Sea Ice Modeling for Climate Applications

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With contributions from: Marika Holland (NCAR), Jennifer Kay (U. Colorado), Cecilia Bitz (U. Washington), Elizabeth Hunke (LANL), Nicole Jeffery (LANL), Adrian Turner (LANL), Andrew Roberts (NPS), and Tony Craig (FA)

NCAR is sponsored by the National Science Foundation.

1 km

10 m

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

440 m

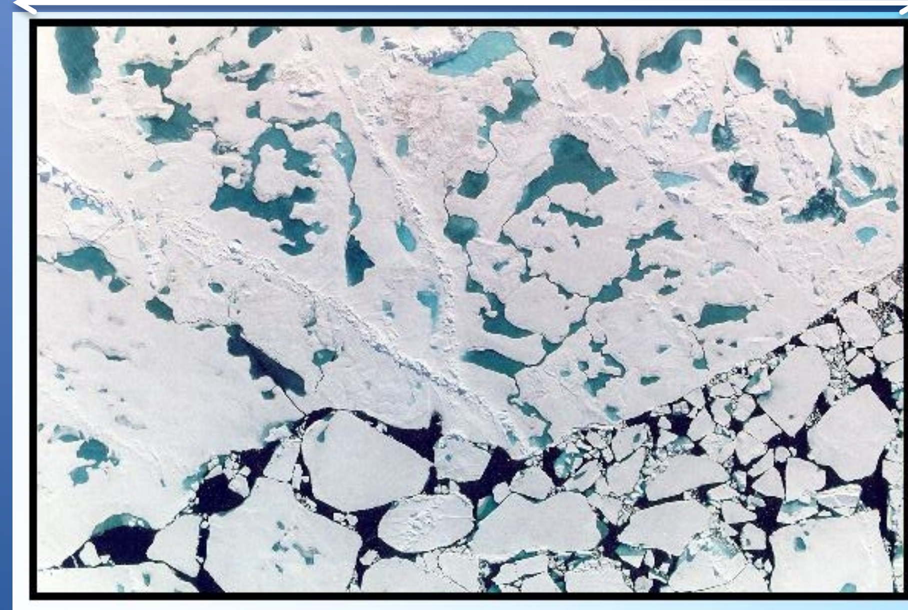
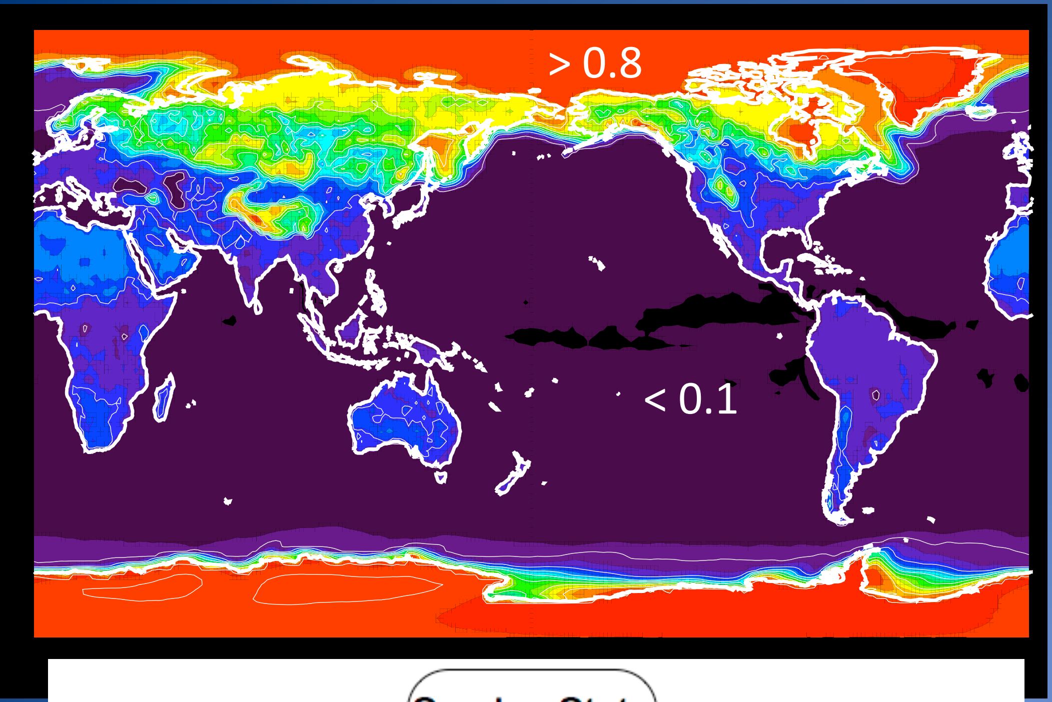
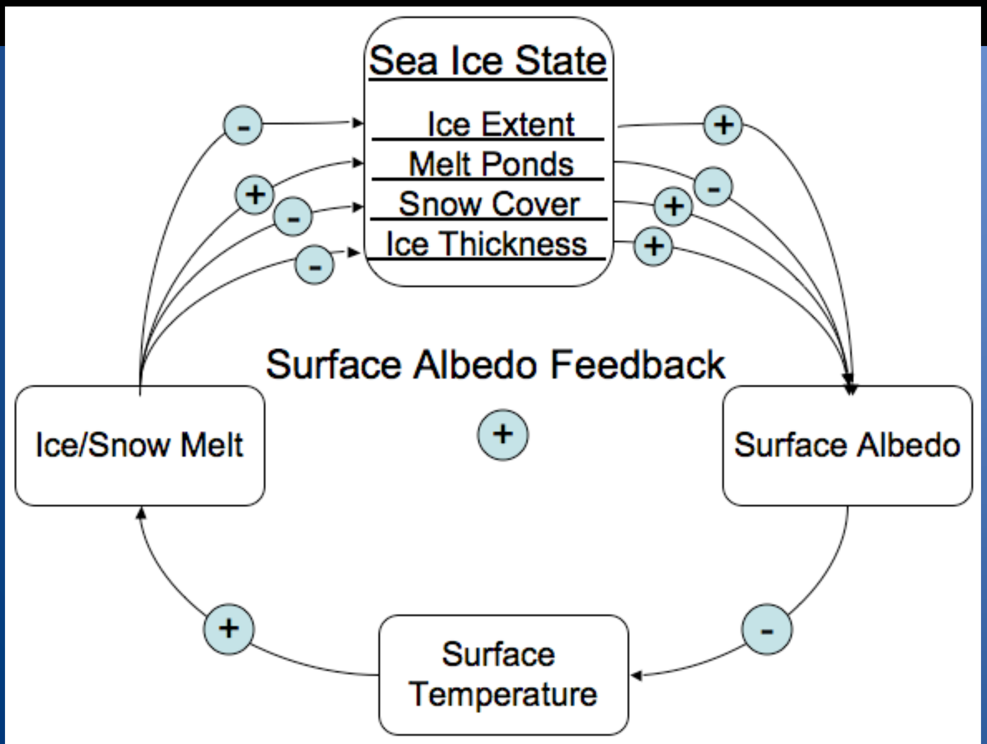


Photo courtesy of Don Perovich

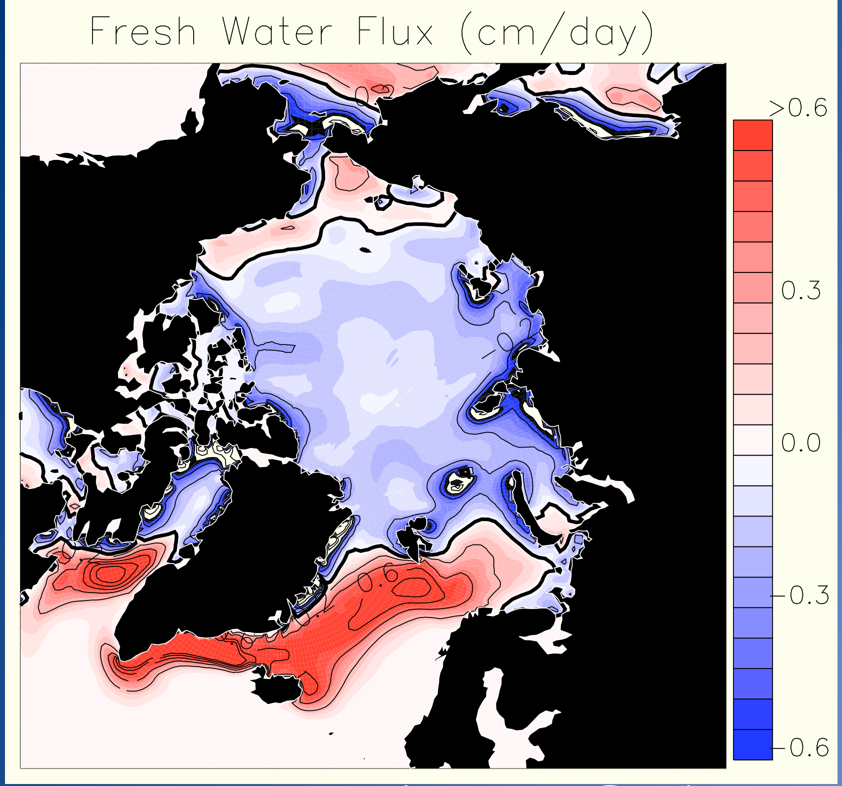
Surface albedo





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

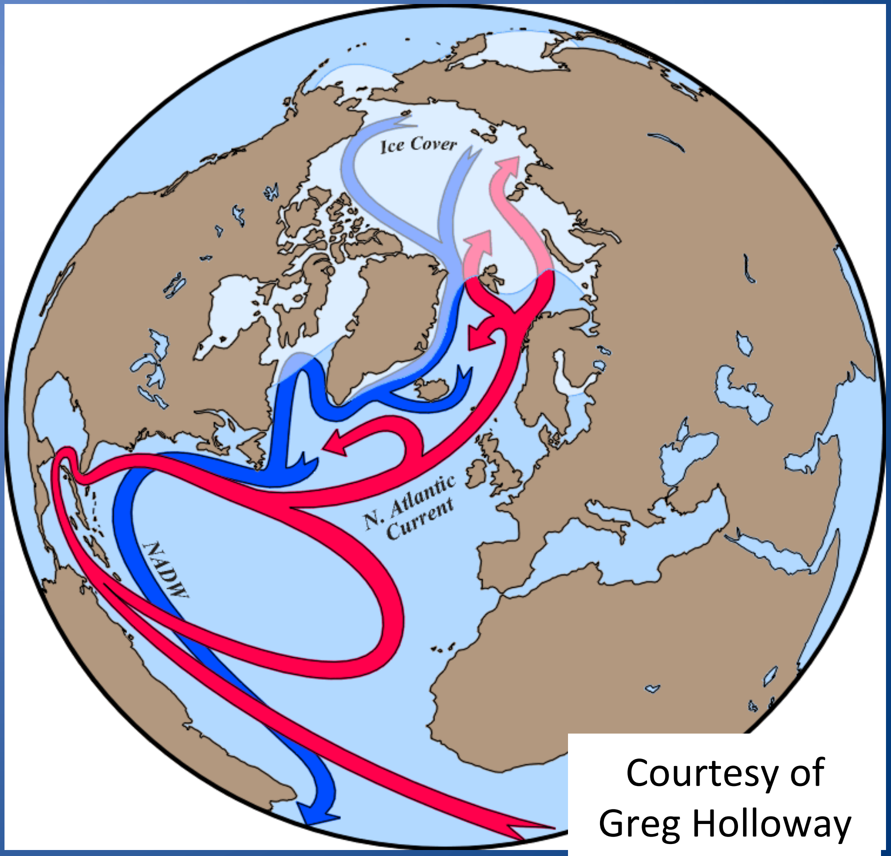
- High albedo of sea ice modifies radiative fluxes
- Sea ice insulates ocean from atmosphere influencing turbulent heat & moisture exchange



