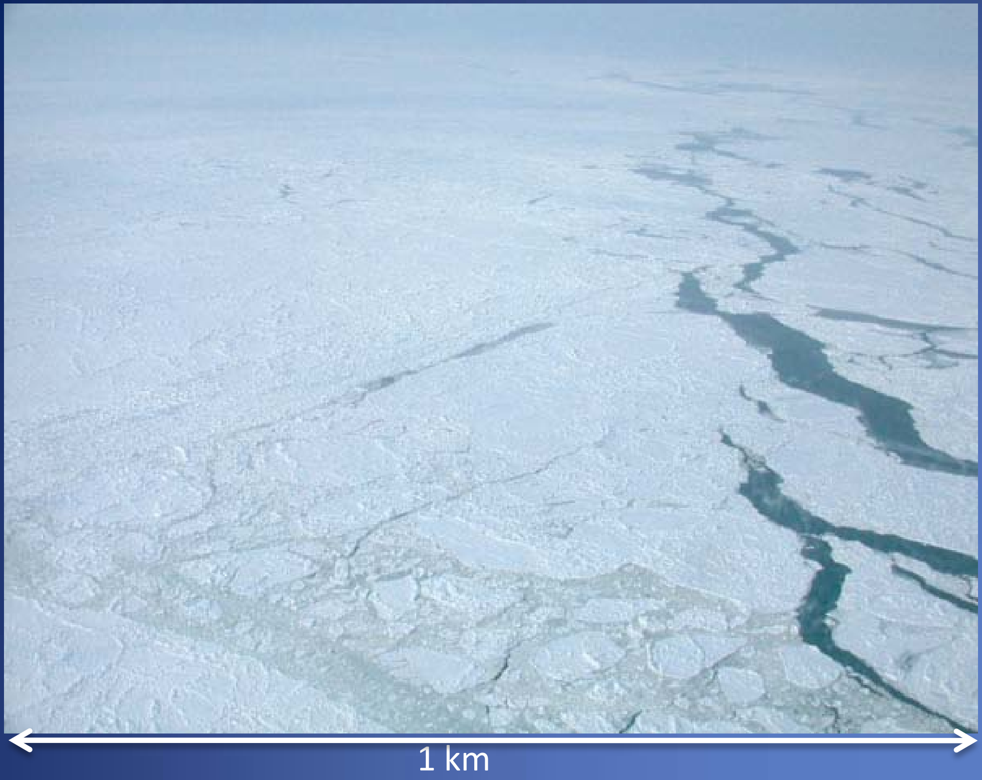
Why do we care about sea ice? Hydrological Cycle



Ice-Ocean Freshwater Exchange

- Salt rejection during ice formation leaves sea ice relatively fresh (salt flux to ocean)
- Ice melt releases freshwater back to the ocean
- Can modify ocean circulation





From:
Feltham,
2008
(photos by
Hajo Eicken)

Sea Ice

- Composed of floes (can freeze to form a continuous cover)
- Typical thickness of meters
- Riddled with cracks (leads) and ridges
- Complex mosiac of ice types within small area

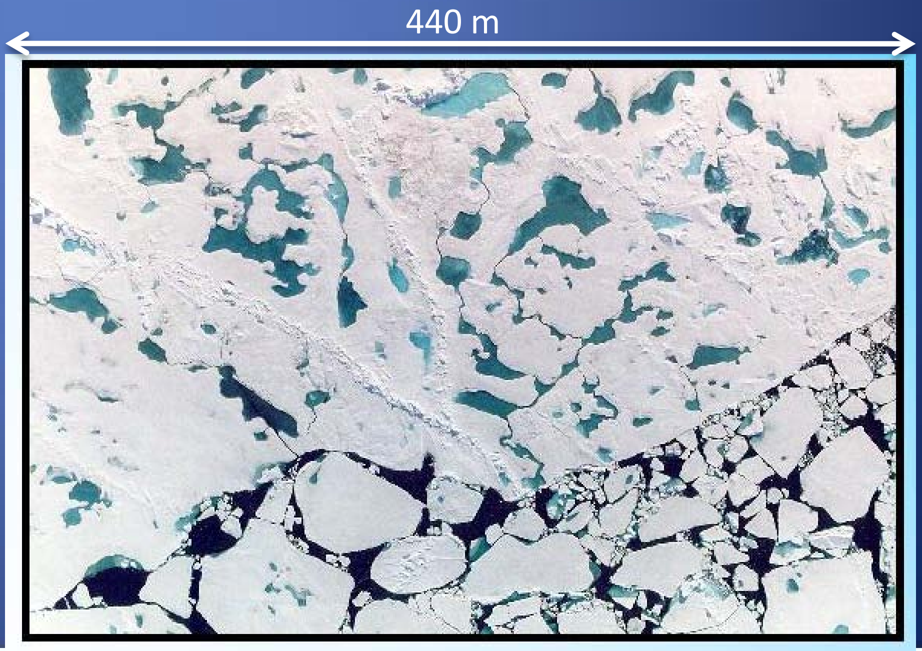
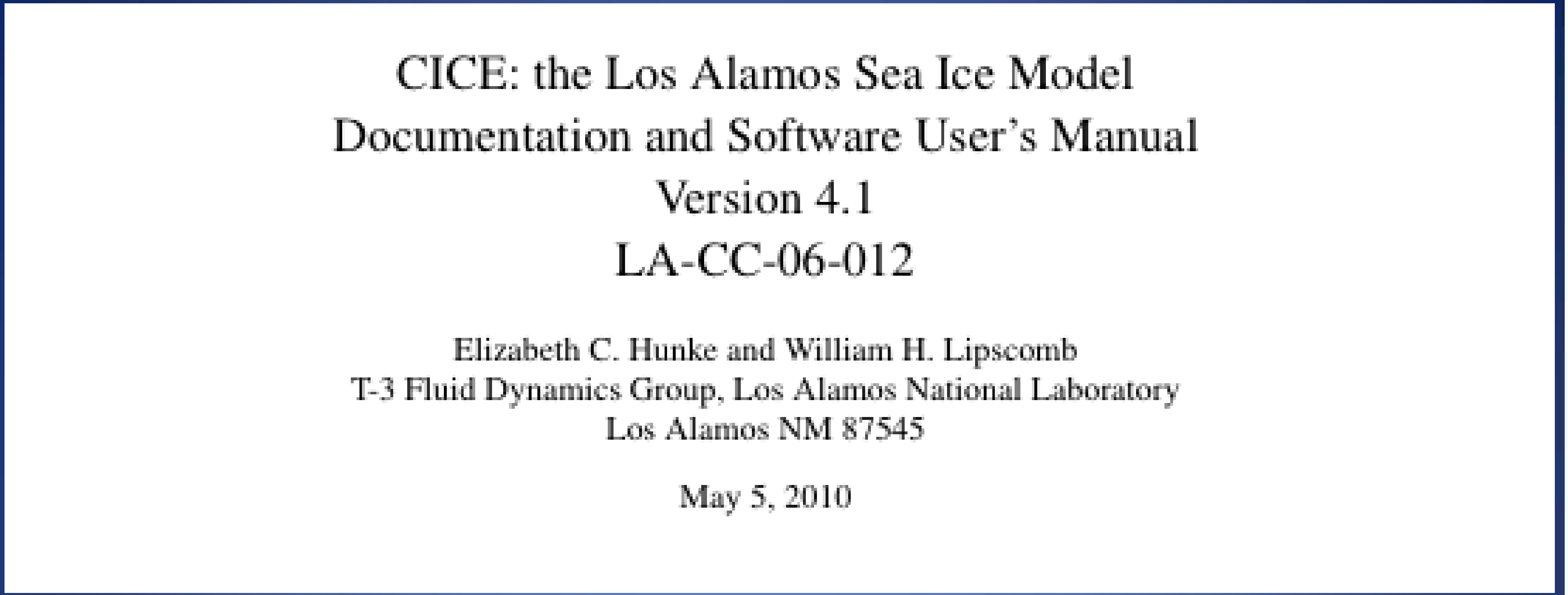


Photo courtesy of Don Perovich

What do we need in a sea ice model for climate applications?

- Model which simulates a reasonable mean state/variability of sea ice
  - Concentration, thickness, mass budgets
- Realistically simulates ice-ocean-atmosphere exchanges of heat and moisture
- Realistically simulates response to climate perturbations - key climate feedbacks



CICE: the Los Alamos Sea Ice Model
Documentation and Software User's Manual
Version 4.1
LA-CC-06-012

Elizabeth C. Hunke and William H. Lipscomb
T-3 Fluid Dynamics Group, Los Alamos National Laboratory
Los Alamos NM 87545

May 5, 2010

CESM1 uses the CICE Los Alamos Sea Ice Model (Hunke and Lipscomb)

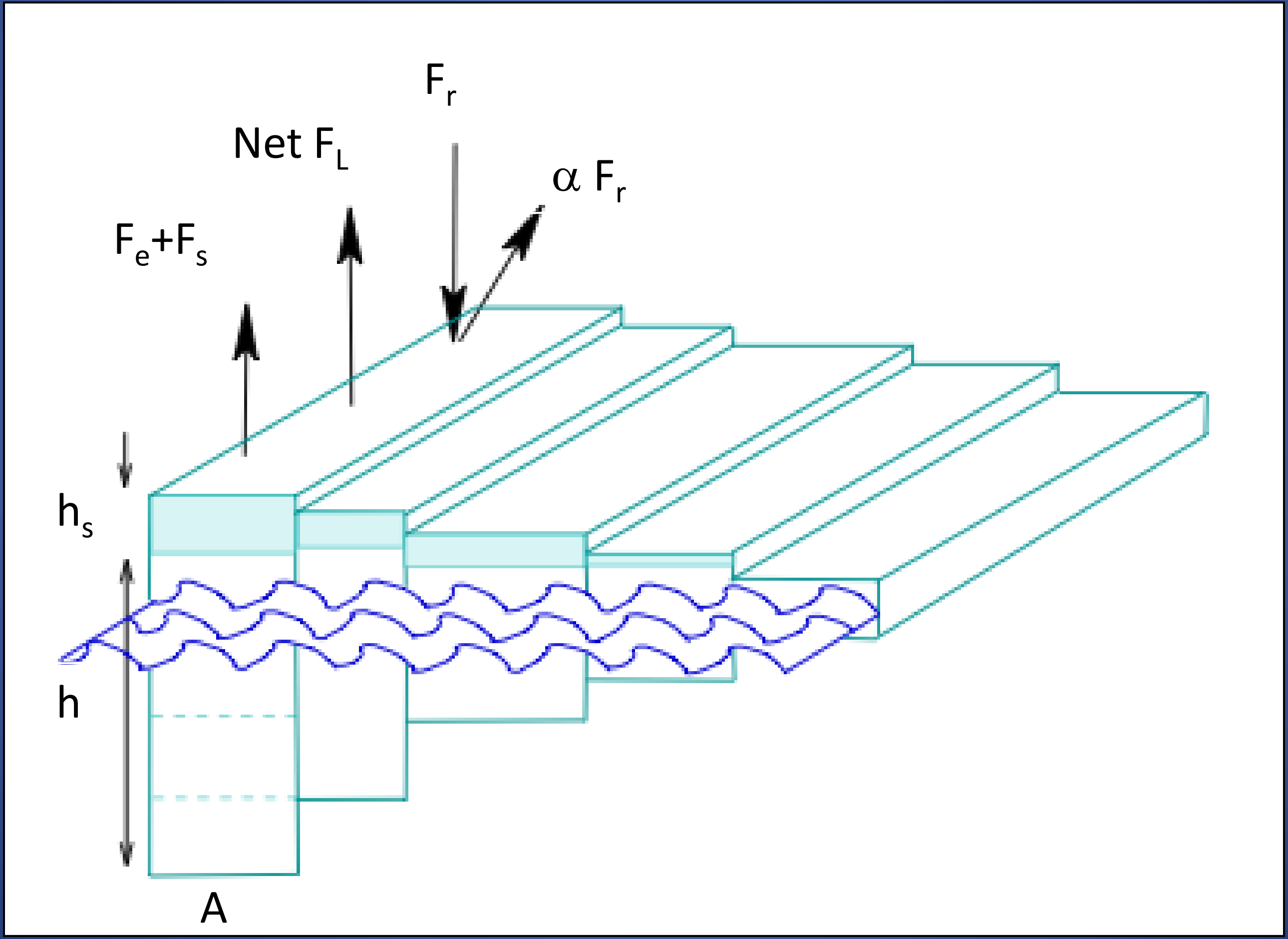
Full documentation available online

Sea Ice Models Used in Climate Simulations

- Two primary components
  - Dynamics
    - Solves force balance to determine sea ice motion
  - Thermodynamics
    - Solves for vertical ice temperature profile
    - Vertical/lateral melt and growth rates
- Some (about 30% of IPCC-AR4) models also include
  - Ice Thickness Distribution
    - Subgridscale parameterization
    - Accounts for high spatial heterogeneity in ice