Ice-Ocean Freshwater Exchange

Why do we care about sea ice? Hydrological Cycle

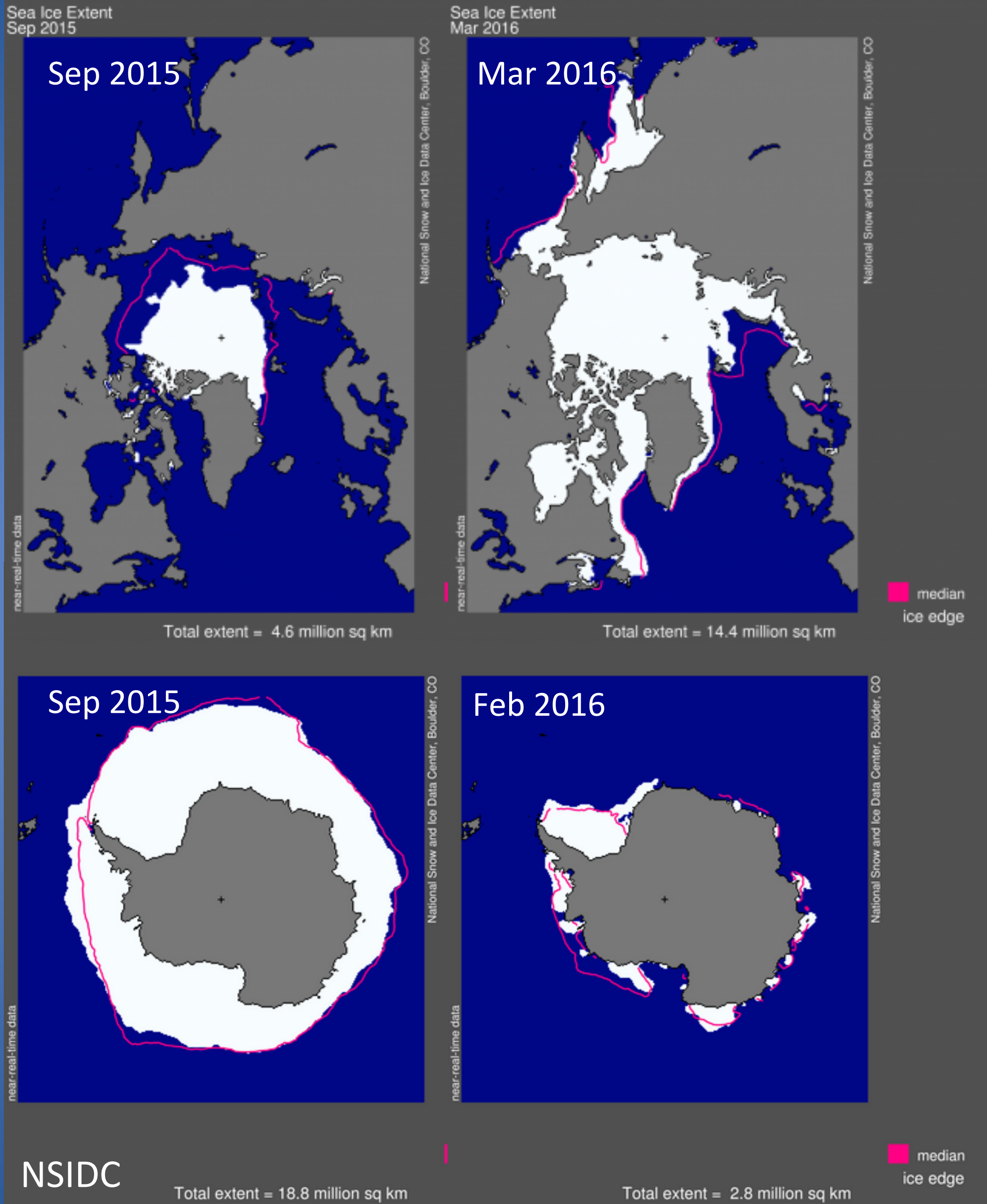
- Salt rejection during ice formation leaves sea ice relatively fresh (salt flux to ocean)
- Ice melt releases freshwater back to the ocean
- Can modify ocean circulation



Courtesy of Greg Holloway

Contrasting the Hemispheres

- Arctic Ocean surrounded by land (thicker ice).
- Southern Ocean unbounded (free drift).
- Larger seasonal cycle in south.
- Winter extent set by ocean in south and land/ocean in north.



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 5.1
LA-CC-06-012

Elizabeth C. Hunke, William H. Lipscomb,
Adrian K. Turner, Nicole Jeffery, Scott Elliott
Los Alamos National Laboratory
Los Alamos NM 87545

March 17, 2015

CESM1 uses the CICE Los Alamos Sea Ice Model (Hunke et al.)

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, 50% for AR5?) models also include
  - Ice Thickness Distribution
    - Subgridscale parameterization
    - Accounts for high spatial heterogeneity in ice

Dynamics

NOAA

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)

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

Sea Ice Model – Dynamics

- Air Stress

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

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

- 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)

$$\underbrace{\mathrm{m}\frac{\mathbf{Du}}{\mathrm{Dt}}}_{\text{Total derivative}} = \underbrace{-\mathrm{mf}\mathbf{k} \times \mathbf{u}}_{\text{Coriolis}} + \underbrace{\boldsymbol{\tau}_{\mathrm{a}}}_{\text{Air stress}} + \underbrace{\boldsymbol{\tau}_{\mathrm{w}}}_{\text{Ocean stress}} - \underbrace{\mathrm{mg_r}\nabla\mathrm{Y}}_{\text{Sea Surface Slope}} + \underbrace{\nabla \cdot \sigma}_{\text{Internal Ice Stress}}$$

Sea Ice Model – Dynamics

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

(e.g. Hibler, 1979)

$$\underbrace{\mathrm{m}\frac{\mathrm{D}\mathbf{u}}{\mathrm{Dt}}}_{\text{Total derivative}} = \underbrace{-\mathrm{mf}\mathbf{k} \times \mathbf{u}}_{\text{Coriolis}} + \underbrace{\boldsymbol{\tau}_{\mathrm{a}}}_{\text{Air stress}} + \underbrace{\boldsymbol{\tau}_{\mathrm{w}}}_{\text{Ocean stress}} - \underbrace{\mathrm{mg_r}\nabla \mathrm{Y}}_{\text{Sea Surface Slope}} + \underbrace{\nabla \cdot \sigma}_{\text{Internal Ice Stress}}$$

Sea Ice Model – Dynamics

- Ice Interaction Term (Internal Ice Stress)
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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

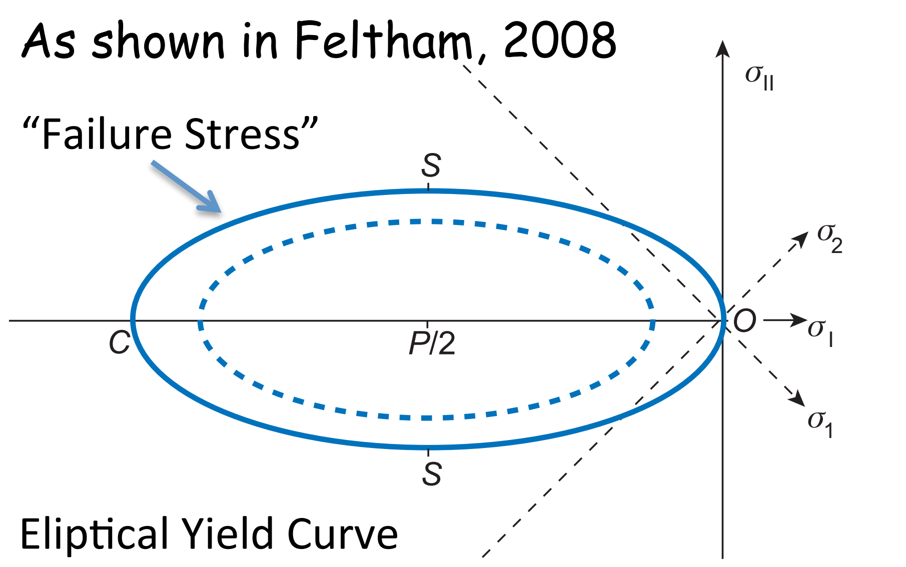
$L+\delta L$

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

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

Sea Ice Model – Dynamics

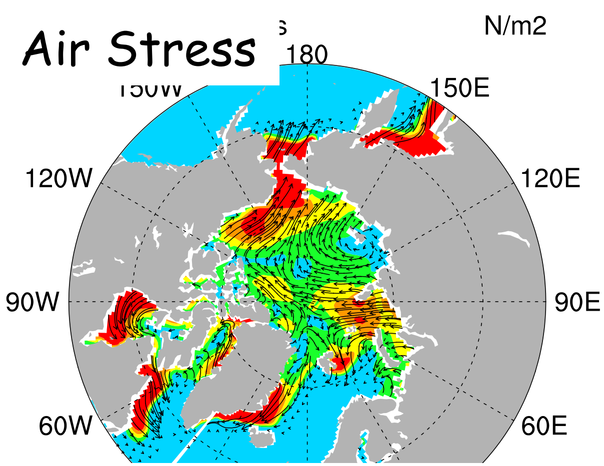
- Ice Interaction Term (Internal Ice Stress)
  - Use variant of Viscous-Plastic Rheology (Hibler, 1979)
  - Treats ice as a continuum - plastic at normal strain rates and viscous at very small strain rates.
  - Ice has no tensile strength (freely diverges) but resists convergence and shear (strength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

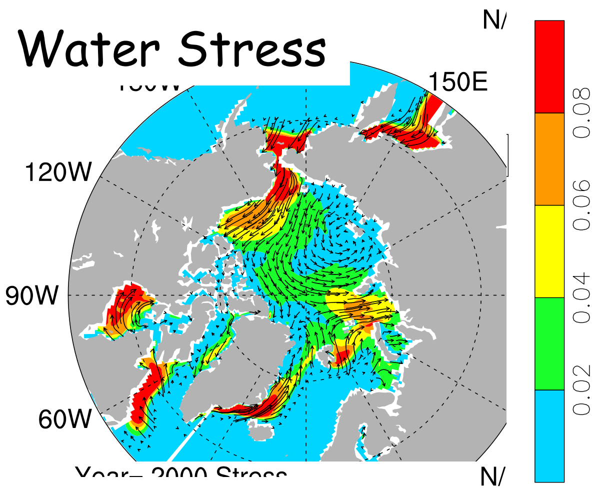


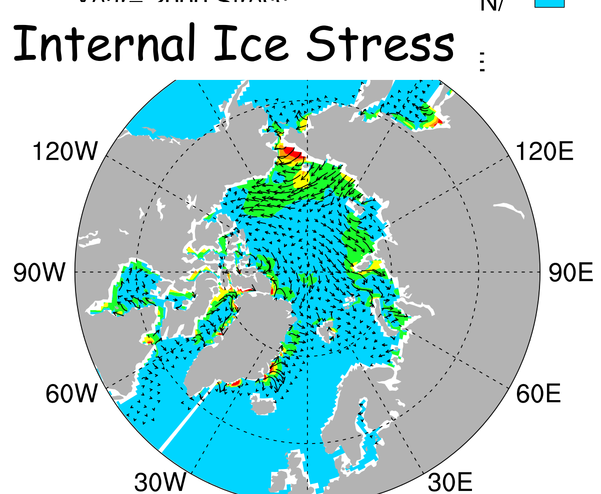
Elastic-Viscous-Plastic Model

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

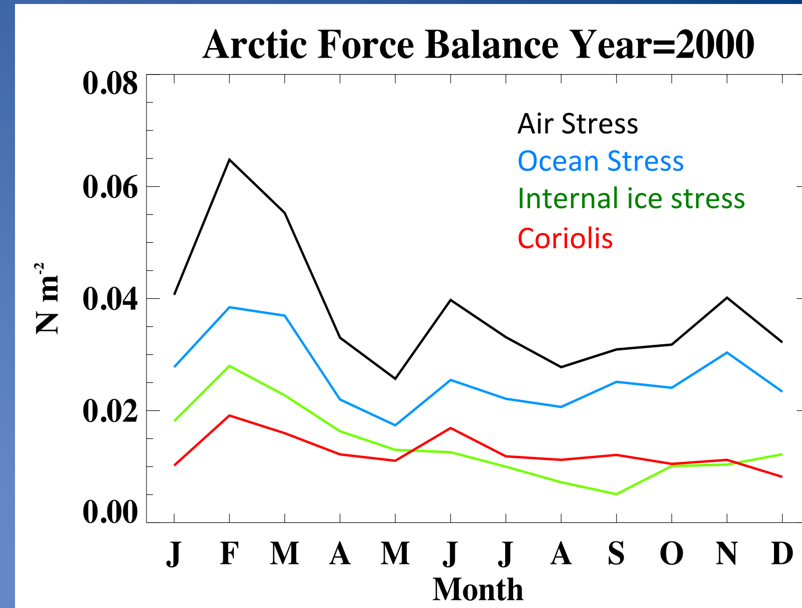
Simulated Force Balance

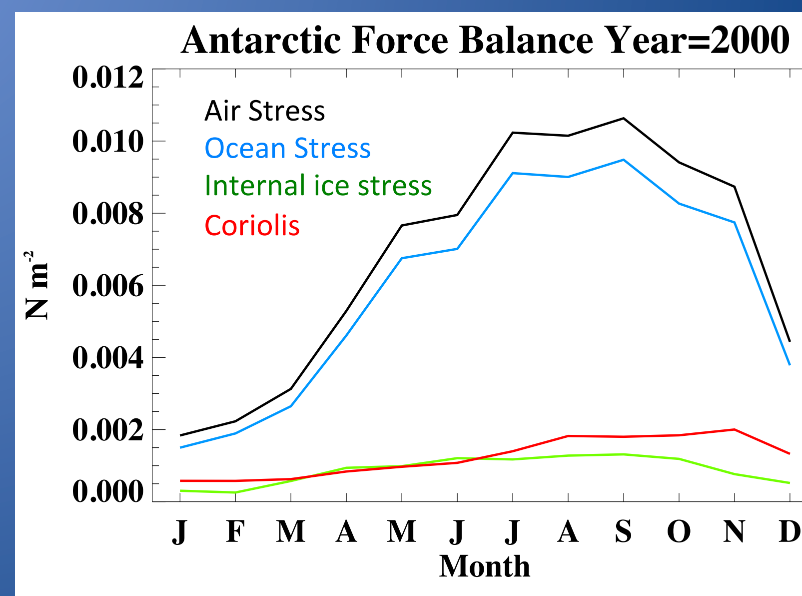




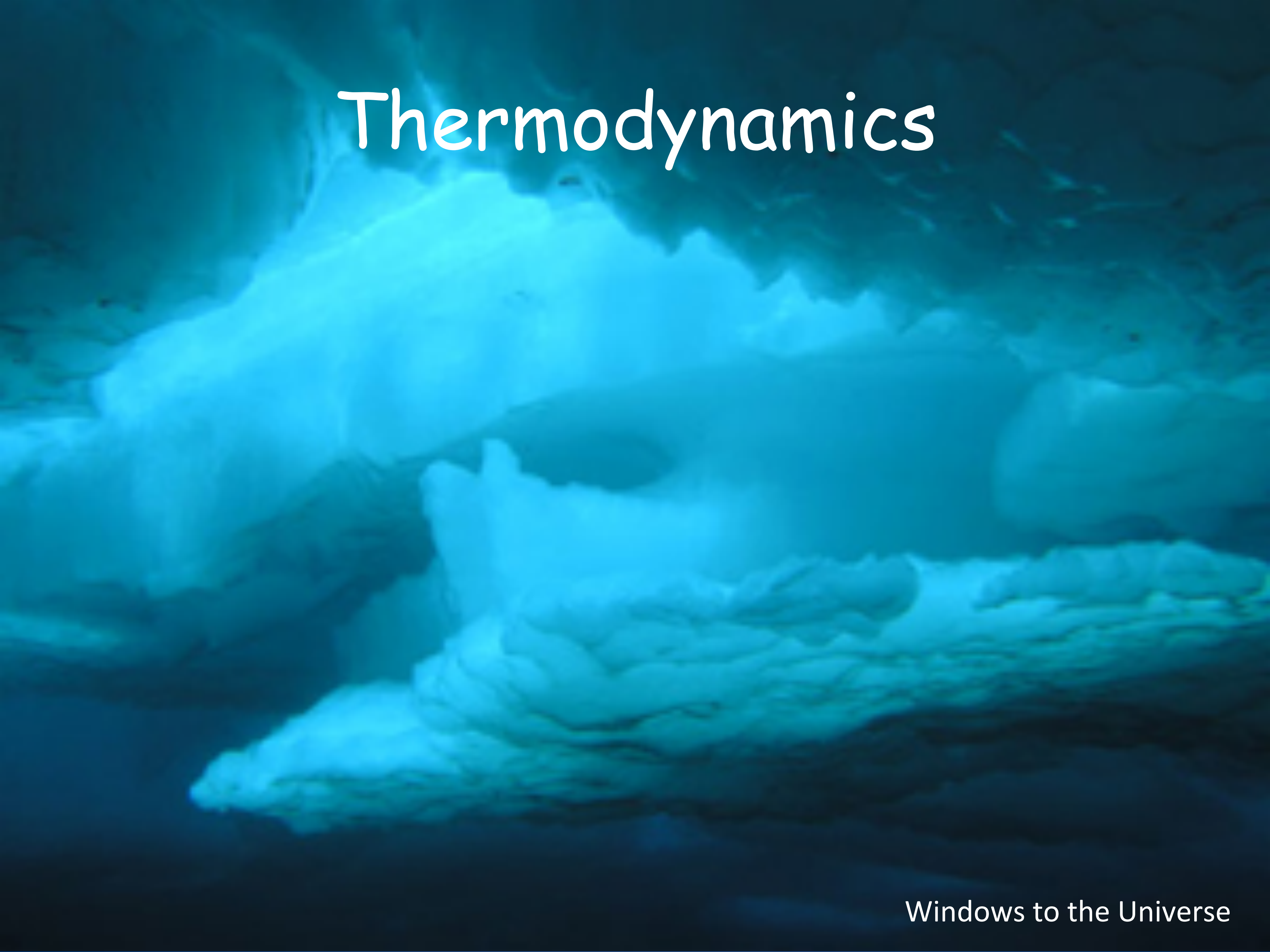


- Air stress largely balanced by ocean stress.
- Internal ice stress has smaller role
- In Antarctic ice in nearly free drift - weak ice interaction term





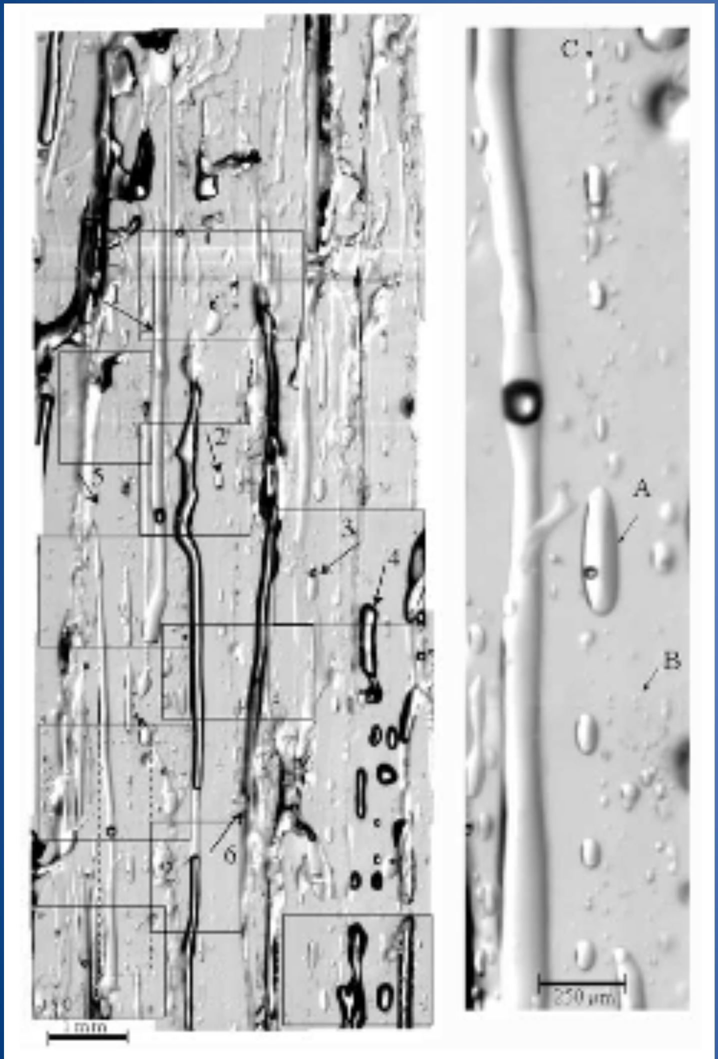
Thermodynamics



Windows to the Universe

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:

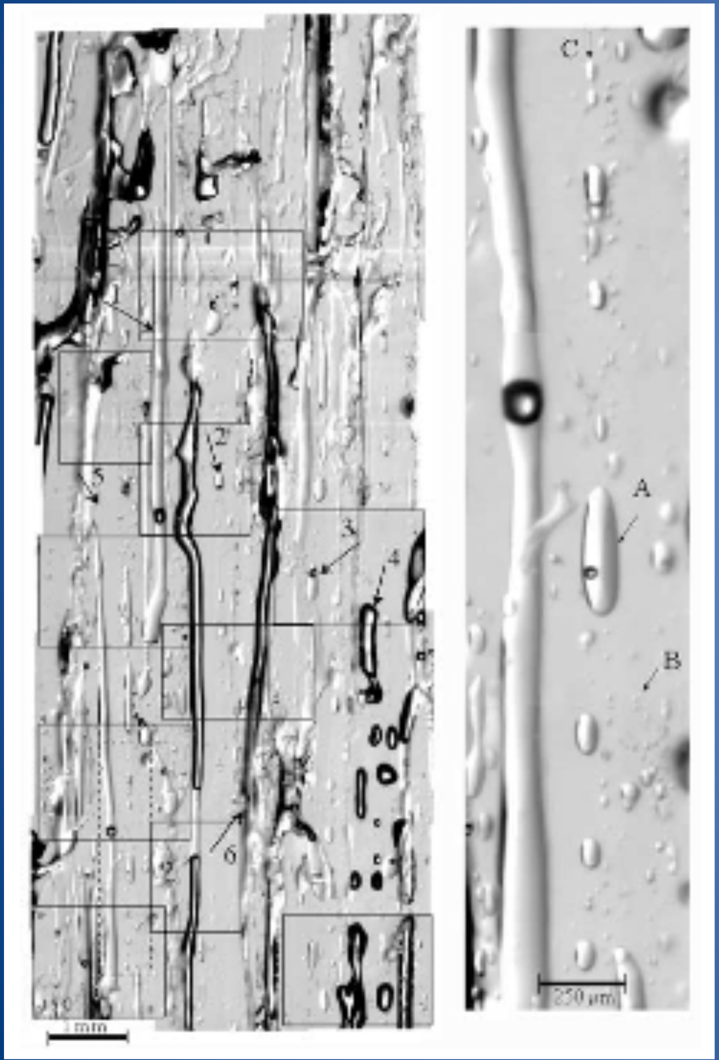
$$Q_{SW} = -\frac{d}{dz} I_{SW} e^{-\kappa z} \quad \text{where}$$

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

(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)

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

where T is in Celsius,

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

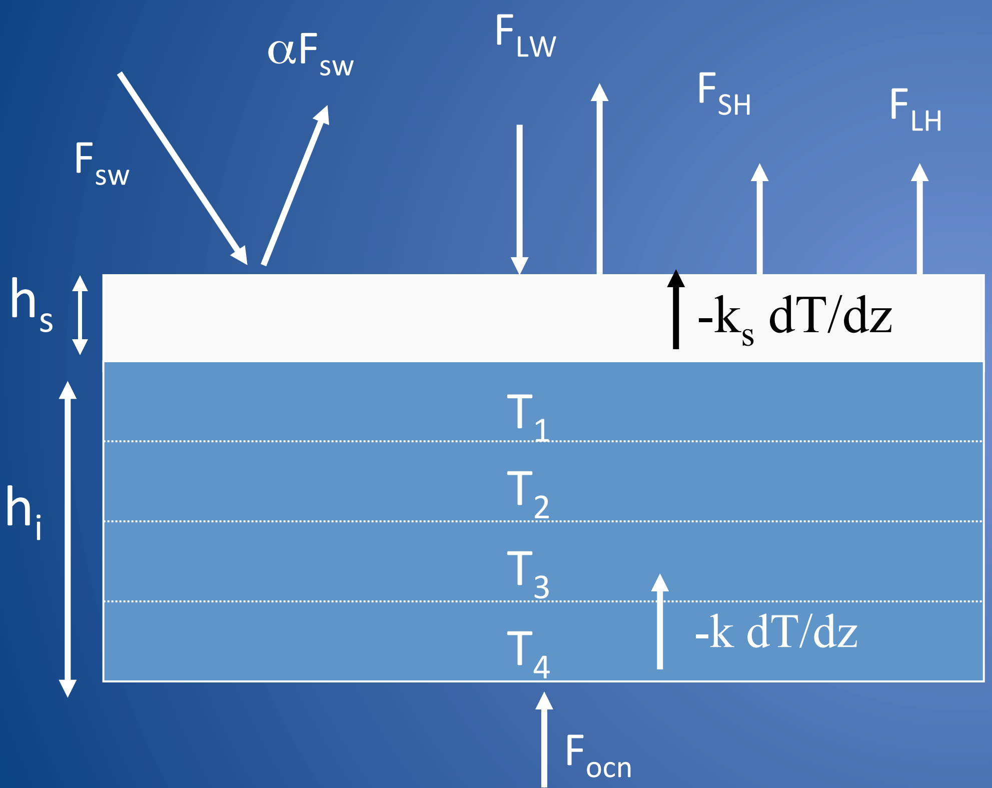
Untersteiner, 1961

Enthalpy:
Heat required to melt a unit of ice

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

(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)

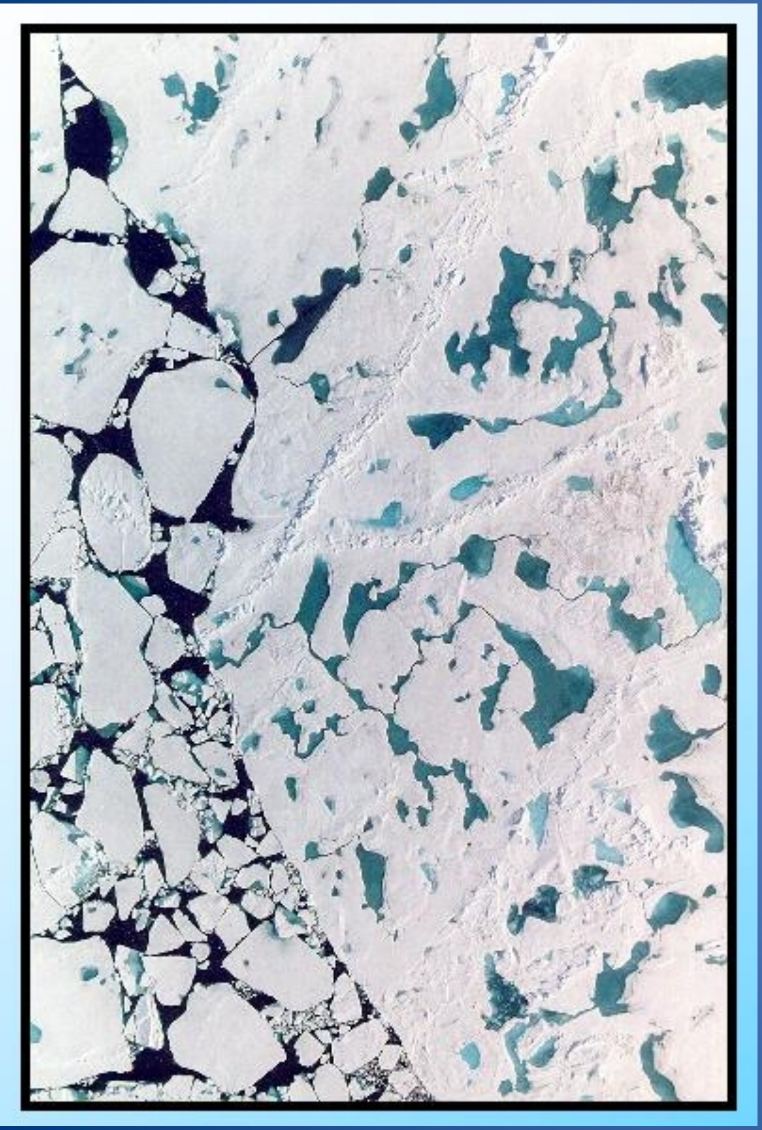
$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z} + Q_{SW}$$