Ice Thickness Distribution

To represent high spatial heterogeneity of sea ice
Schematic of model representation with five ice "categories"

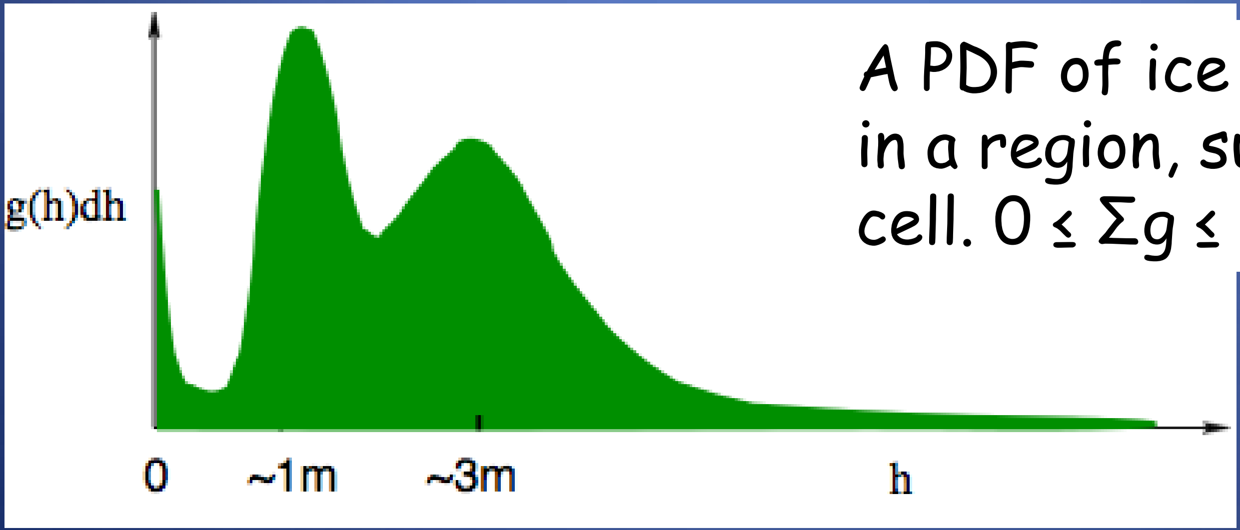


A=fractional coverage of a category

Ice Thickness Distribution

Ice thickness distribution g(x,y,h,t) evolution equation from Thorndike et al. (1975)

$$\frac{\partial g}{\partial t} = \underbrace{-\frac{\partial}{\partial h}(fg)}_{\text{Ice Growth}} + \underbrace{L(g)}_{\text{Lateral Melt}} - \underbrace{\nabla \bullet (\vec{v}g)}_{\text{Convergence}} + \underbrace{\Psi(h,g,\vec{v})}_{\text{Mechanical Redistribution}}$$

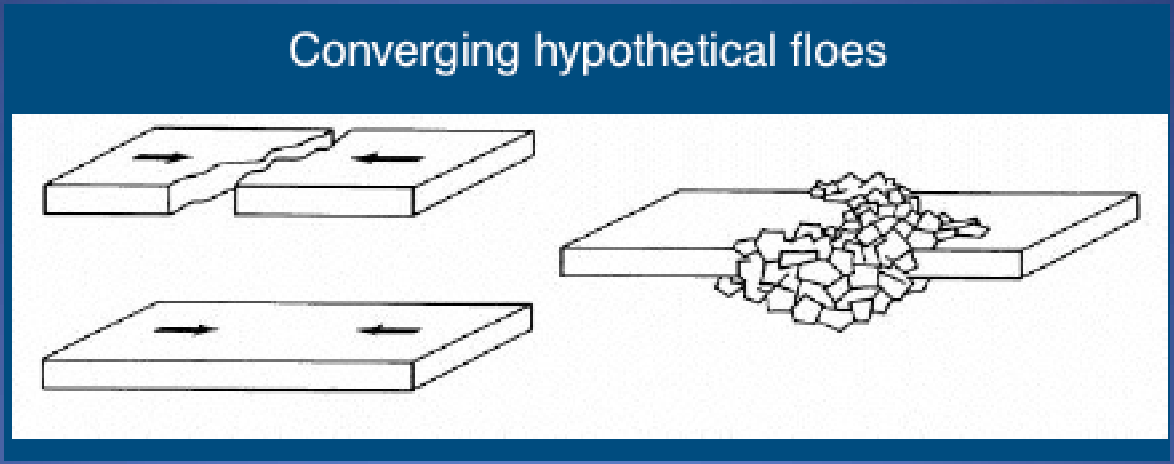


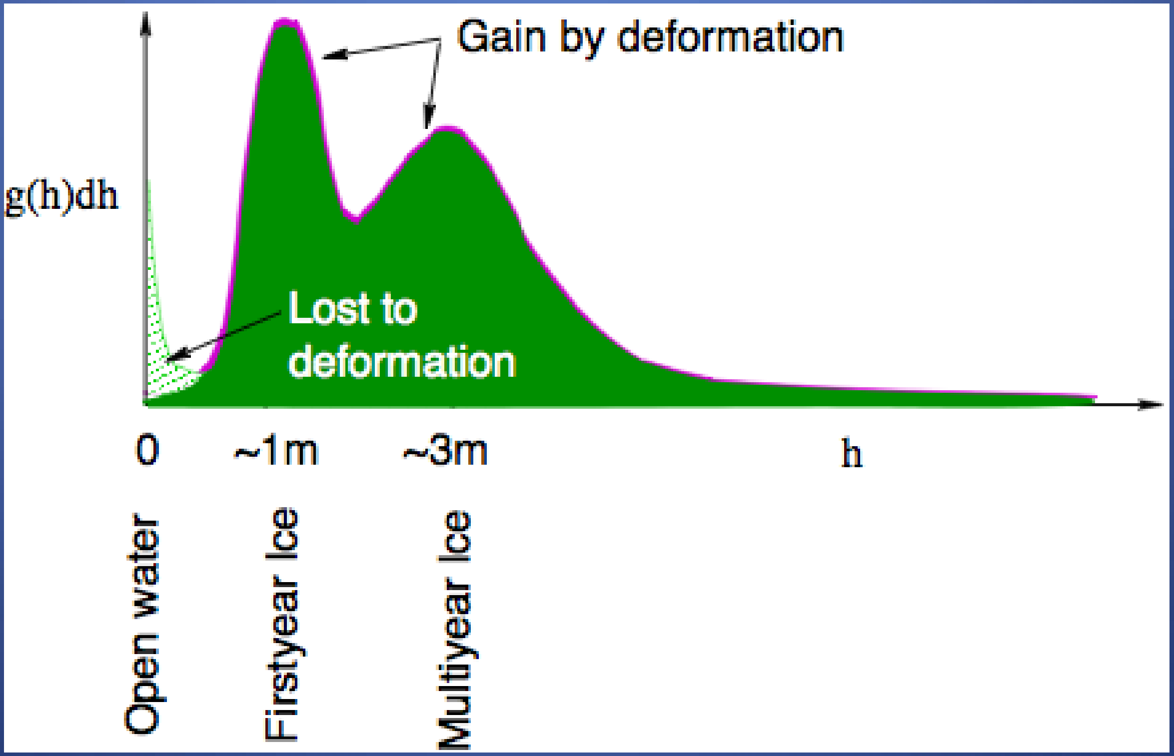
A PDF of ice thickness h in a region, such as a grid cell. $0 \leq \Sigma g \leq 1$

g(h)dh is the fractional area covered by ice of thickness h to h+dh

Ψ = Mechanical redistribution

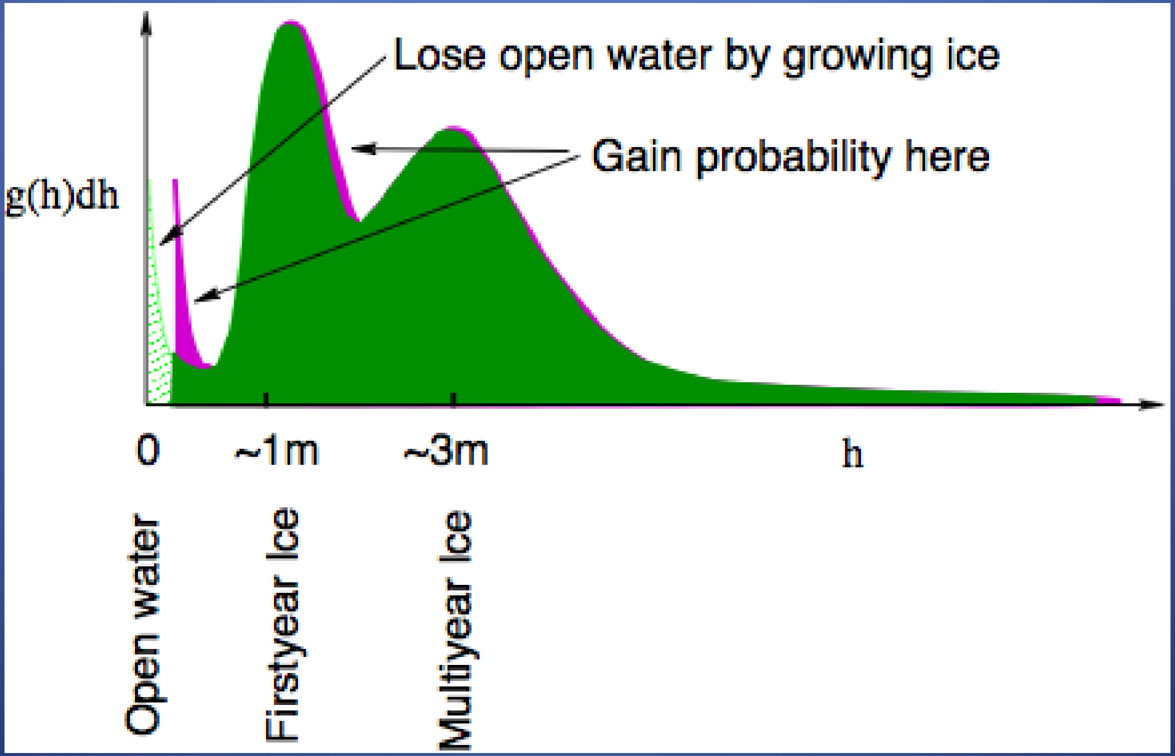
Transfers ice from thin part of distribution to thicker categories