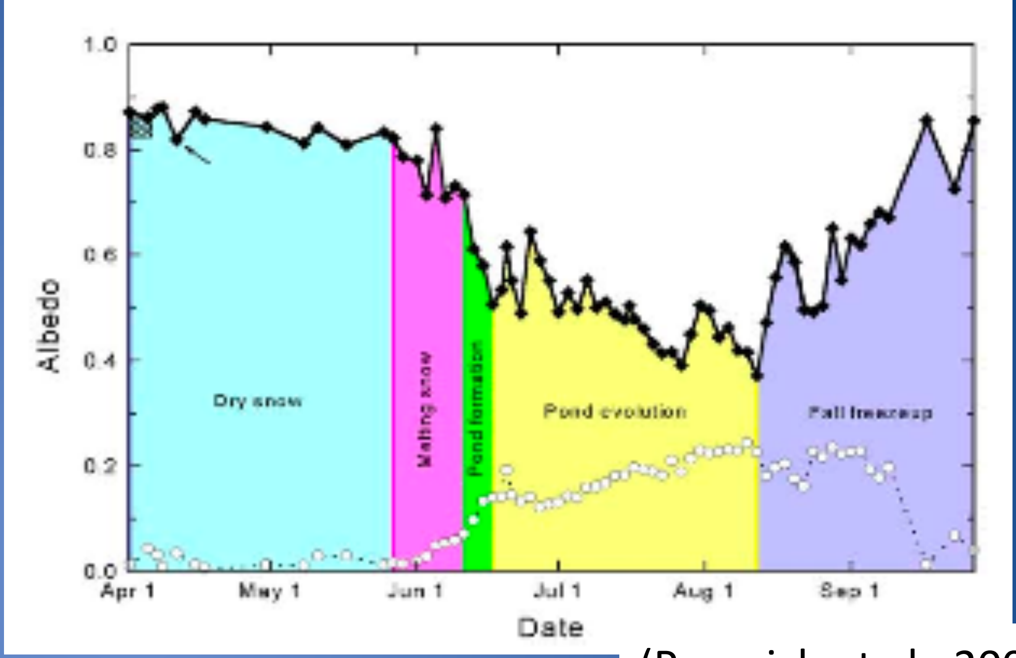
Balance of fluxes at ice base

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

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).

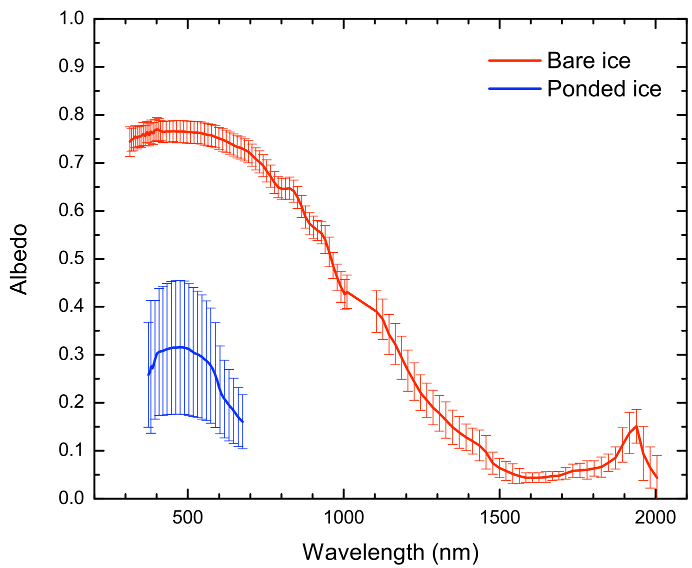
Surface albedo accounts for fraction of gridcell covered by ice vs open ocean

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

Improved Solar Radiation parameterization

Better physics:

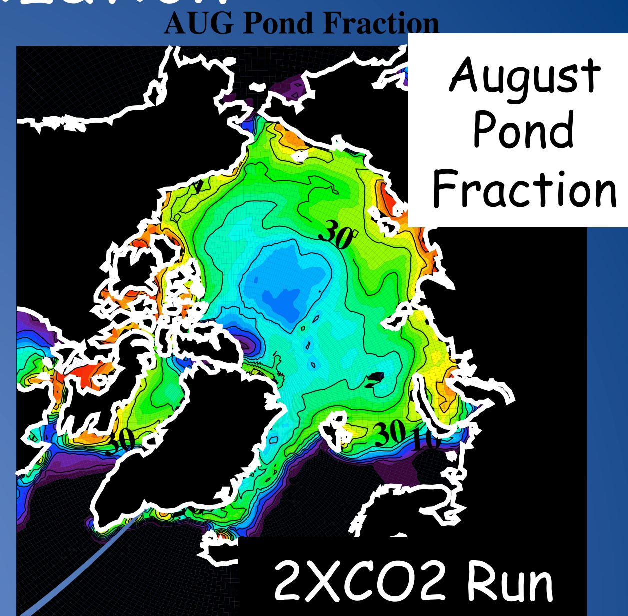
- makes use of inherent optical properties to define scattering and absorption of snow, sea ice and included absorbers

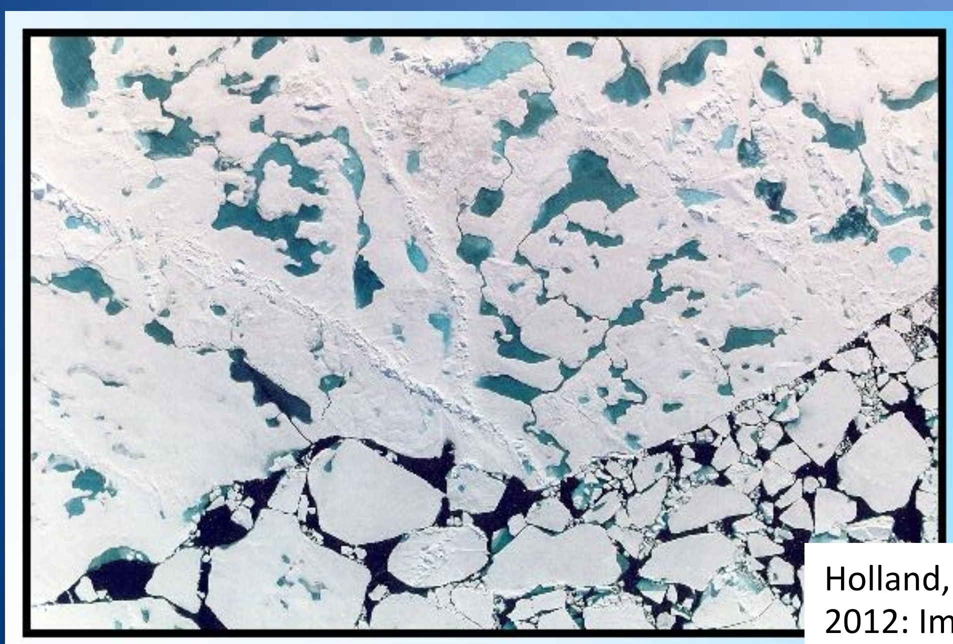
More flexible

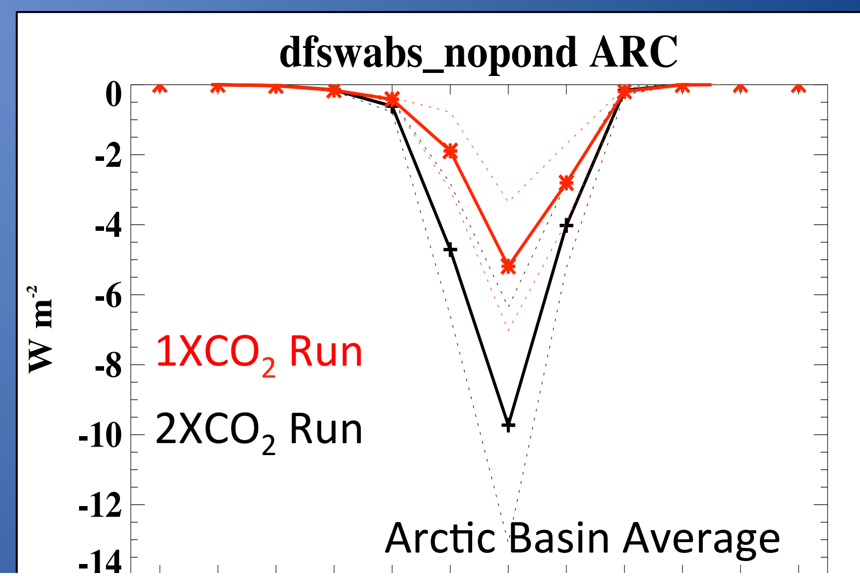
- Explicitly allows for included absorbers in sea ice

Melt Pond Parameterization

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





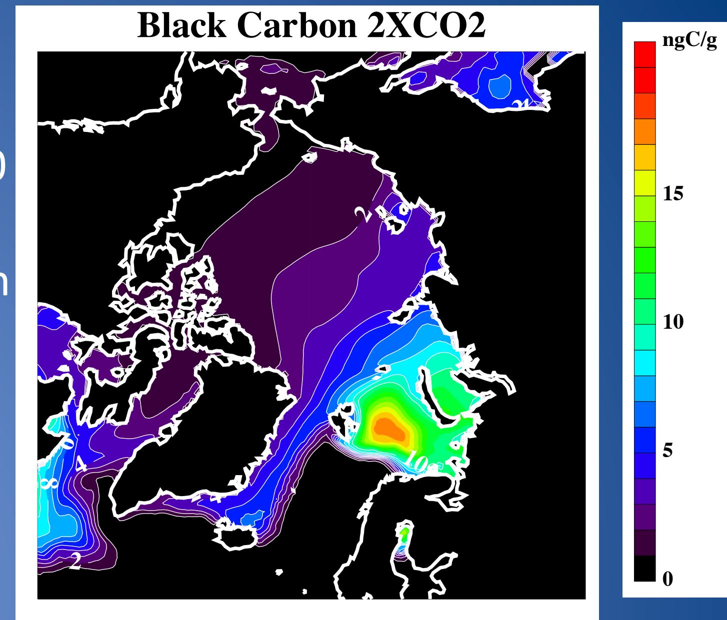


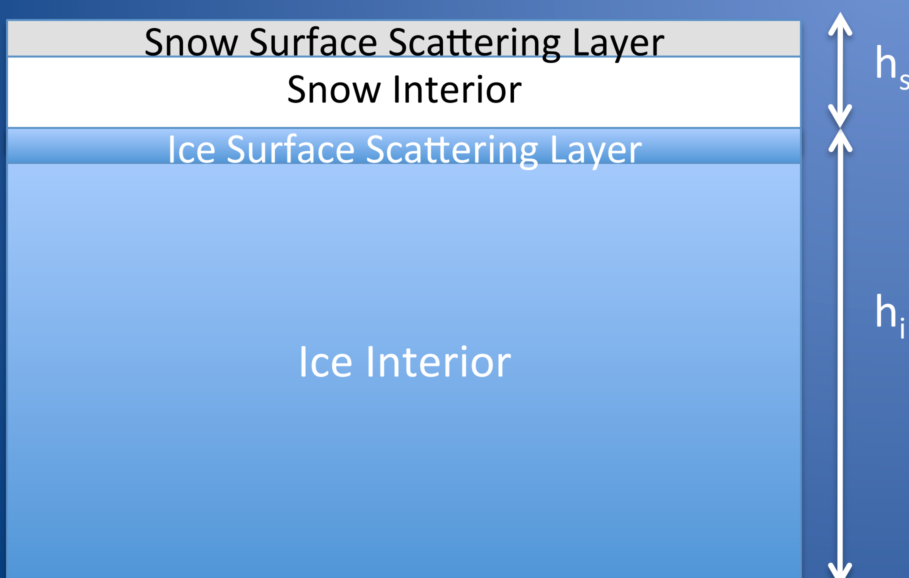
Holland, M. M., D. A. Bailey, B. P. Briegleb, B. Light, and E. C. Hunke, 2012: Improved sea ice shortwave radiation physics in CCSM4: The impact of melt ponds and black carbon. J. Climate, 25, 1413-1430.