Converging hypothetical floes

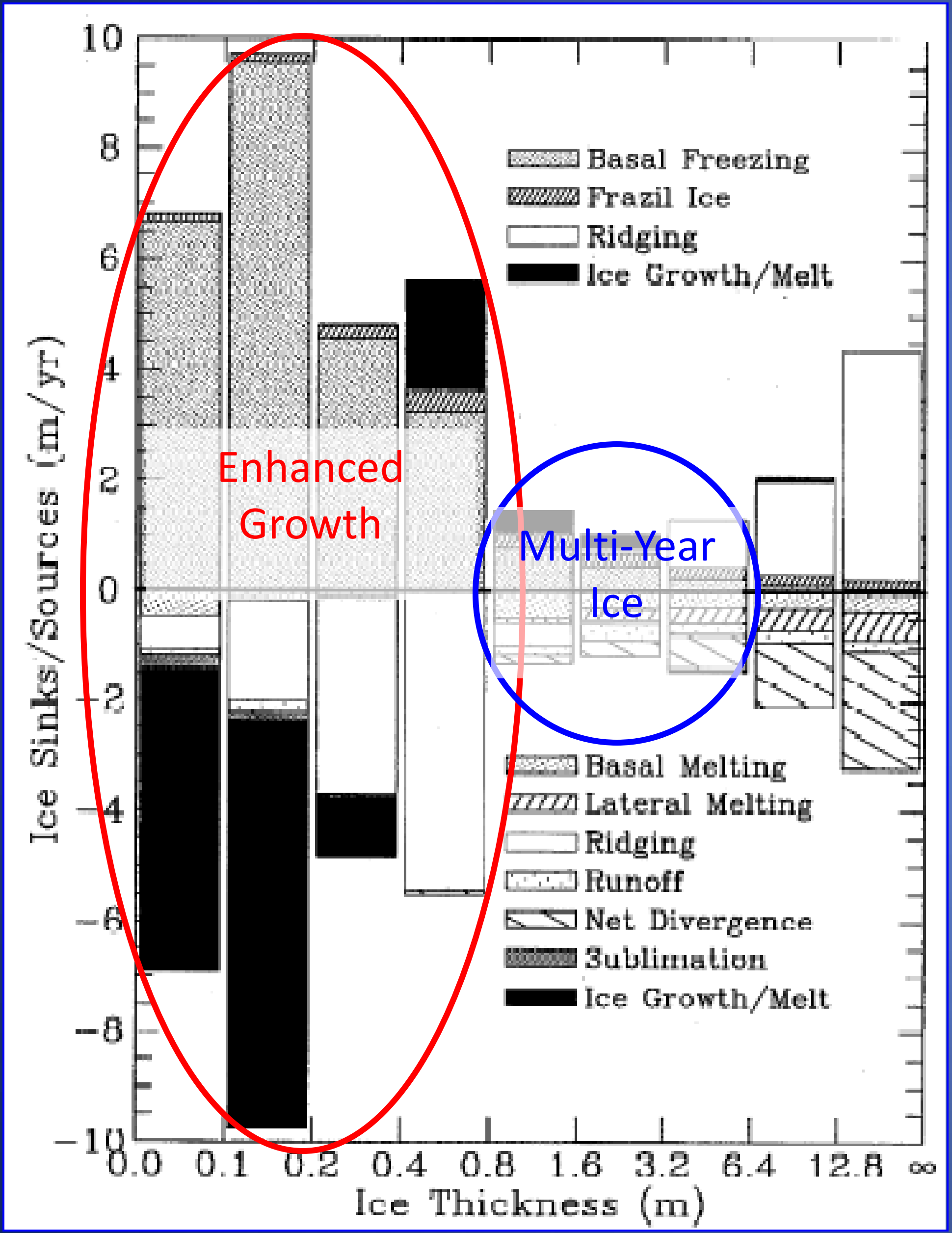


Ice growth:

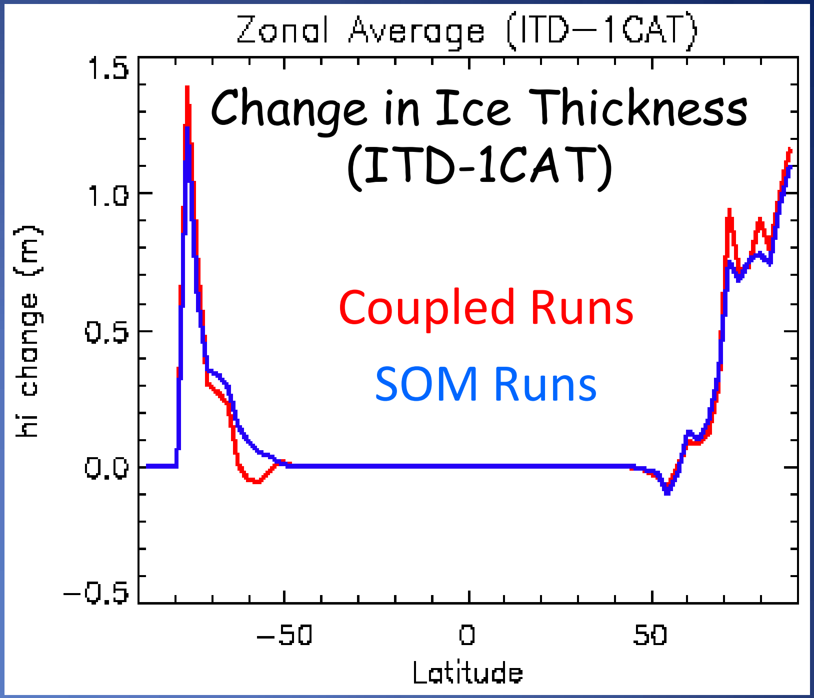

Ice Floe
Ice growth

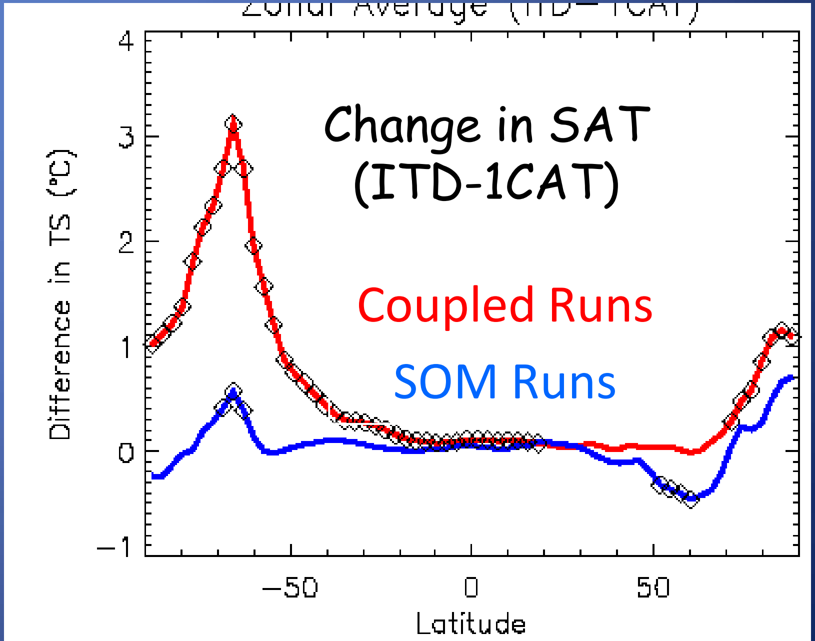

Lose open water by growing ice
Gain probability here
g(h)dh
0
~1m
~3m
h
Open water
Firstyear Ice
Multiyear Ice

Influence of including an Ice Thickness Distribution



Schramm et al., 1997





(Holland et al., 2006)

Sea Ice Model - Dynamics

- Force balance between wind stress, water stress, internal ice stress, coriolis and stress associated with sea surface slope
- Ice treated as a continuum with an effective large-scale rheology describing the relationship between stress and deformation
- Ice freely diverges (no tensile strength)
- Ice resists convergence and shear

(e.g. Hibler, 1979)

$$\underset{\substack{\uparrow\\\text{Total derivative}}}{m\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t}} = \underset{\substack{\uparrow\\\text{Coriolis}}}{-mf\mathbf{k}\times\mathbf{u}} + \underset{\substack{\uparrow\\\text{Air}\\\text{stress}}}{\boldsymbol{\tau}_a} + \underset{\substack{\uparrow\\\text{Ocean}\\\text{stress}}}{\boldsymbol{\tau}_w} - \underset{\substack{\uparrow\\\text{Sea Surface}\\\text{Slope}}}{mg_r\nabla Y} + \underset{\substack{\uparrow\\\text{Internal}\\\text{Ice Stress}}}{\nabla\cdot\sigma}$$

Sea Ice Model - Dynamics

- Air Stress

$$\vec{\tau}_a = \frac{\rho_a u^{*2} \vec{U}_a}{\left|\vec{U}_a\right|},$$

$$u^* = c_u \left|\vec{U}_a\right|$$

- Ocean Stress

$$\vec{\tau}_w = c_w \rho_w \left|\vec{U}_w - \vec{u}\right| \left[\left(\vec{U}_w - \vec{u}\right)\cos\theta + \hat{k} \times \left(\vec{U}_w - \vec{u}\right)\sin\theta\right]$$

(e.g. Hibler, 1979)

$$\underset{\substack{\uparrow \\ \text{Total derivative}}}{m\frac{D\mathbf{u}}{Dt}} = \underset{\substack{\uparrow \\ \text{Coriolis}}}{-mf\mathbf{k} \times \mathbf{u}} + \underset{\substack{\uparrow \\ \text{Air} \\ \text{stress}}}{\boldsymbol{\tau}_a} + \underset{\substack{\uparrow \\ \text{Ocean} \\ \text{stress}}}{\boldsymbol{\tau}_w} - \underset{\substack{\uparrow \\ \text{Sea Surface} \\ \text{Slope}}}{mg_r\nabla Y} + \underset{\substack{\uparrow \\ \text{Internal} \\ \text{Ice Stress}}}{\nabla \cdot \sigma}$$

Sea Ice Model - Dynamics

- Ice Interaction Term (Internal Ice Stress)
  - – Requires a constitutive law to relate ice stress (σ) to ice strain rate (ε)˙

(e.g. Hibler, 1979)

$$m\frac{Du}{Dt} = -mf\mathbf{k}\times\mathbf{u} + \boldsymbol{\tau}_a + \boldsymbol{\tau}_w - mg_r\nabla Y + \nabla\cdot\sigma$$

Total derivative

Coriolis

Air stress

Ocean stress

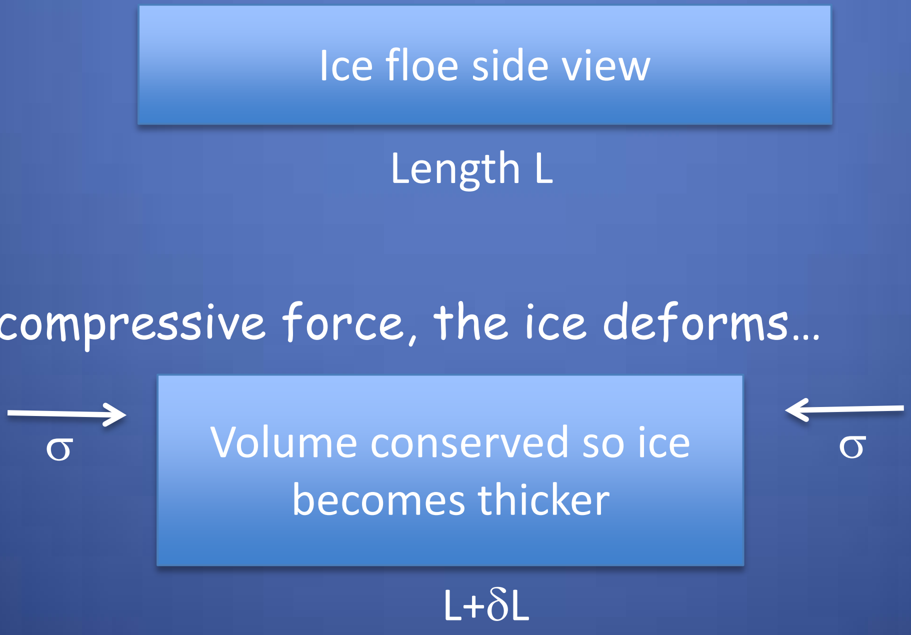
Sea Surface Slope

Internal Ice Stress

Sea Ice Model - Dynamics

- Ice Interaction Term (Internal Ice Stress)
  - – Requires a constitutive law to relate ice stress (σ) to ice strain rate $(\varepsilon)^{\cdot}$

For example – A compressive stress test



At first:

Ice floe side view

Length L

After applying a compressive force, the ice deforms…

σ → Volume conserved so ice becomes thicker ← σ

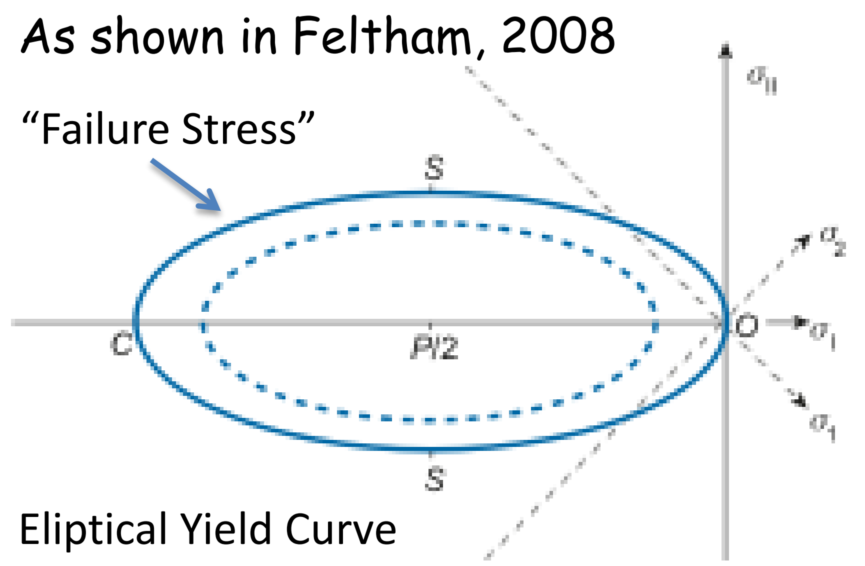
L+δL

Strain: $\varepsilon=\delta L/L$

Strain Rate: $\dot{\varepsilon}=\delta L/Ldt$

Sea Ice Model - Dynamics

- Ice Interaction Term (Internal Ice Stress)
  - Use variant of Viscous-Plastic Rheology (Hibler, 1979)
  - Treats ice as a continuum - plastic at normal strain rates and viscous at very small strain rates.
  - Ice has no tensile strength (freely diverges) but resists convergence and shear (strength dependent on ice state)



As shown in Feltham, 2008

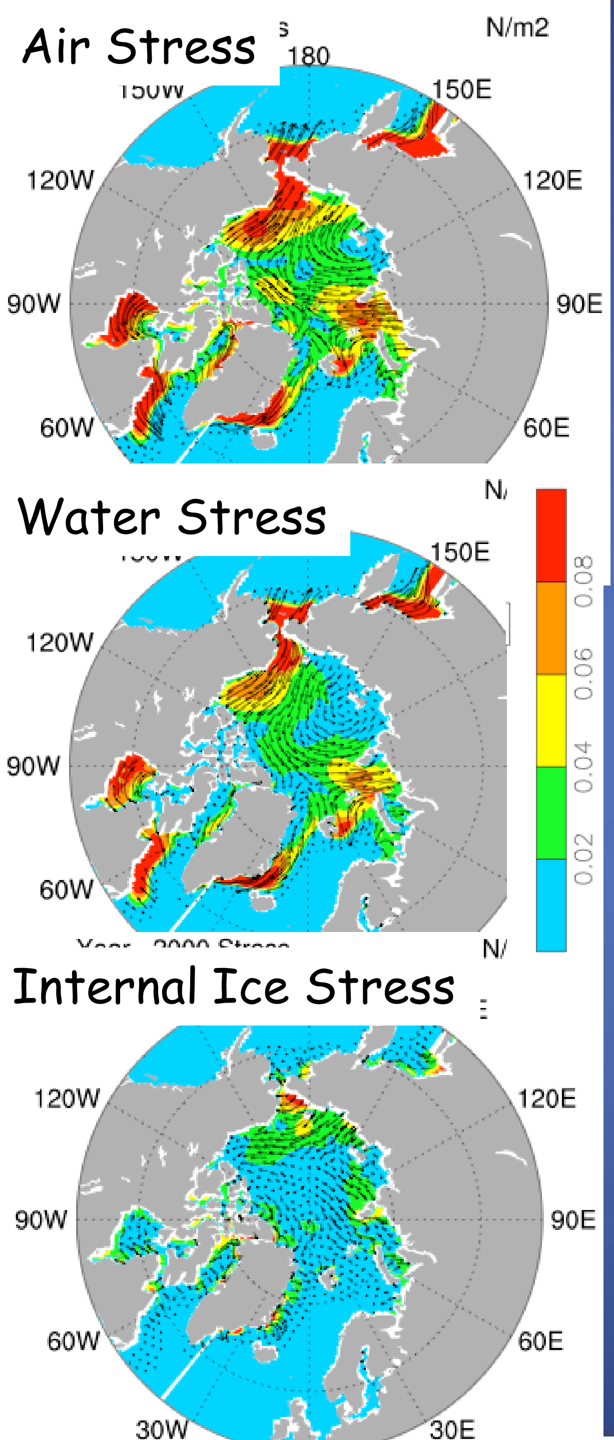
“Failure Stress”

Eliptical Yield Curve

Elastic-Viscous-Plastic Model

EVP model uses explicit time stepping by adding elastic waves to constitutive law (Hunke and Dukowicz, 1997)

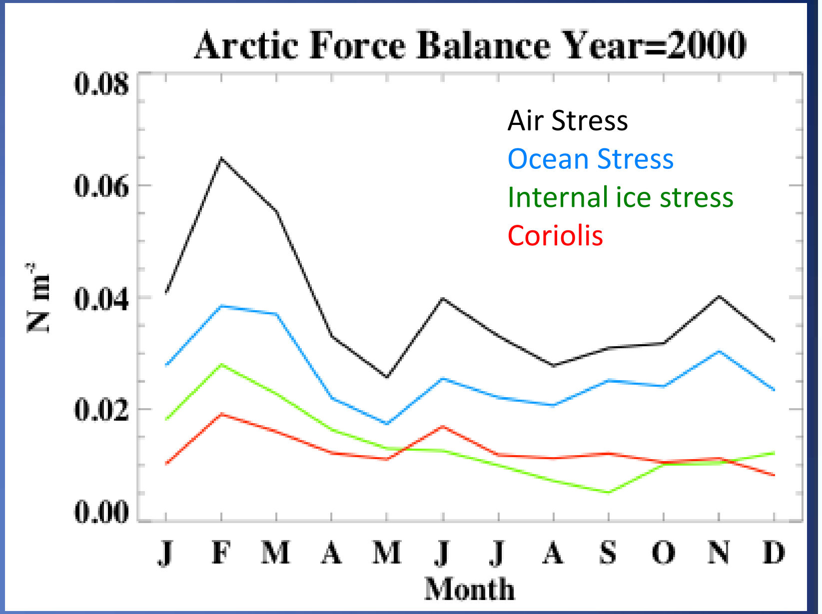
Simulated Force Balance

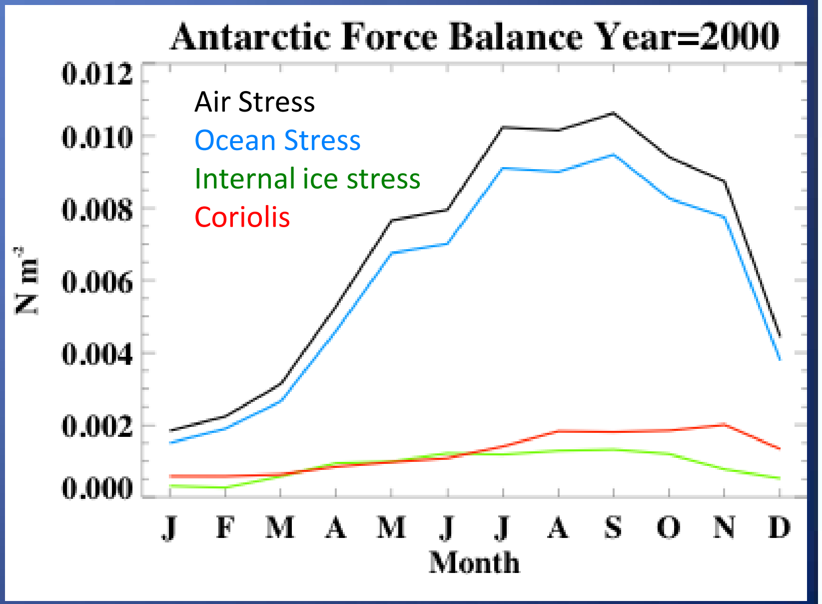

Air Stress

Water Stress

Internal Ice Stress

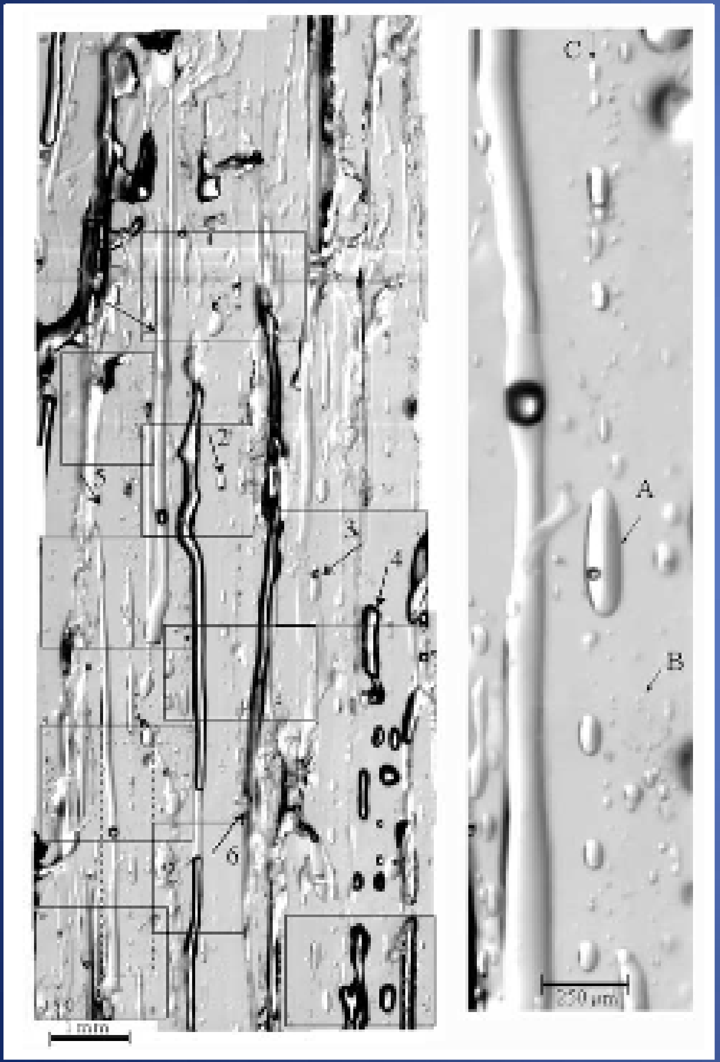
- Air stress largely balanced by ocean stress.
- Internal ice stress has smaller role
- In Antarctic ice in nearly free drift - weak ice interaction term





Thermodynamics
Vertical heat transfer

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z} + Q_{SW}$$



(from Light, Maykut, Grenfell, 2003)

- Assume brine pockets are in thermal equilibrium with ice
- Heat capacity and conductivity are functions of T/S of ice
- Assume constant salinity profile
- Assume non-varying density
- Assume pockets/channels are brine filled
- Traditionally:

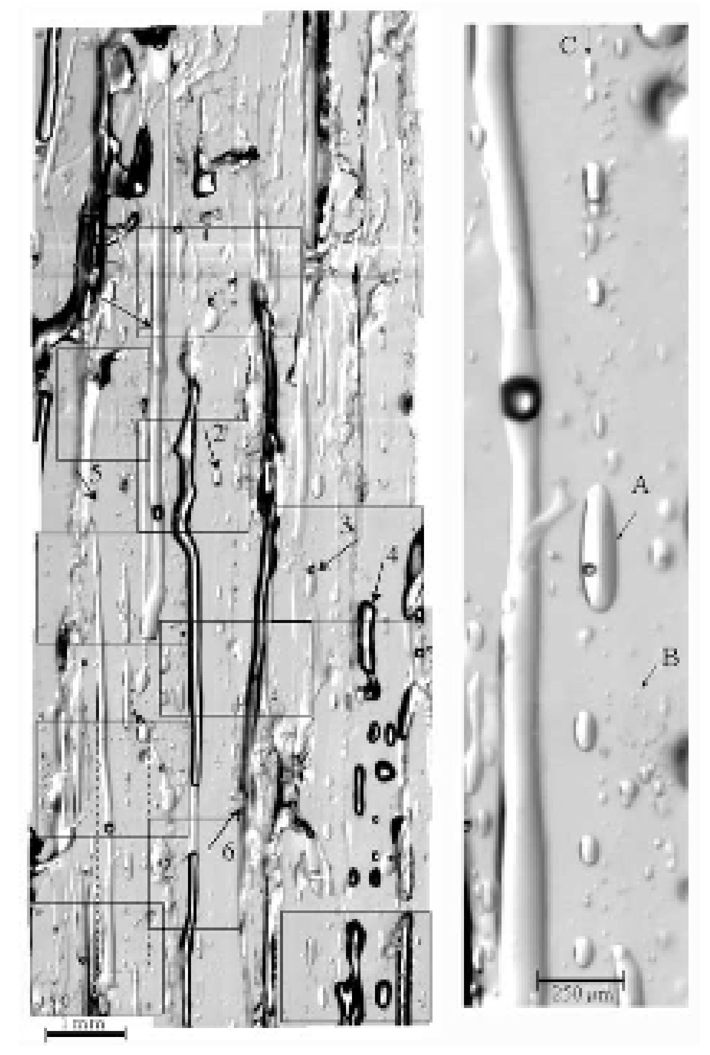
$$Q_{SW} = -\frac{d}{dz} I_{SW} e^{-\kappa z} \quad \text{where}$$

$$I_{SW} = i_0 (1-\alpha) F_{SW}$$

(Maykut and Untersteiner, 1971; Bitz and Lipscomb, 1999; others)