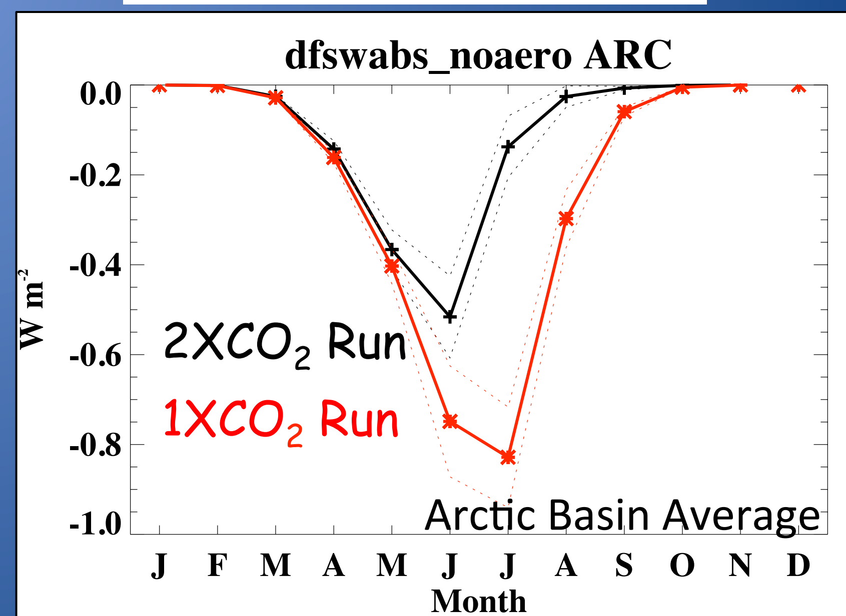
Aerosol deposition and cycling

- 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



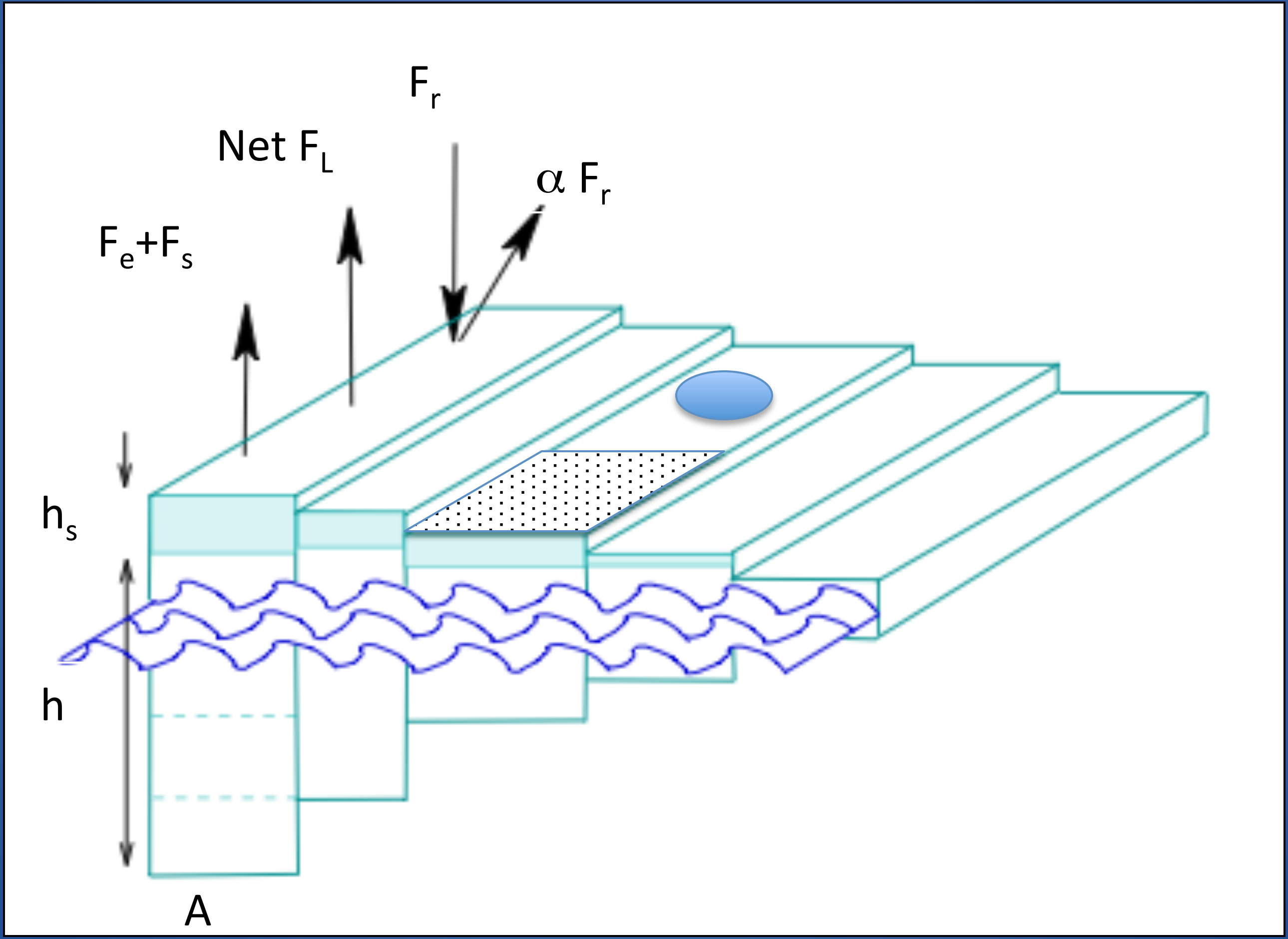




Holland, Bailey, Briegleb, Light, and Hunke, 2012

Ice Thickness Distribution

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



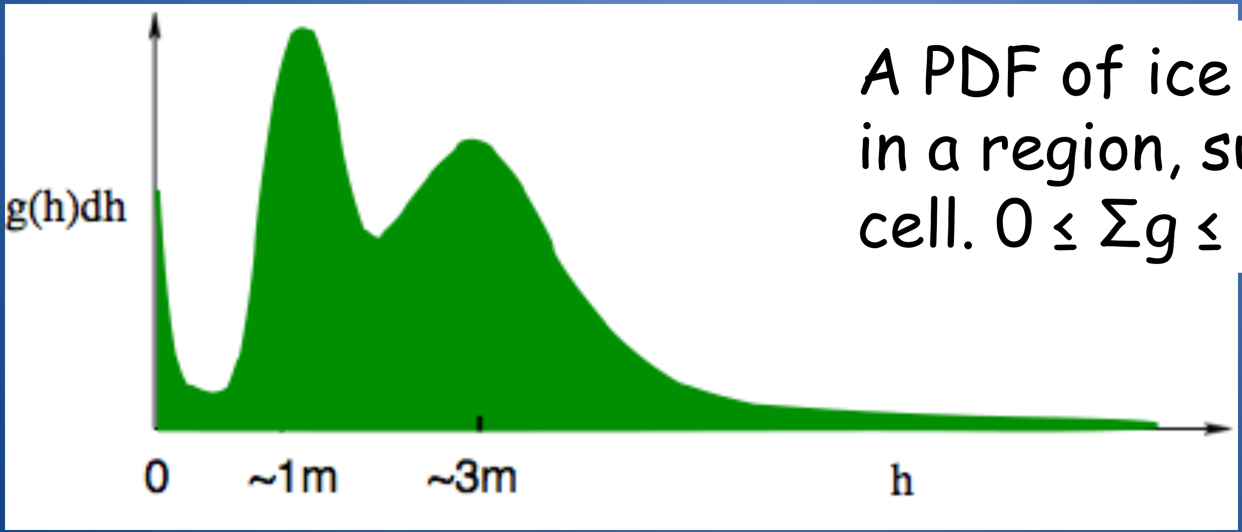
A=fractional coverage of a category

Ice Thickness Distribution

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

$$\frac{\partial g}{\partial t} = -\frac{\partial}{\partial h}(fg) + L(g) - \nabla \bullet (\vec{v}g) + \Psi(h,g,\vec{v})$$

Ice Growth — Lateral Melt — Convergence — Mechanical Redistribution



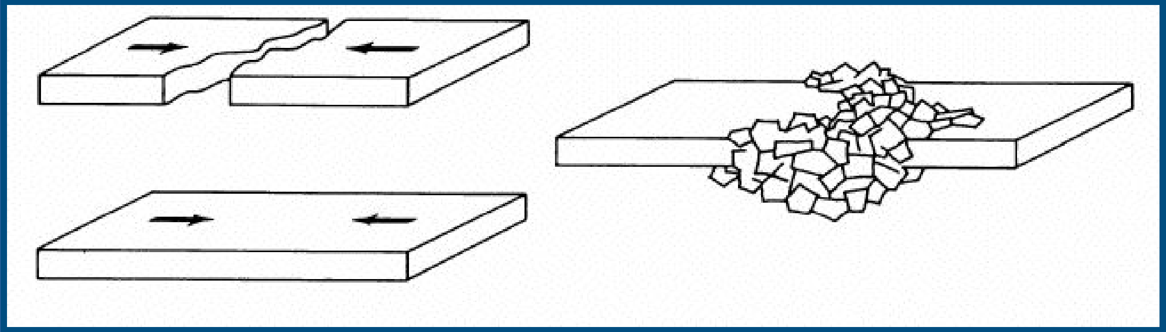
A PDF of ice thickness h in a region, such as a grid cell. $0 \leq \Sigma g \leq 1$

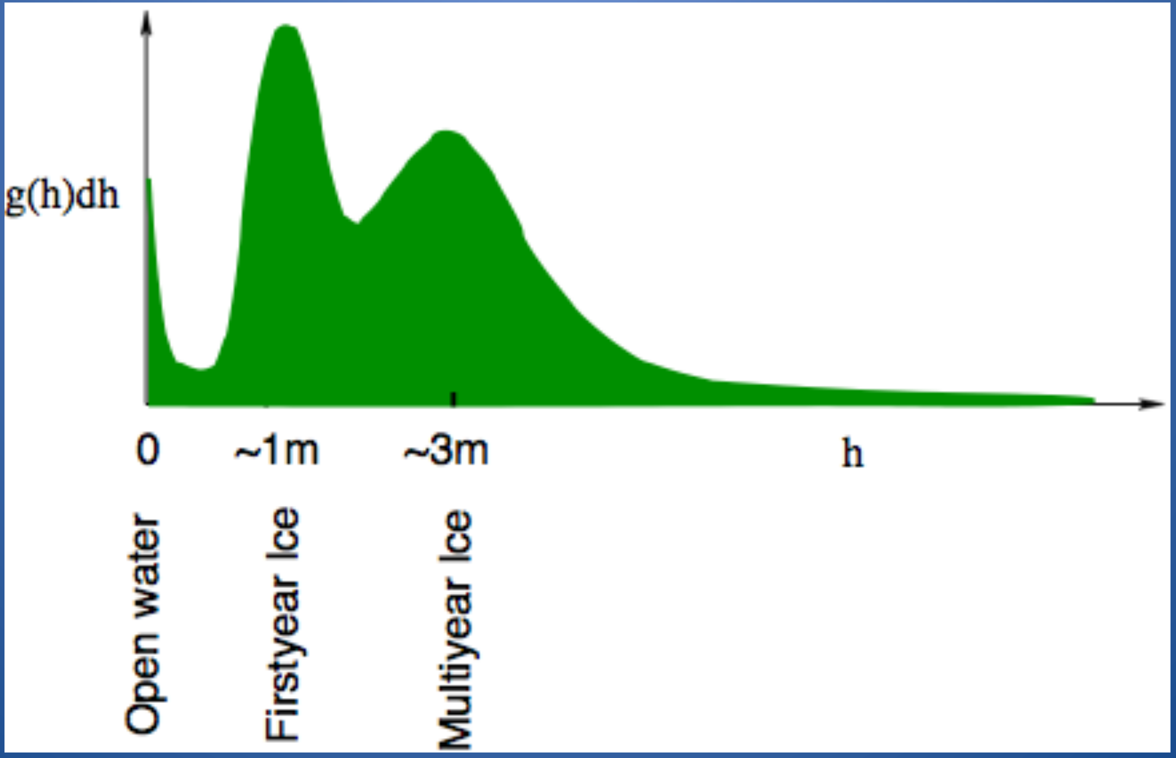
g(h)dh is the fractional area covered by ice of thickness h to h+dh

Ψ = Mechanical redistribution

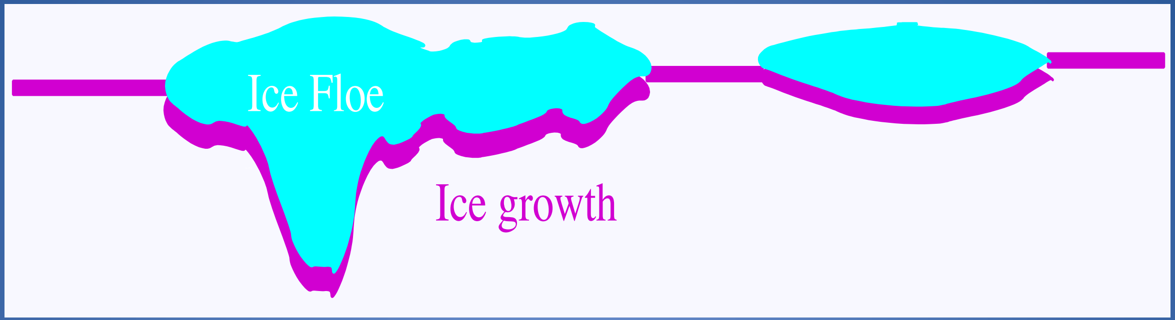
Transfers ice from thin part of distribution to thicker categories

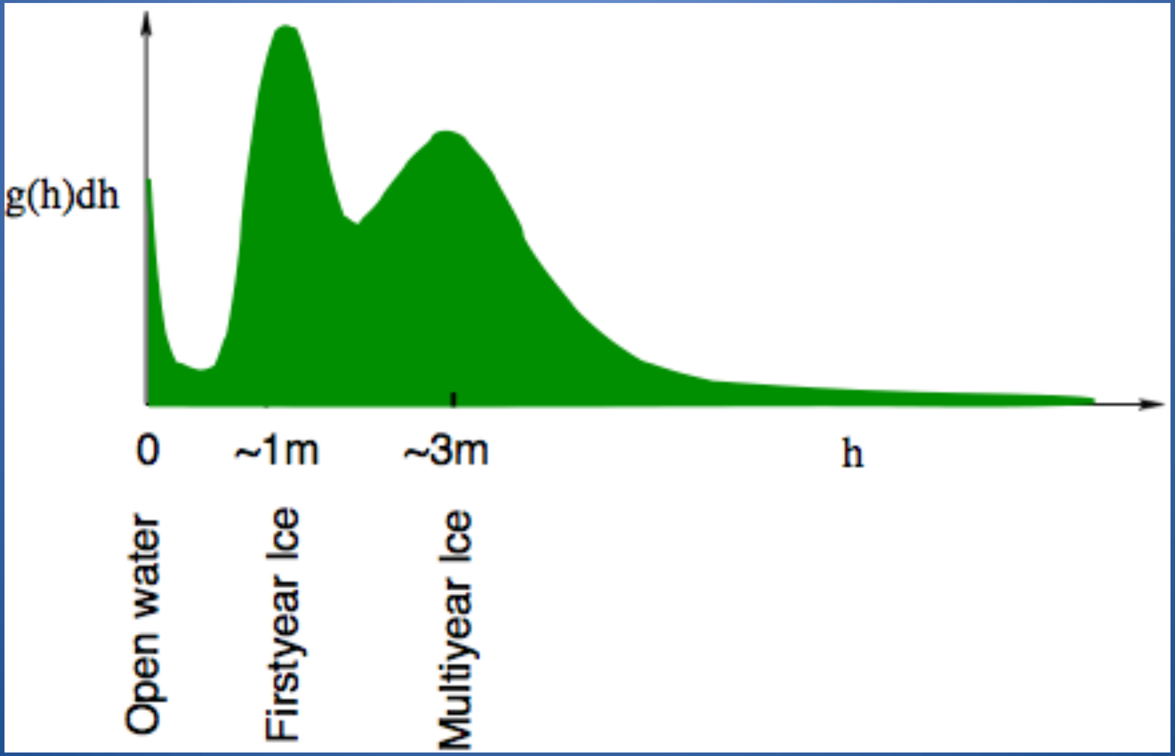
Converging hypothetical floes



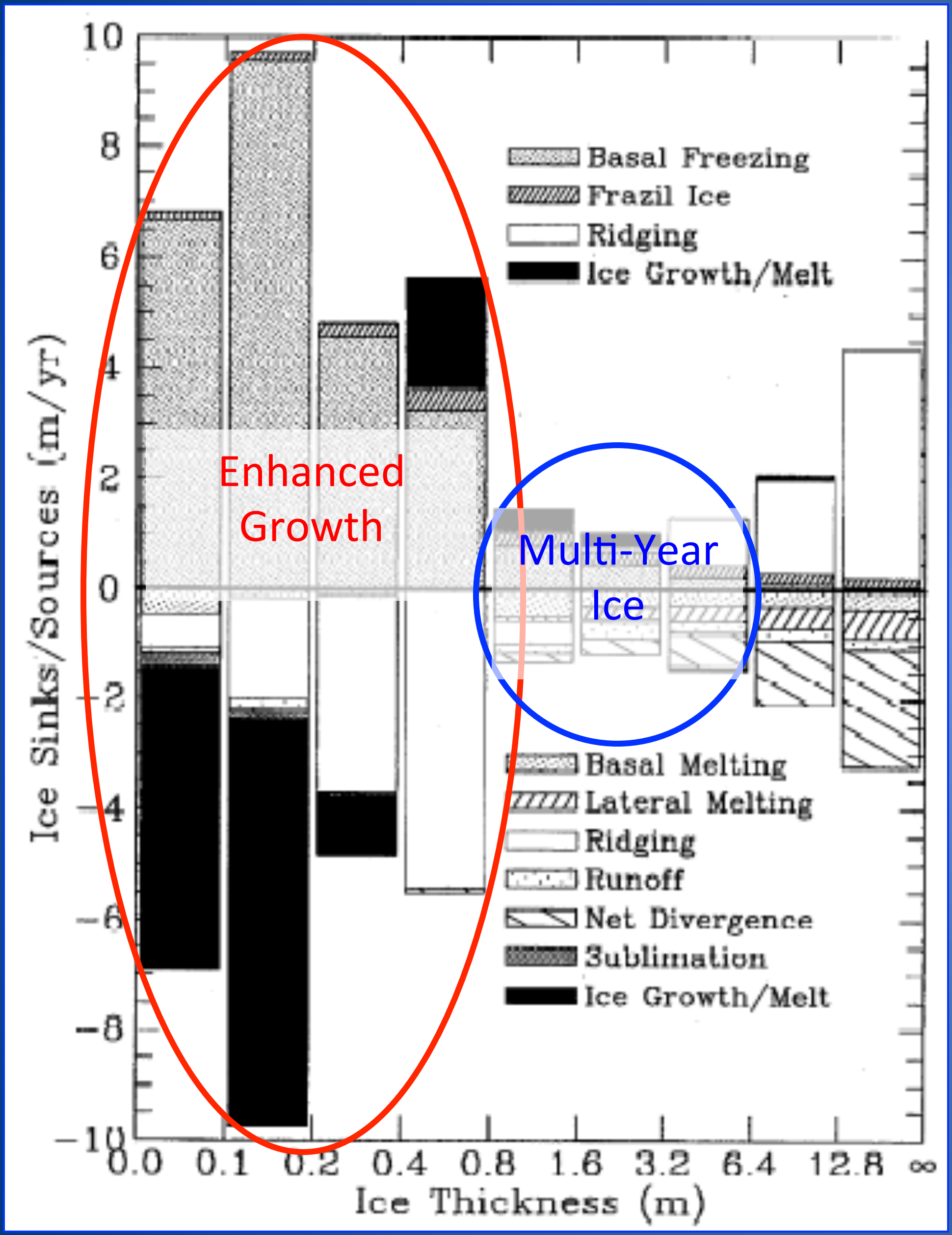


Ice growth:

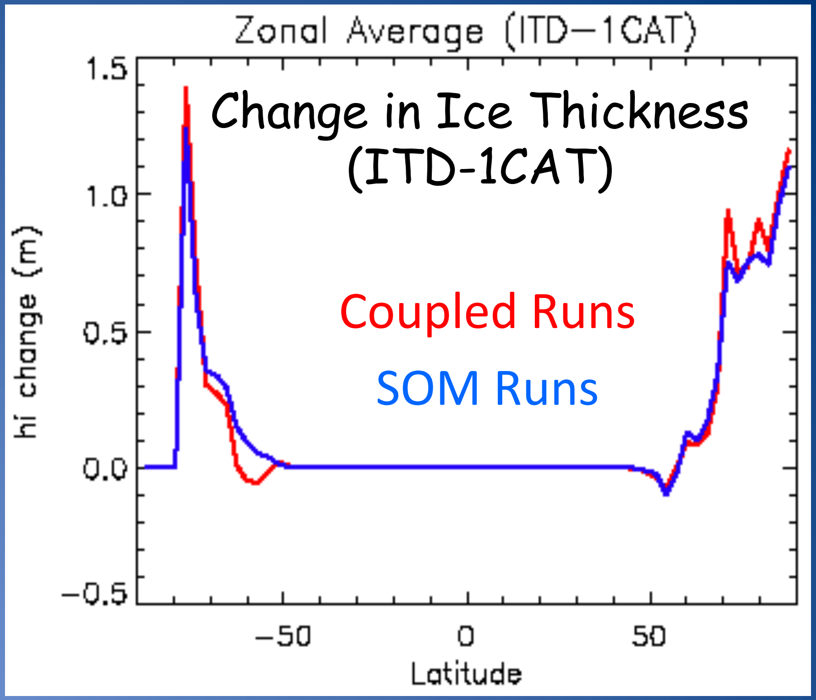

Ice Floe
Ice growth

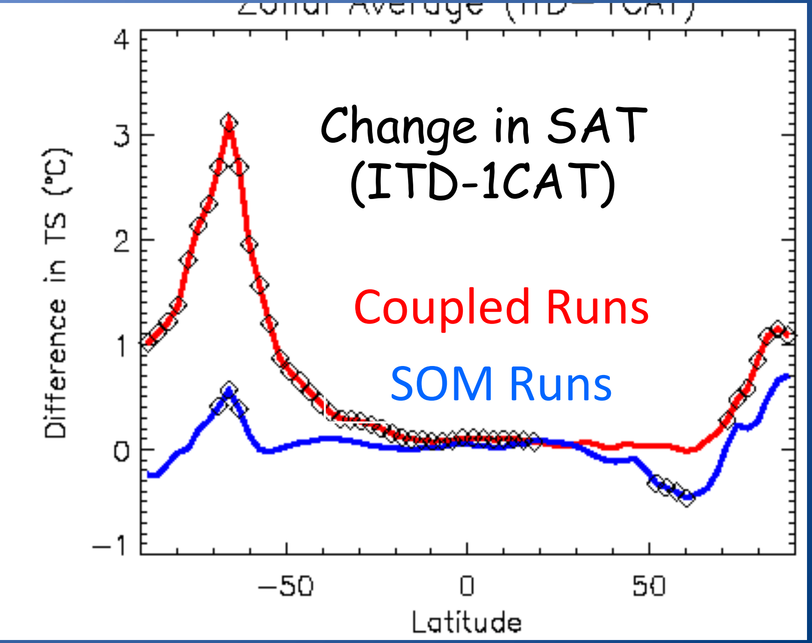

g(h)dh
0
~1m
~3m
h
Open water
Firstyear Ice
Multiyear Ice

Influence of including an Ice Thickness Distribution



Schramm et al., 1997





(Holland et al., 2006)

State variables for each category:

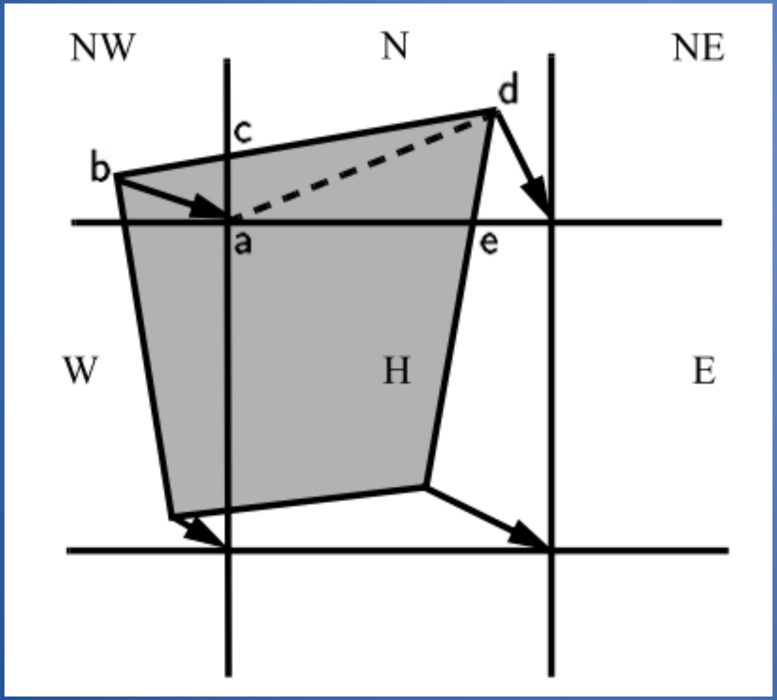
A, V_i, V_s, $E_i(z)$, $E_s(z)$, T_{surf}, melt pond state, aerosol contents (z), etc.

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.