Thermodynamics Vertical heat transfer

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z} + Q_{SW}$$



(from Light, Maykut, Grenfell, 2003)

$$c(T, S) = c_o + \frac{\gamma S}{T^2}$$

where T is in Celsius,

$$\gamma = L_o \mu \quad \text{and} \quad T_m = -\mu S$$

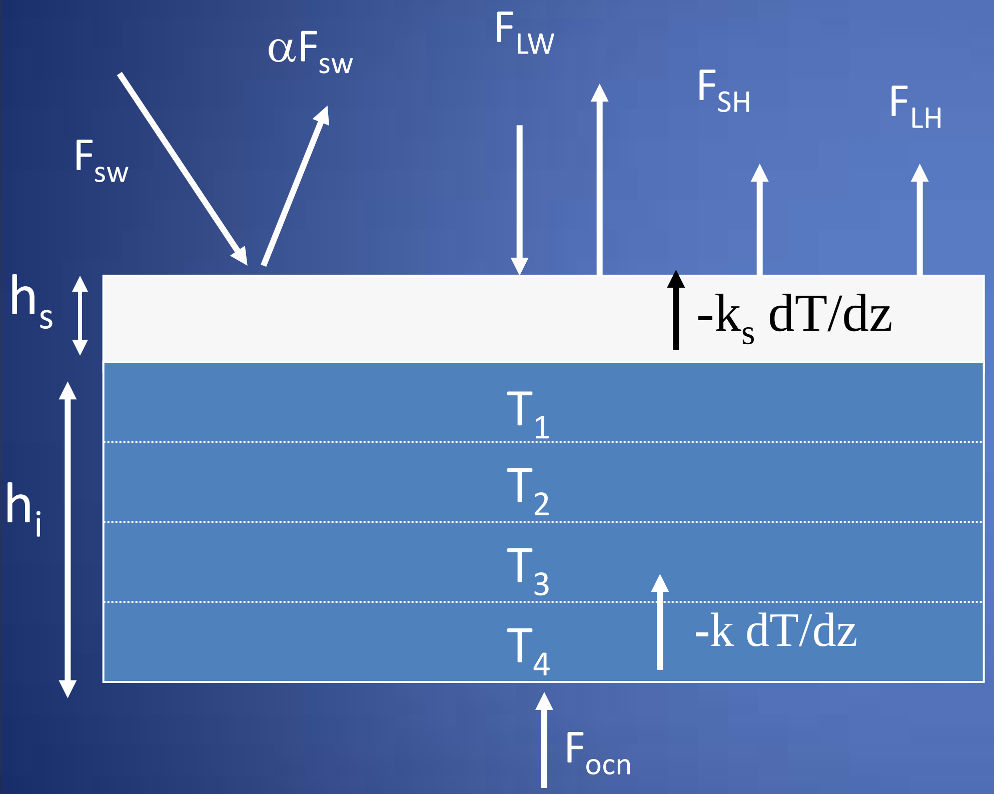
Untersteiner, 1961

Enthalpy:
Heat required to melt a unit of ice

$$q(S, T) = \rho c_o(-\mu S - T) + \rho L_o \left(1 + \frac{\mu S}{T}\right)$$

(Maykut and Untersteiner, 1971; Bitz and Lipscomb, 1999; others)

Sea ice thermodynamics



Balance of fluxes at surface

$$(1-\alpha)F_{SW} + F_{LW} - \sigma T^4 + F_{SH} + F_{LH} + k\frac{\partial T}{\partial z} = -q\frac{dh}{dt}$$

Vertical heat transfer (conduction, SW absorption)

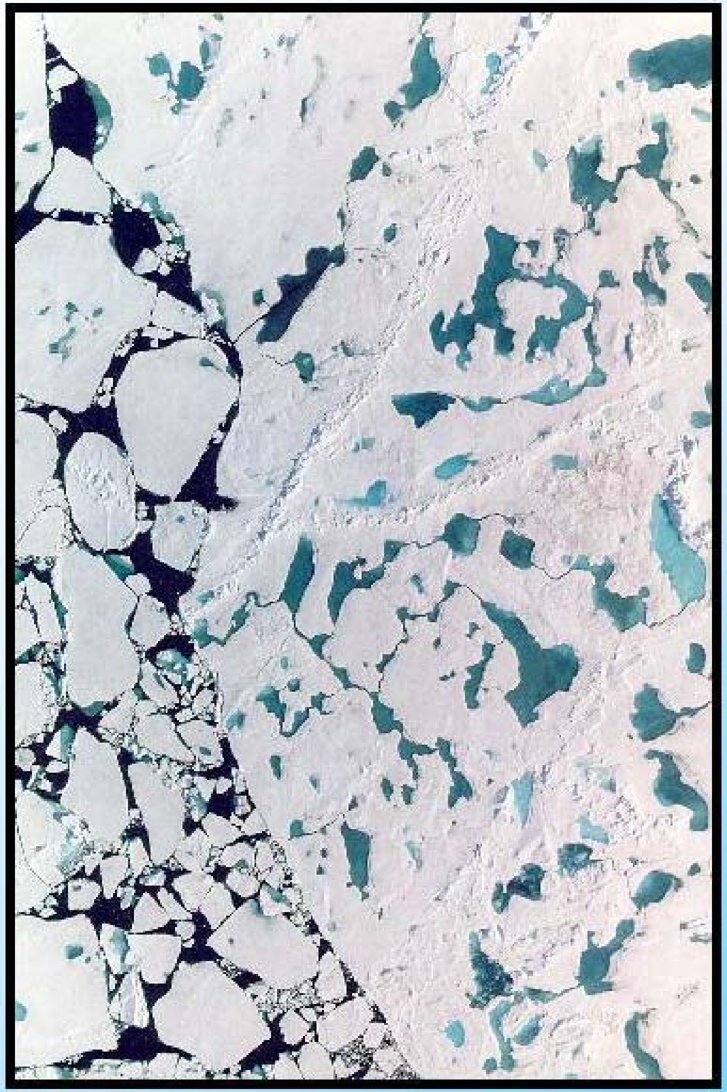
$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}k\frac{\partial T}{\partial z} + Q_{SW}$$

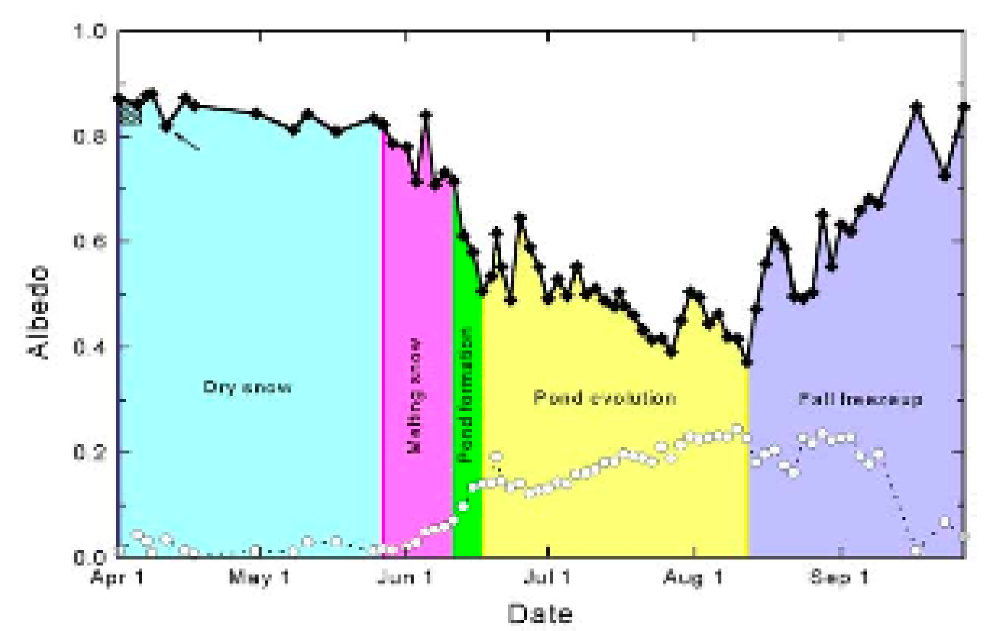
Balance of fluxes at ice base

$$F_{ocn} - k\frac{\partial T}{\partial z} = -q\frac{dh}{dt}$$

Allows us to compute surface melt (snow or ice), ice basal melt and ice growth

Albedo

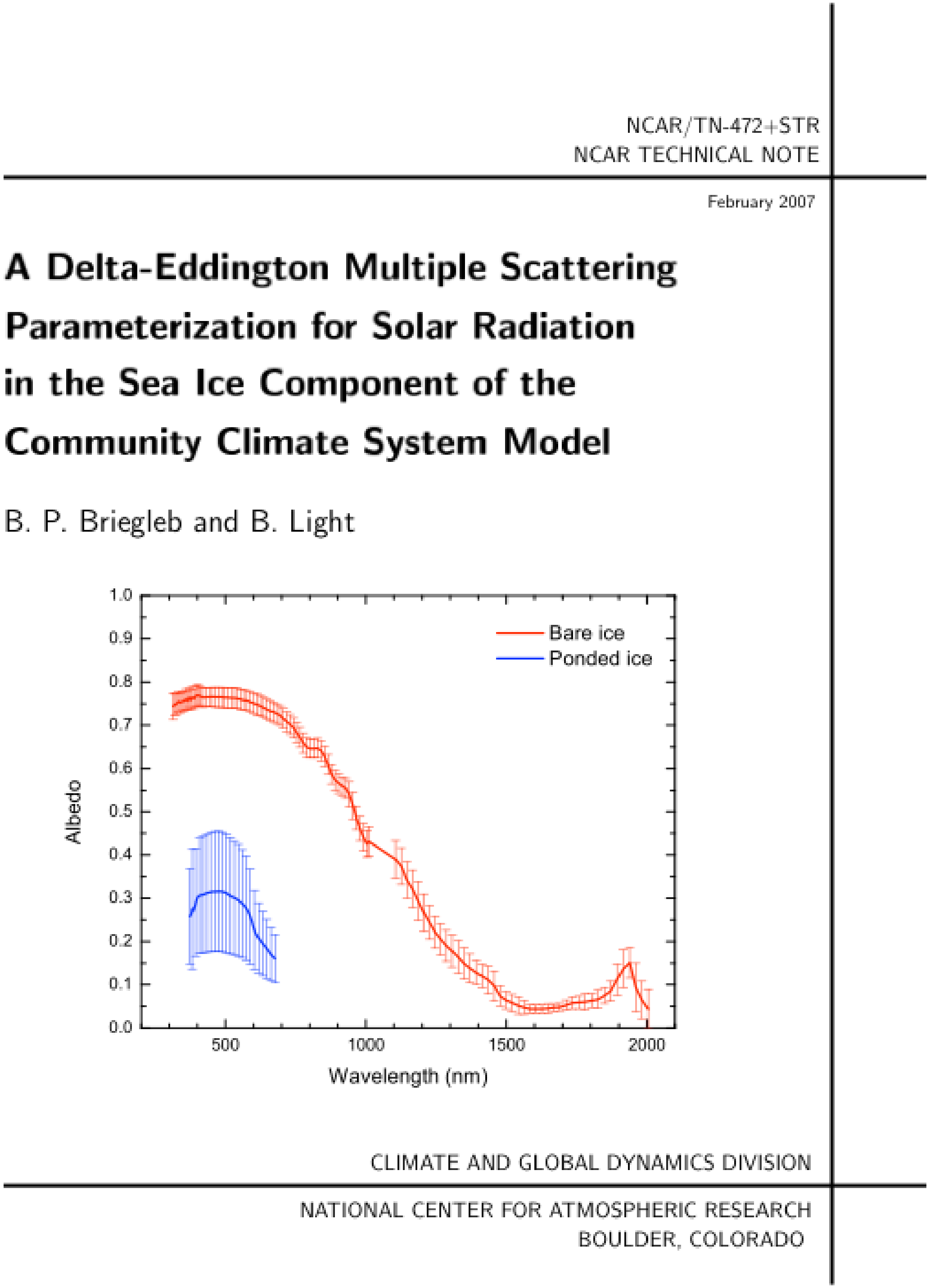




(Perovich et al., 2002)

Often the parameterized sea ice albedo depends on characteristics of surface state (snow, temp, ponding, h_i).