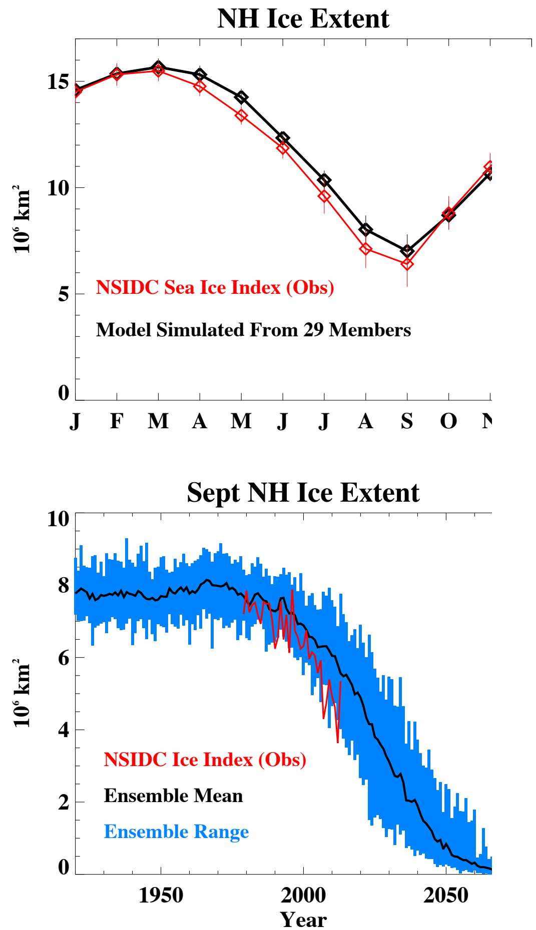


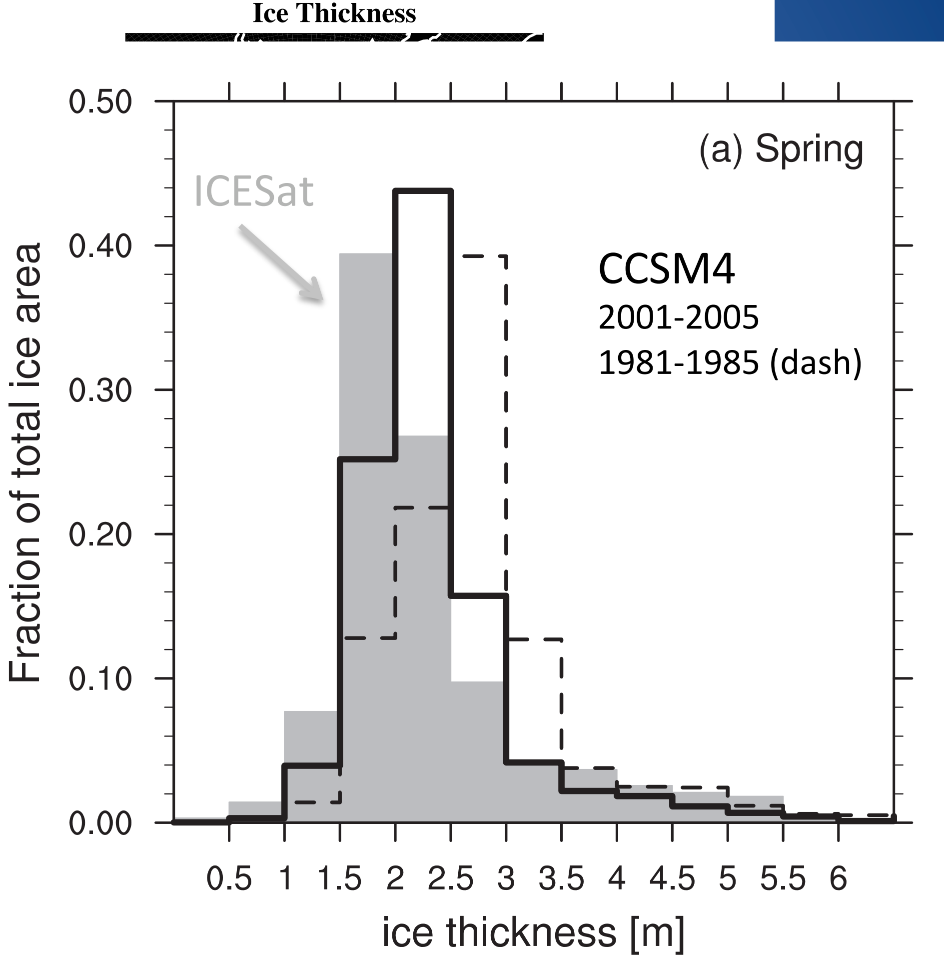
Conserved quantities are remapped from the shaded "departure region", which is computed from backward trajectories of the ice motion field.

Science Highlights

- How well does the model actually simulate the sea ice cover?
- What does the model say about the future of sea ice?
- Northern versus Southern Hemisphere?

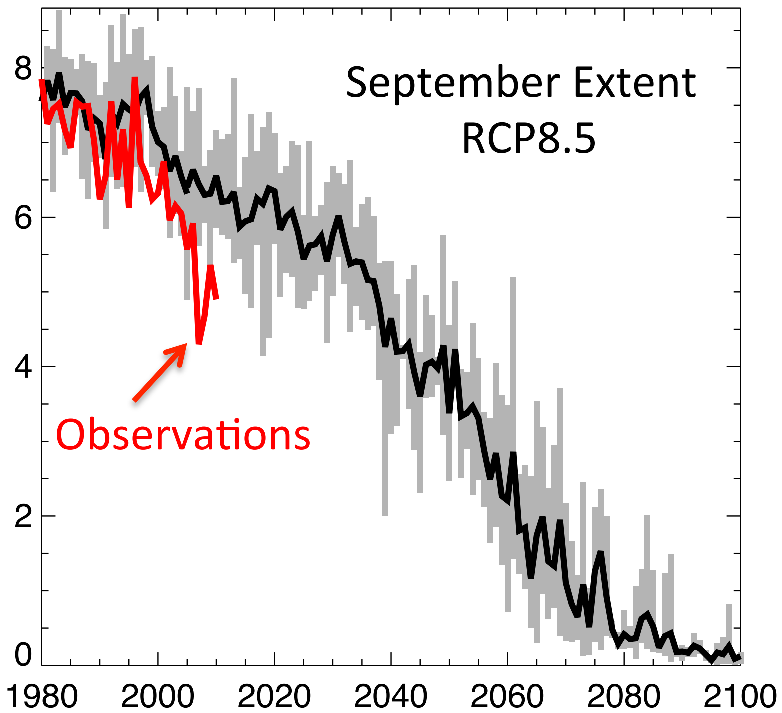
CCSM4/CESM1 Simulation of Arctic sea ice cover

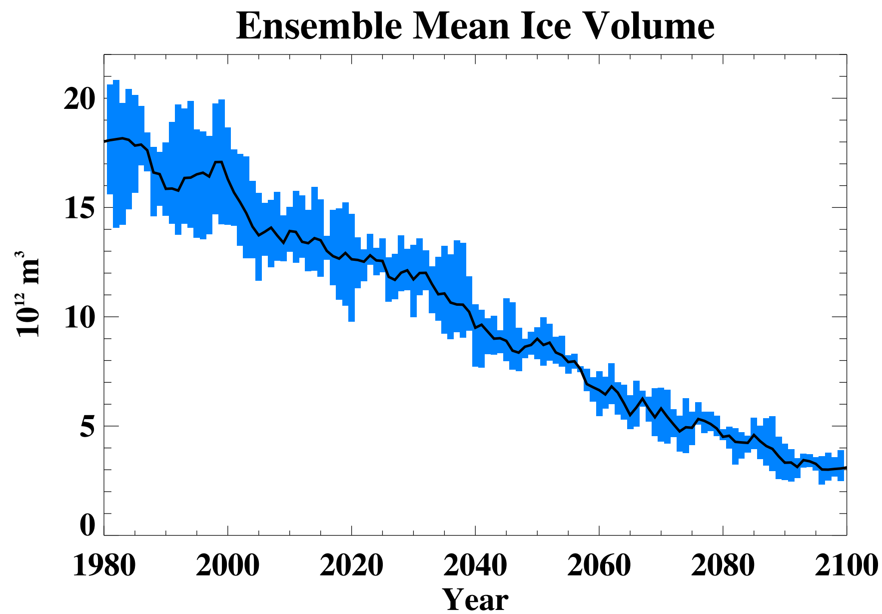


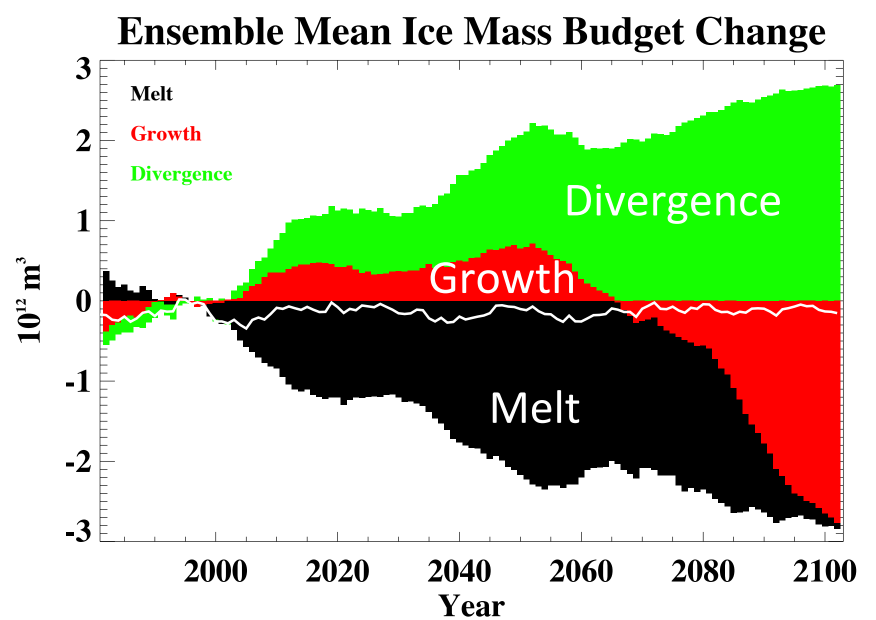


Jahn, A and Coauthors, 2012: Late-Twentieth-Century Simulation of Arctic Sea Ice and Ocean Properties in the CCSM4. J. Climate, 25, 1431–1452.

CCSM4 21st Arctic Ice Loss

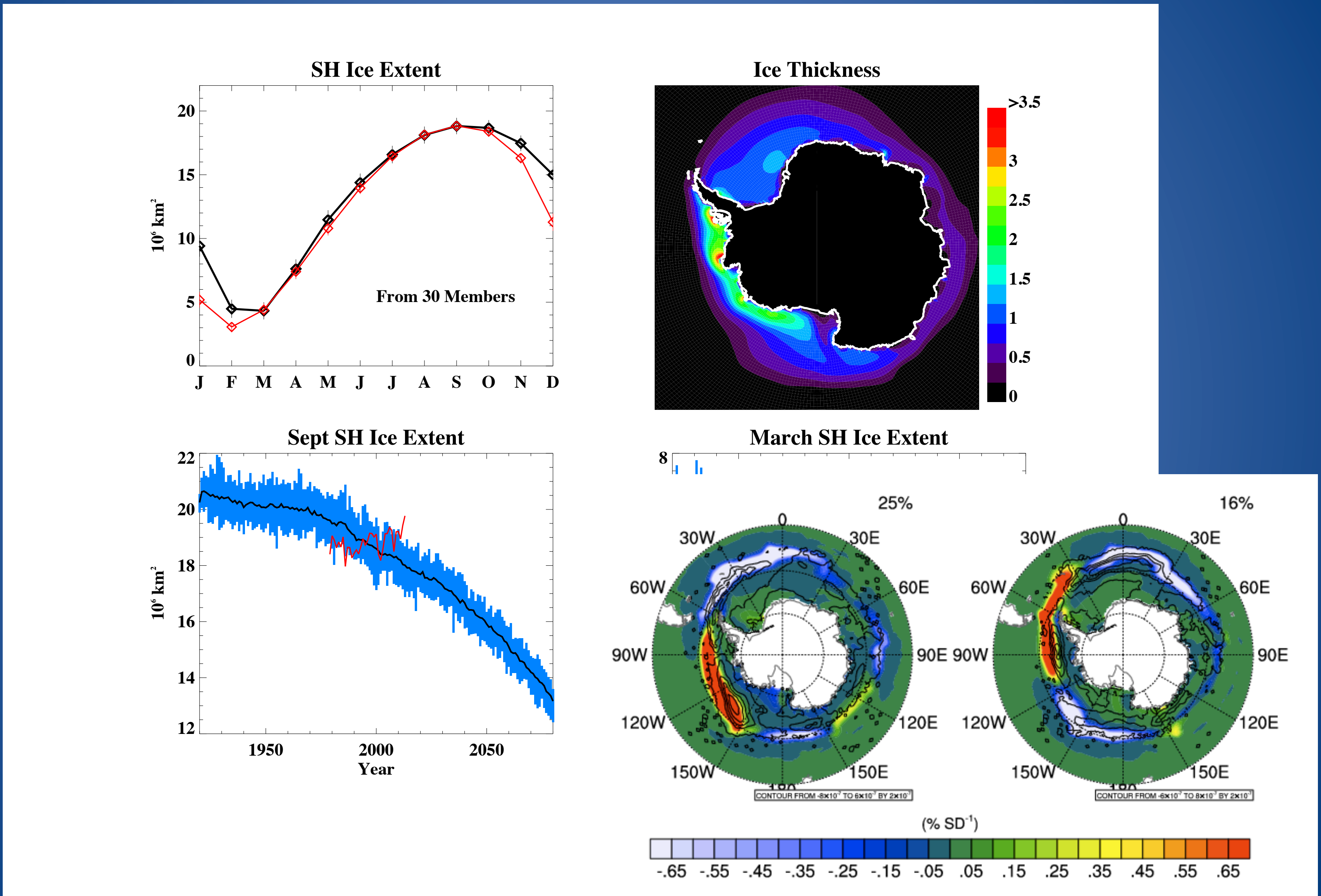






Vavrus, SJ, MM Holland, A Jahn, DA Bailey, BA Blazey, 2012: Twenty-First-Century Arctic Climate Change in CCSM4. J. Climate, 25, 2696–2710.