Surface albedo accounts for fraction of gridcell covered by ice vs open ocean



NCAR/TN-472+STR
NCAR TECHNICAL NOTE

February 2007

A Delta-Eddington Multiple Scattering Parameterization for Solar Radiation in the Sea Ice Component of the Community Climate System Model

B. P. Briegleb and B. Light

CLIMATE AND GLOBAL DYNAMICS DIVISION

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

New Solar Radiation parameterization

Better physics:

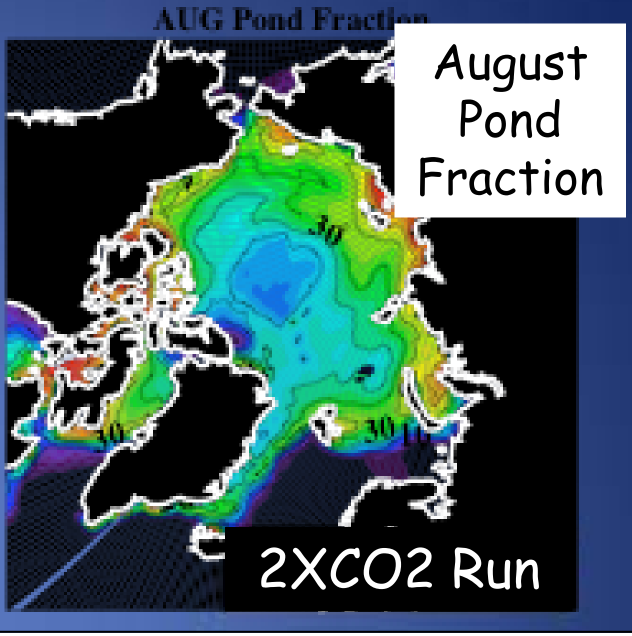
- makes use of inherent optical properties to define scattering and absorption of snow, sea ice and included absorbers

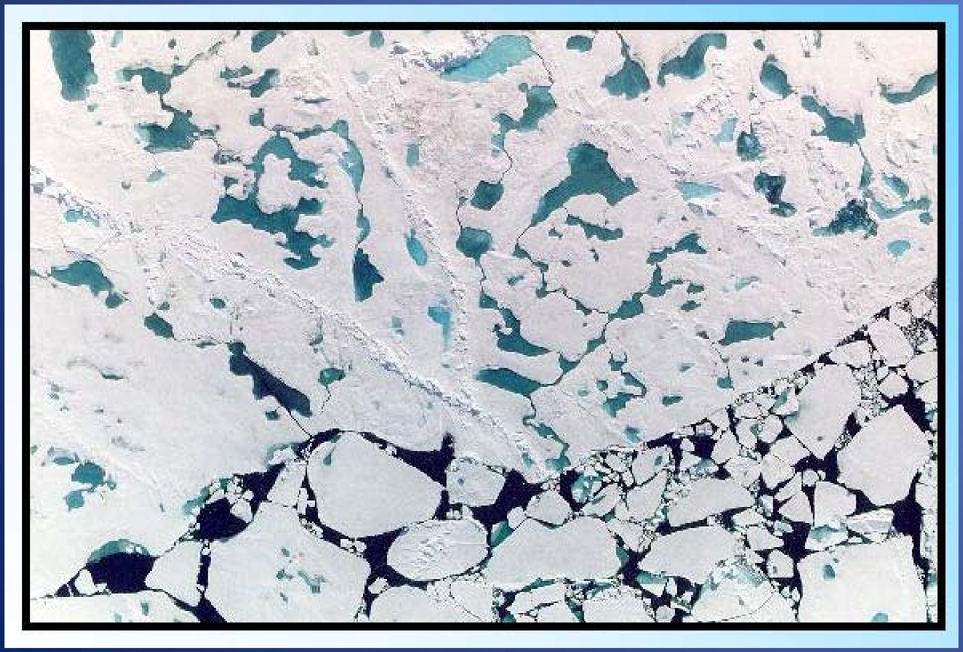
More flexible

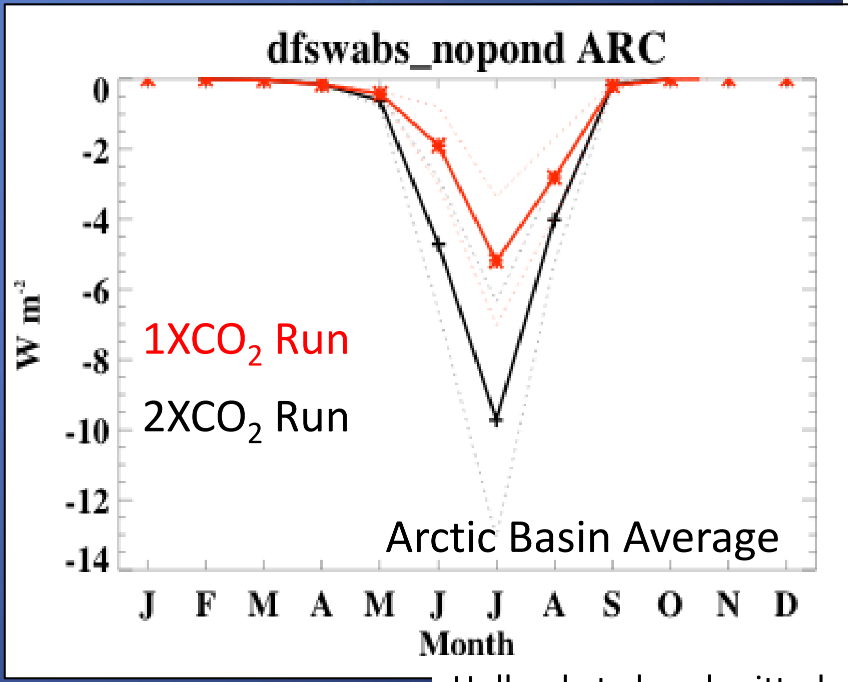
- Explicitly allows for included absorbers in sea ice

Melt Pond Parameterization

- New radiative transfer allows (requires) a pond parameterization
- Only influences radiation
- Pond volume depends on surface meltwater, assuming a runoff fraction





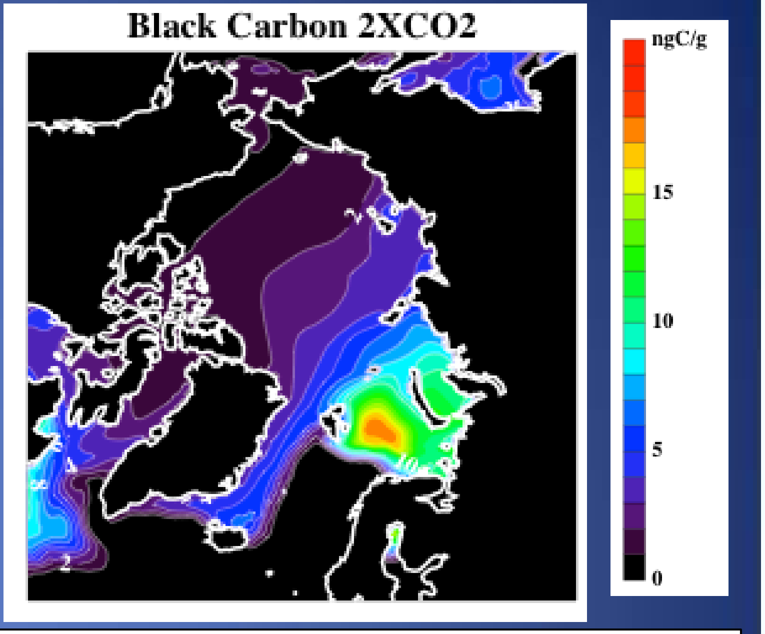


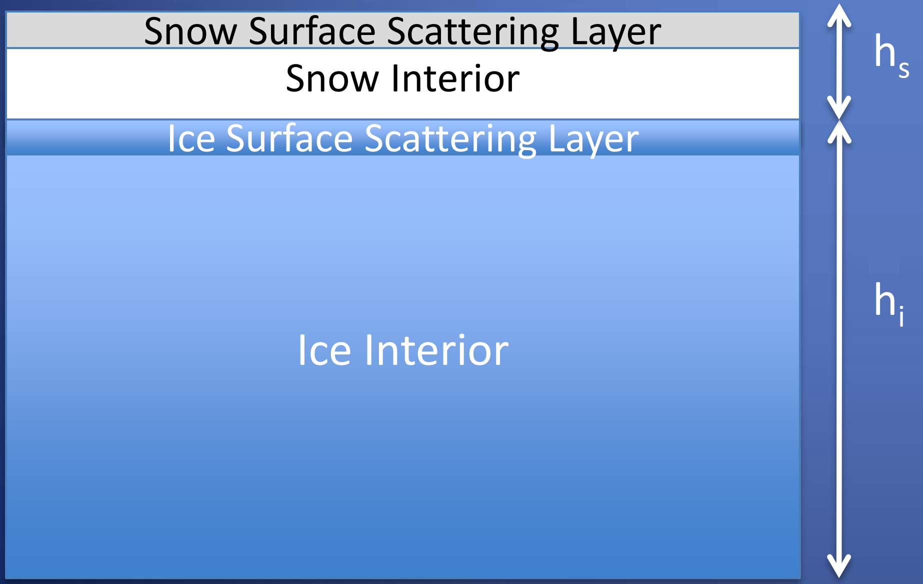
Holland et al., submitted

Aerosol deposition and cycling

- Aerosol deposition and cycling now included.
- Account for black carbon and dust aerosols
- These are deposited from the atmosphere and modified by melt and transport

With 1850 Aerosol Deposition




Snow Surface Scattering Layer

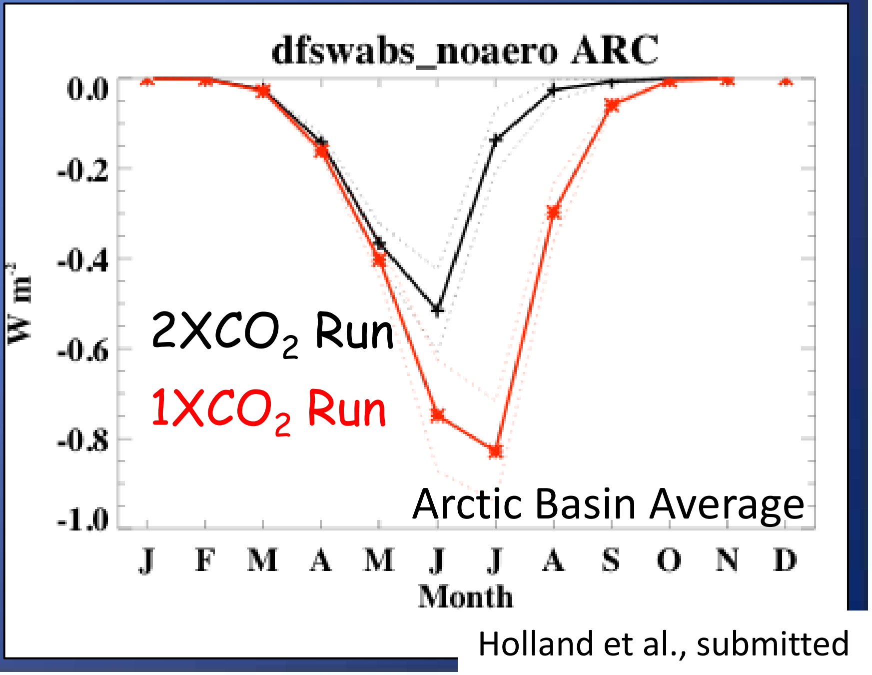
Snow Interior

Ice Surface Scattering Layer

Ice Interior

h_s

h_i



Holland et al., submitted

State variables for each category:

A, V, V_s, $E(z)$, $E_s(z)$, T_{surf}, melt pond state, aerosol contents (z), etc.

A = category area per unit gridcell area (or fractional coverage)

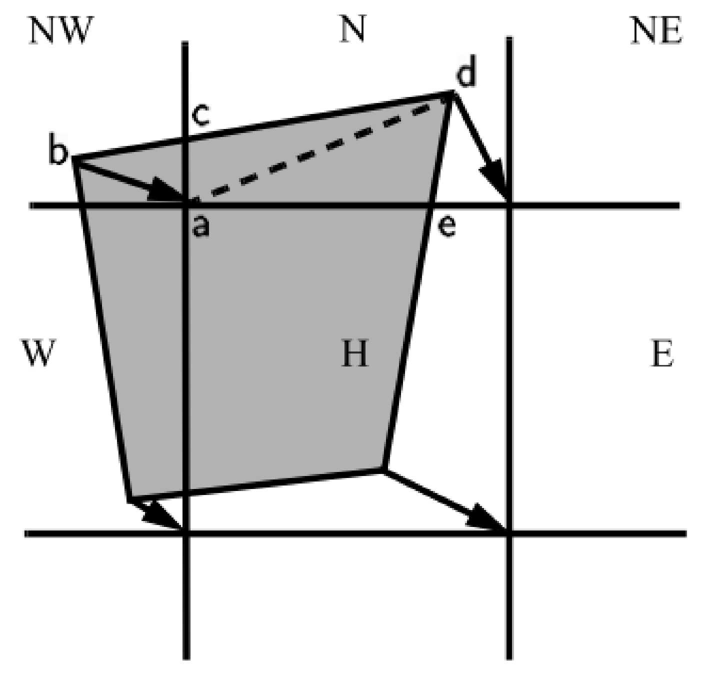
$V = hA$ is the category volume per unit gridcell area

$E = Vq$ is the category enthalpy per unit gridcell area

V and E are preferred as state variables because they are conserved quantities (rather than T).

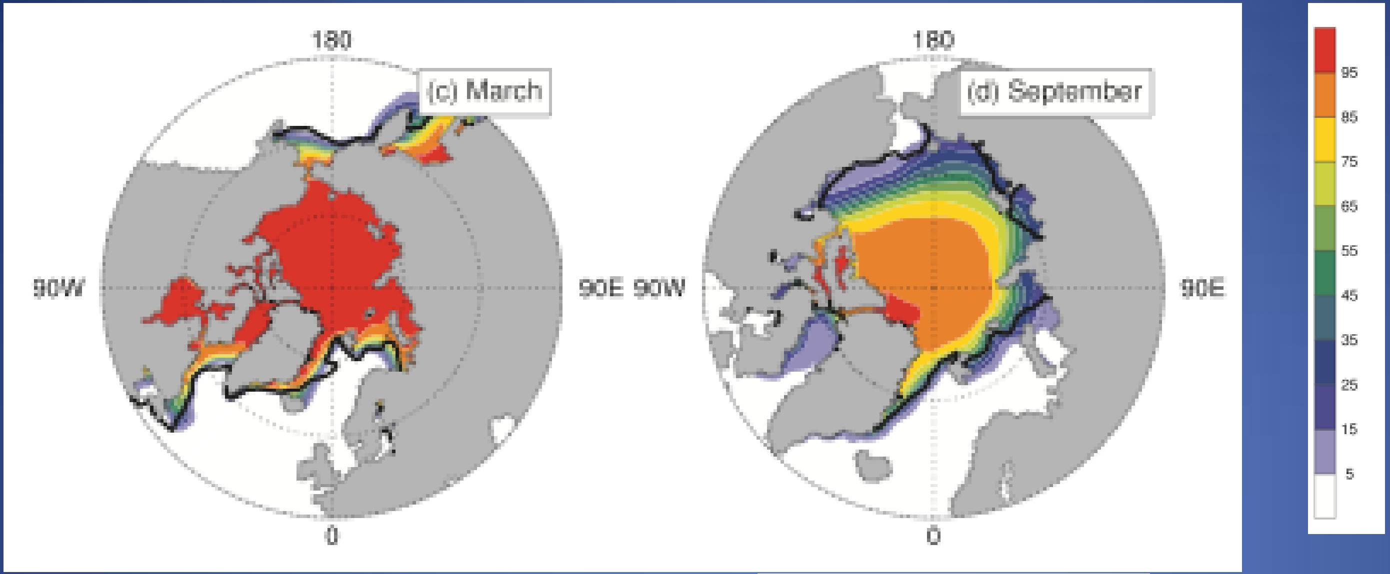
Advection

Would make so many state variables prohibitive, if it weren't for remapping by Lipscomb and Hunke 2004

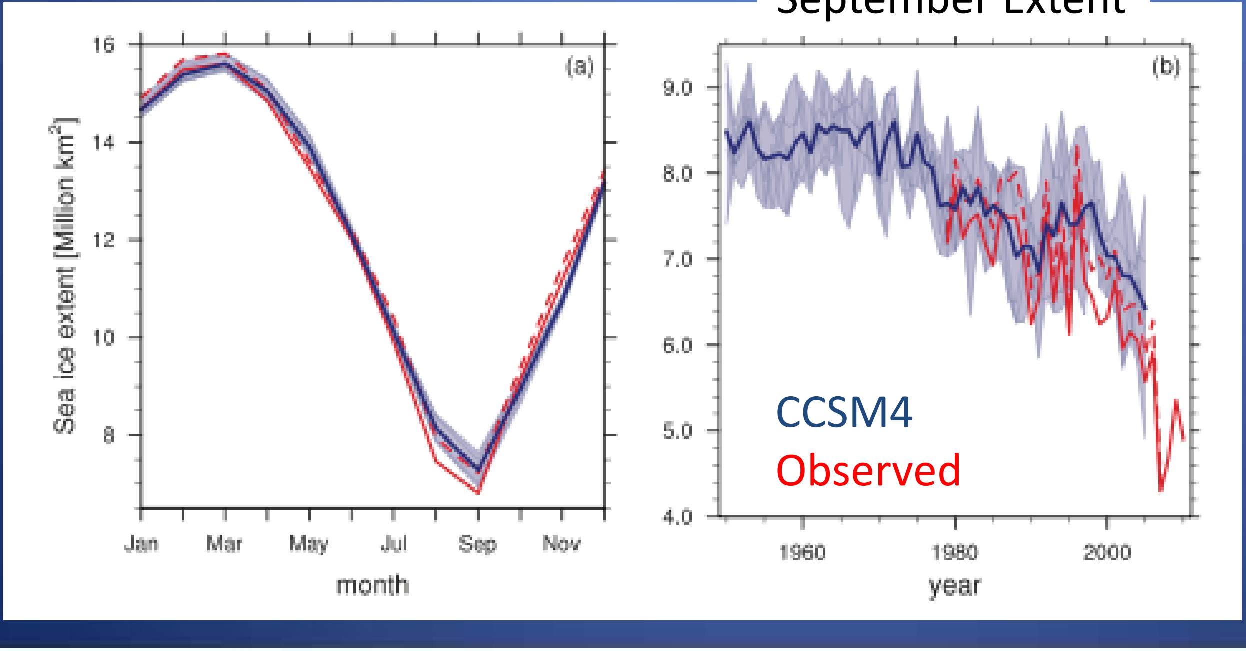


conserved quantities are remapped from the shaded "departure region", which is computed from backward trajectories of the ice motion field

CCSM4 Simulation of Arctic sea ice cover

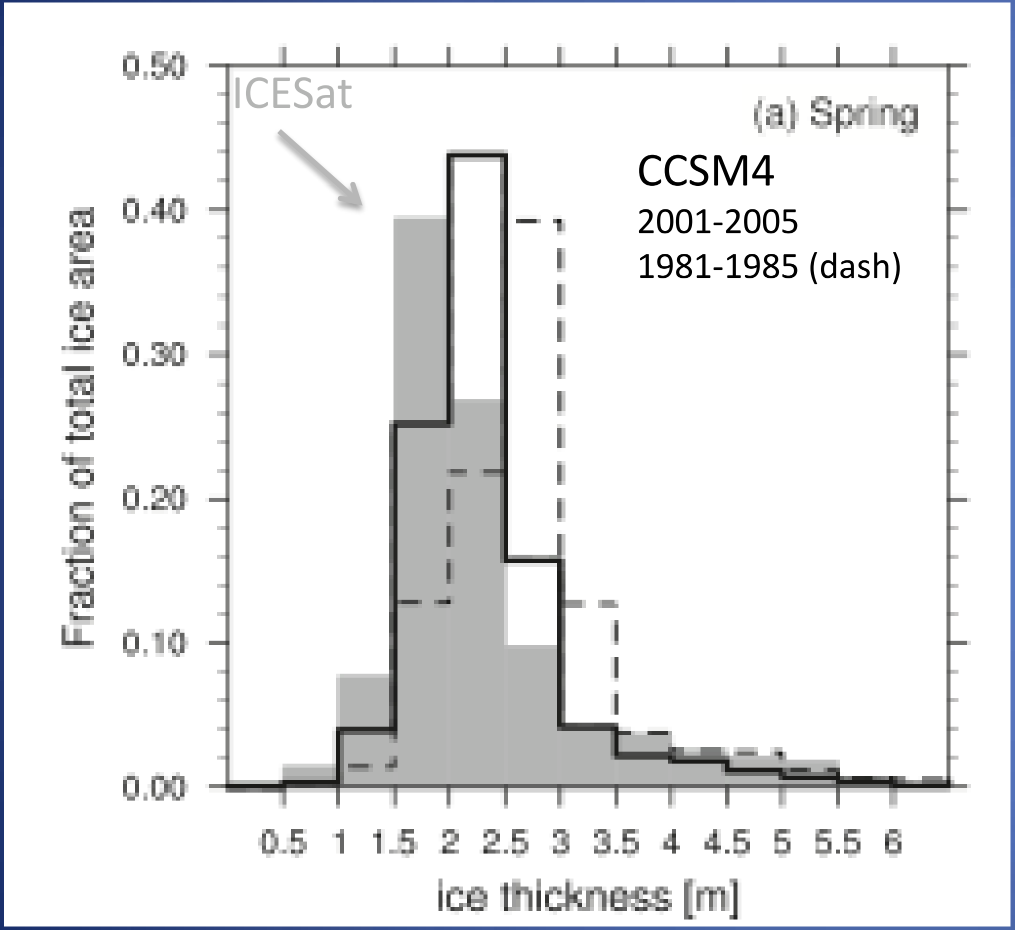


September Extent



From Jahn et al., submitted

CCSM4 Simulation of Arctic sea ice thickness



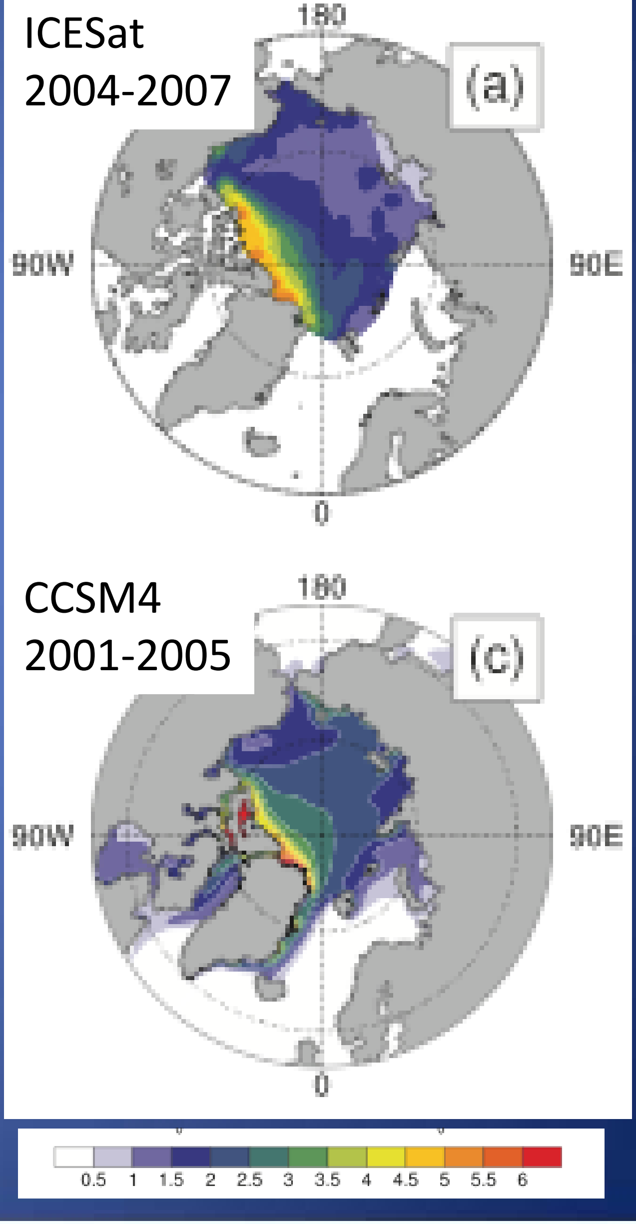
ICESat

CCSM4

2001-2005

1981-1985 (dash)

Feb/March Thickness

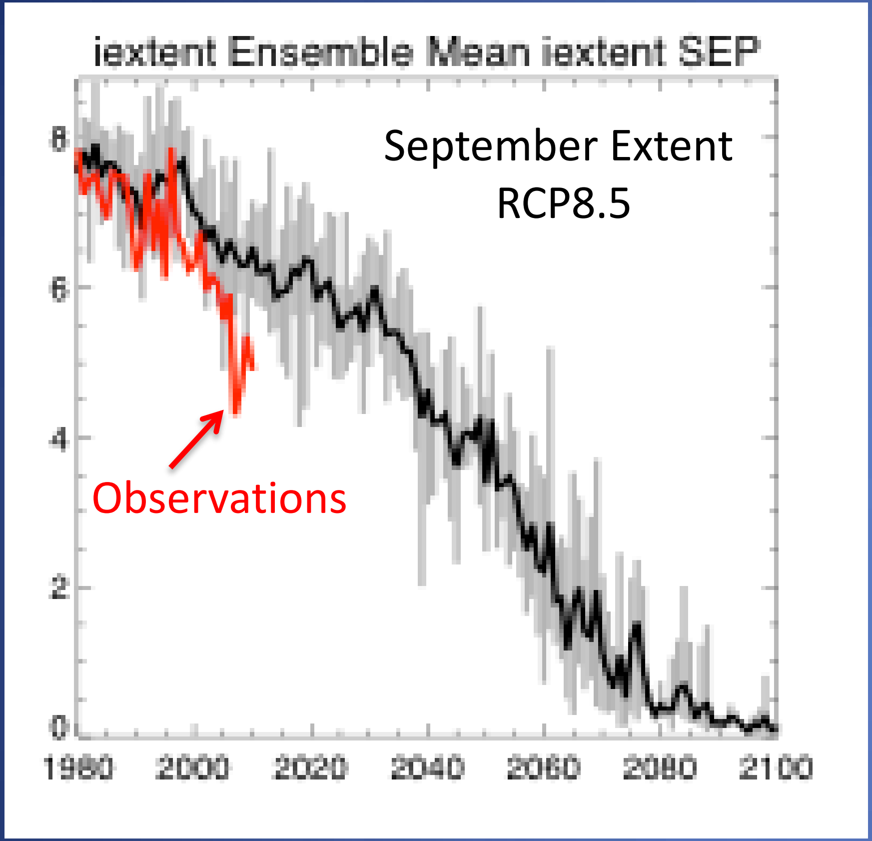


ICESat 2004-2007

CCSM4 2001-2005

From Jahn et al., submitted

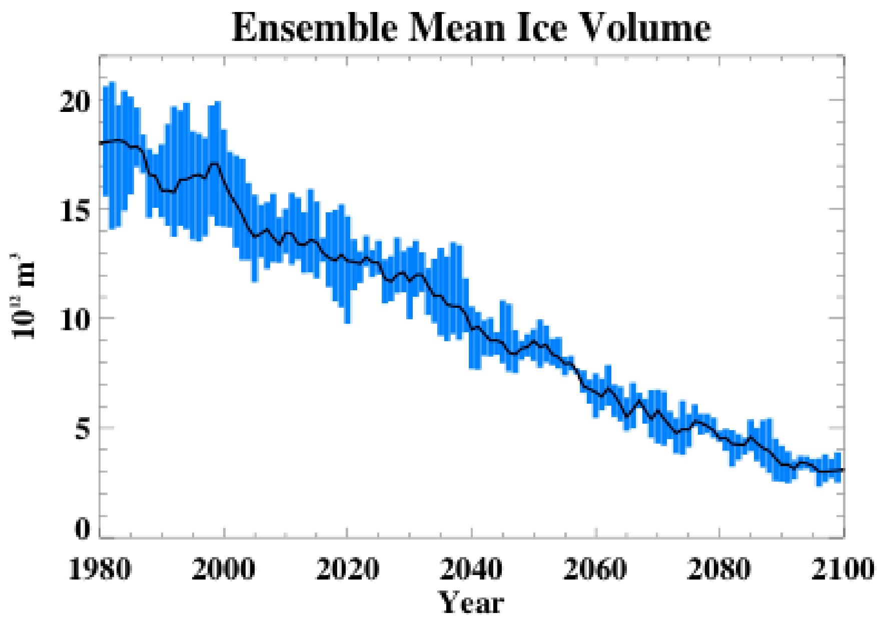
CCSM4 21st Arctic Ice Loss

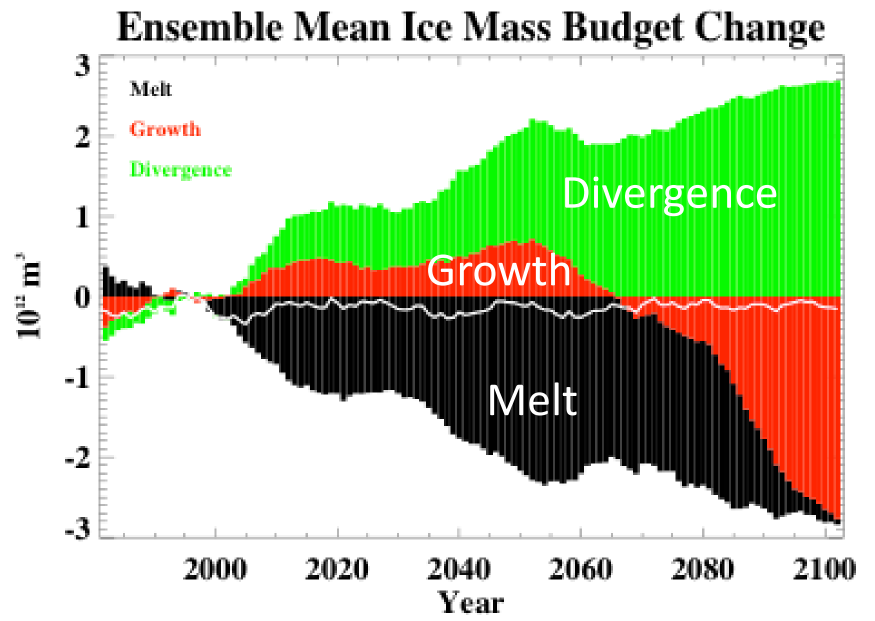


September Extent
RCP8.5

Observations

(Vavrus et al., submitted)



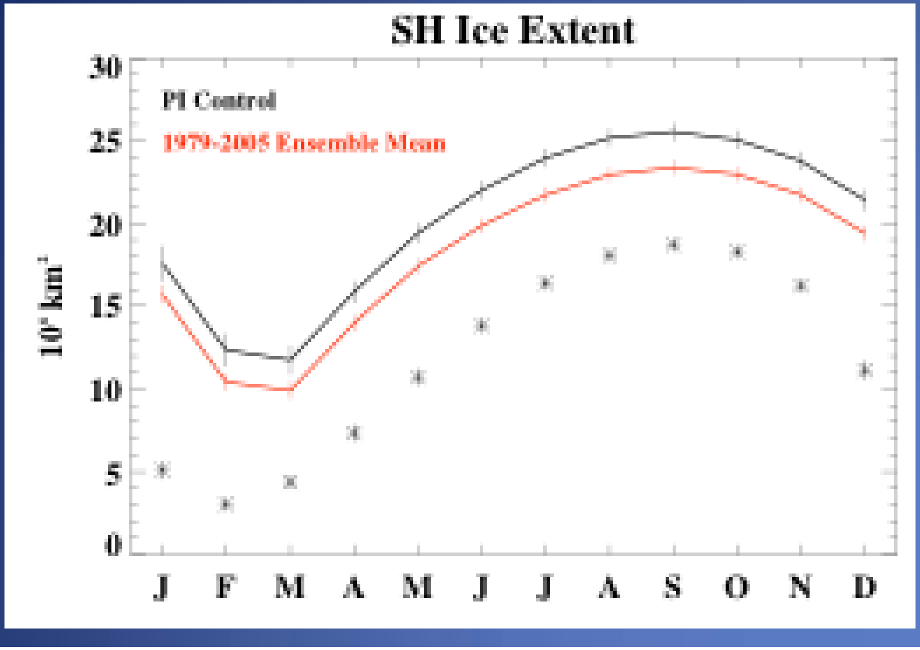


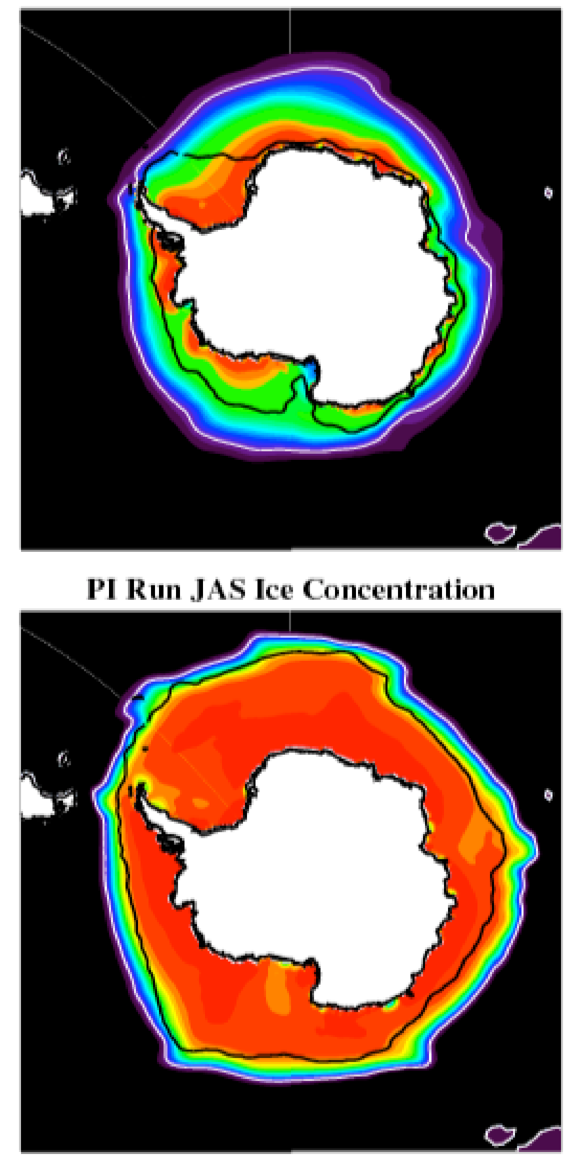
Divergence

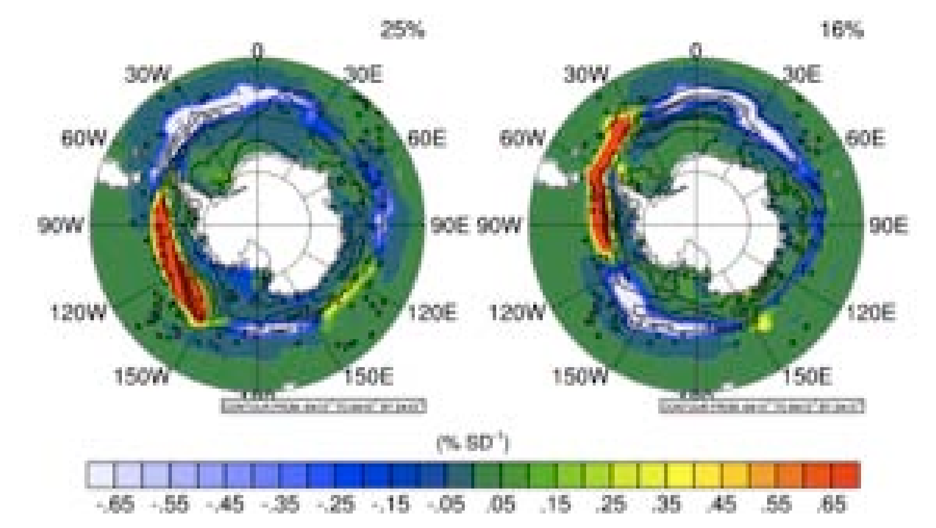
Growth

Melt

CCSM4 Simulation of Antarctic sea ice







From Landrum et al., submitted

Summary

- CESM1 uses the Los Alamos CICE model
- This includes
  - EVP dynamics,
  - a subgridscale ice thickness distribution and
  - thermodynamics that account for brine inclusions
- CCSM4 simulates very good Arctic sea ice
- CCSM4 Antarctic sea ice is too extensive but variability in ice concentration looks realistic

Where are we heading?

- Prognostic salinity
- Biogeochemistry
- More sophisticated melt pond modeling
- Snow model improvements
- Improved ice-ocean coupling

Much of this work is being done by collaborators at DOE Labs (primarily LANL) and Universities.

Questions?