CCSM4/CESM1 Simulation of Antarctic sea ice



From Landrum et al. 2012

Summary

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

Coming in CESM version 2:

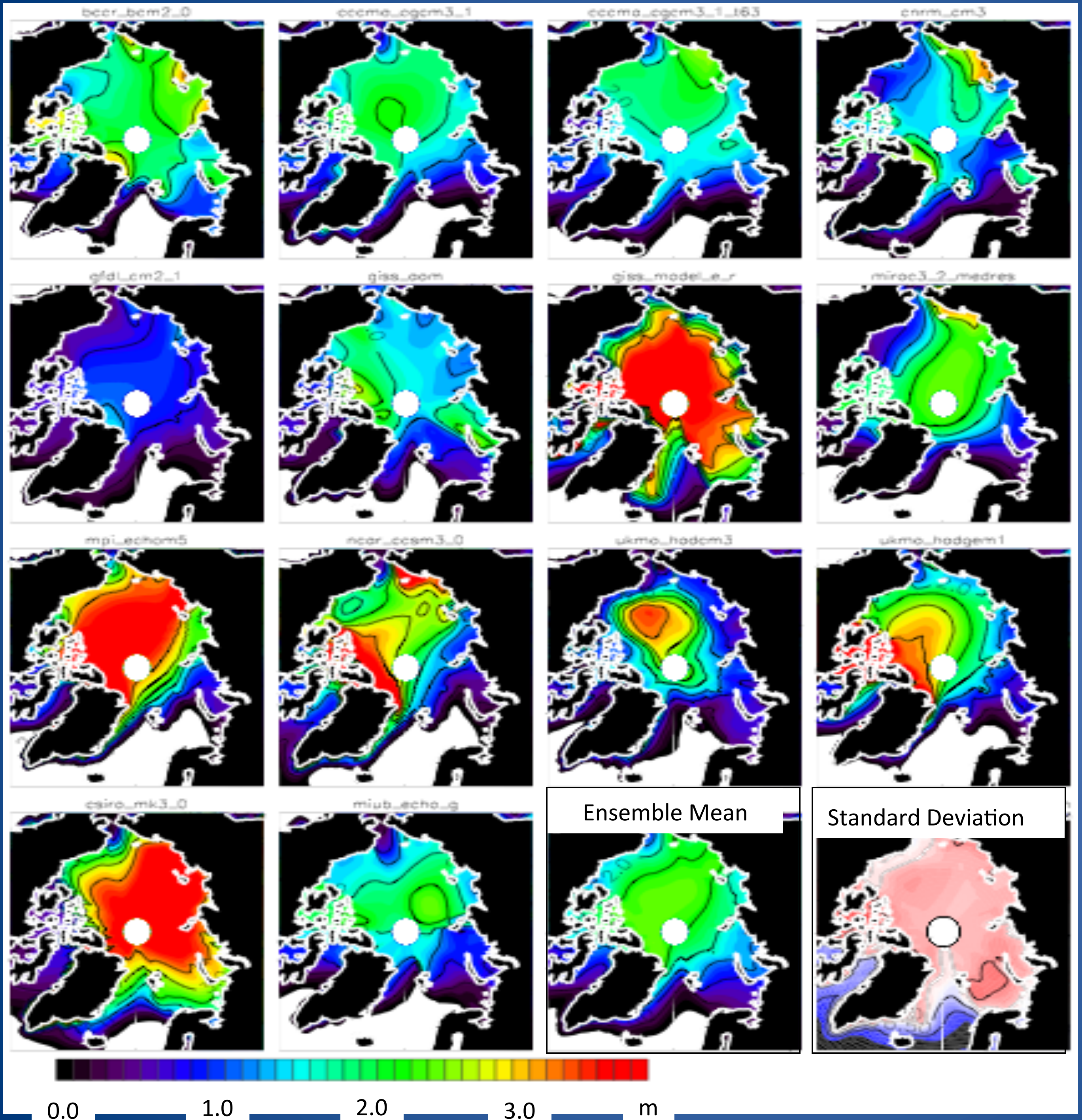
- New thermodynamics with prognostic salinity.
- More sophisticated melt pond modeling.
- Water isotopes.

Beyond CESM2:

- Biogeochemistry (Iron, Isotopes, Algae.)
- Snow model improvements.
- Satellite simulators, data assimilation.

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


Questions?



Simulated Ice Thickness Climatology

1980-1999

Thickness varies considerably across models

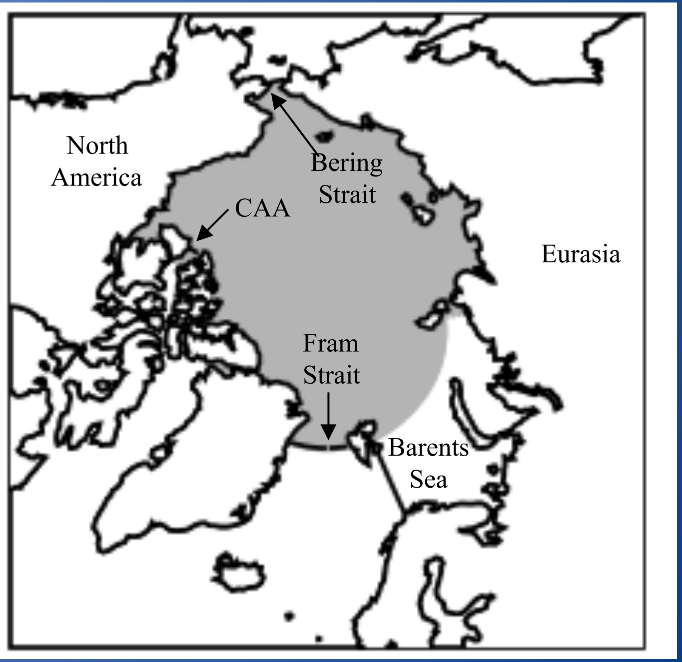
Differences in mean and distribution

Largest inter-model scatter is in the Barents Sea region

Assessing Sea Ice Mass Budgets

- Equilibrium Ice Thickness Reached when
  - Ice growth is balanced by ice melt + ice divergence
  - Illustrative to consider how different models achieve this balance and how mass budgets change over time

$$\underbrace{\frac{d\bar{h}}{dt}}_{\text{Ice volume change}} = \underbrace{\Gamma_h}_{\text{Thermodynamic source}} - \underbrace{\nabla \bullet (\vec{u}h)}_{\text{Divergence}}$$



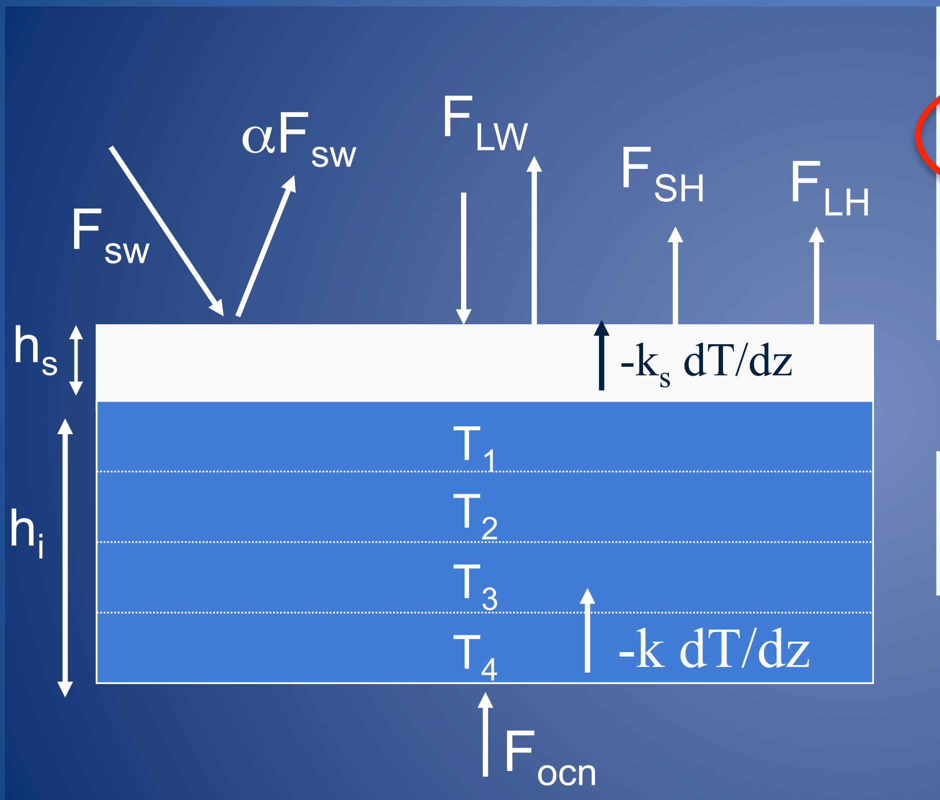
Climate model archive of monthly averaged ice thickness and velocity

Assess Arctic ice volume, transport through Arctic straits, and solve for ice growth/melt as residual

Holland et al., 2010

Sea ice loss is modified by climate feedbacks

- Fundamental sea ice thermodynamics gives rise to a number of important feedbacks



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)

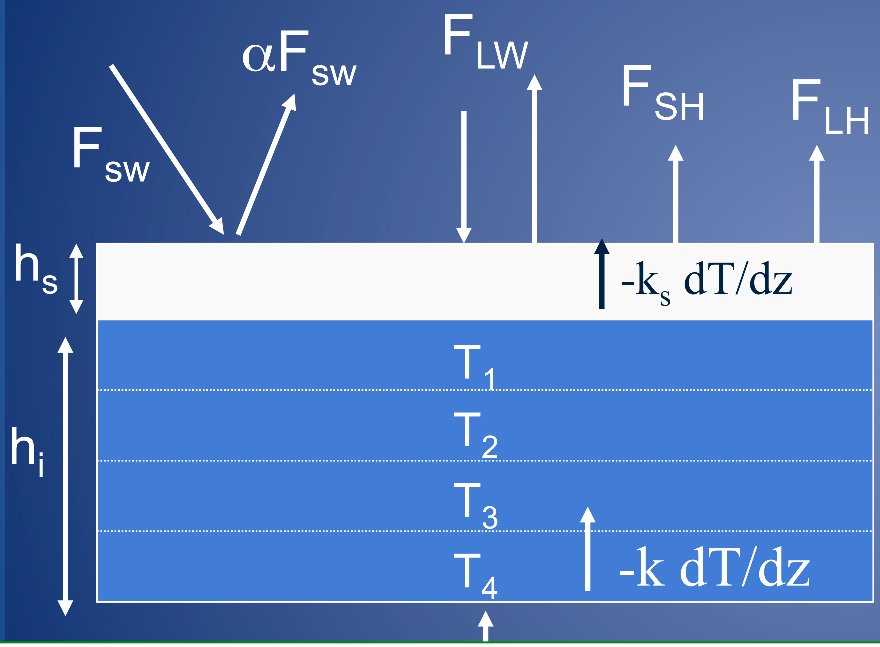
Balance of fluxes at ice base

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

Surface albedo changes modify SW absorption in ice and ocean heat flux
Ice loss lowers albedo – positive feedback

Ice mass budgets affected by climate feedbacks

- Fundamental sea ice thermodynamics gives rise to a number of important feedbacks



Balance of fluxes at surface

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

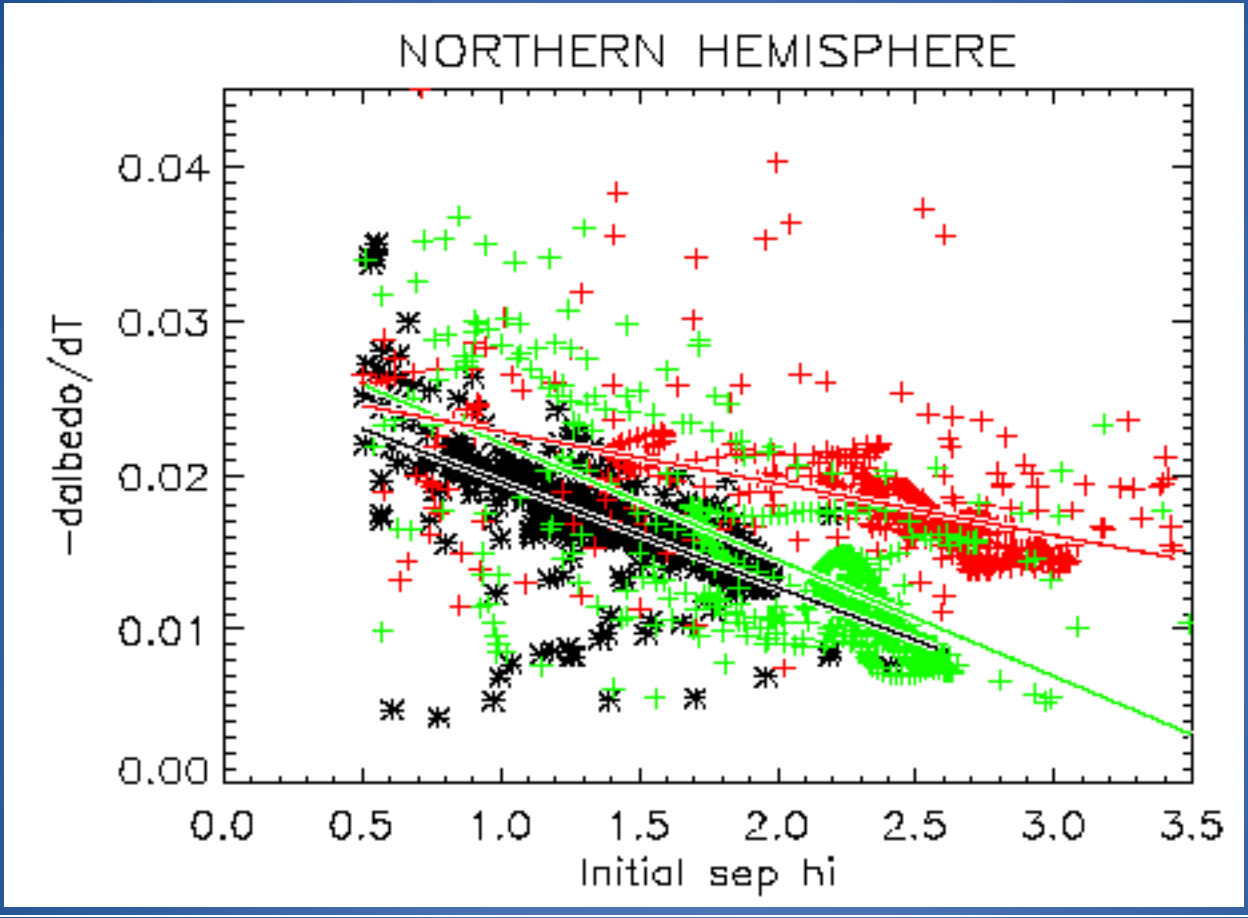
Vertical heat transfer (conduction, SW absorption)

Balance of fluxes at ice base

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

Heat conduction related to vertical temperature gradient
Causes ice growth to vary as 1/h
Has a stabilizing effect on ice thickness since thin ice grows more rapidly

Evidence that model parameterizations influence feedback strength
Enhanced albedo feedback in ITD run

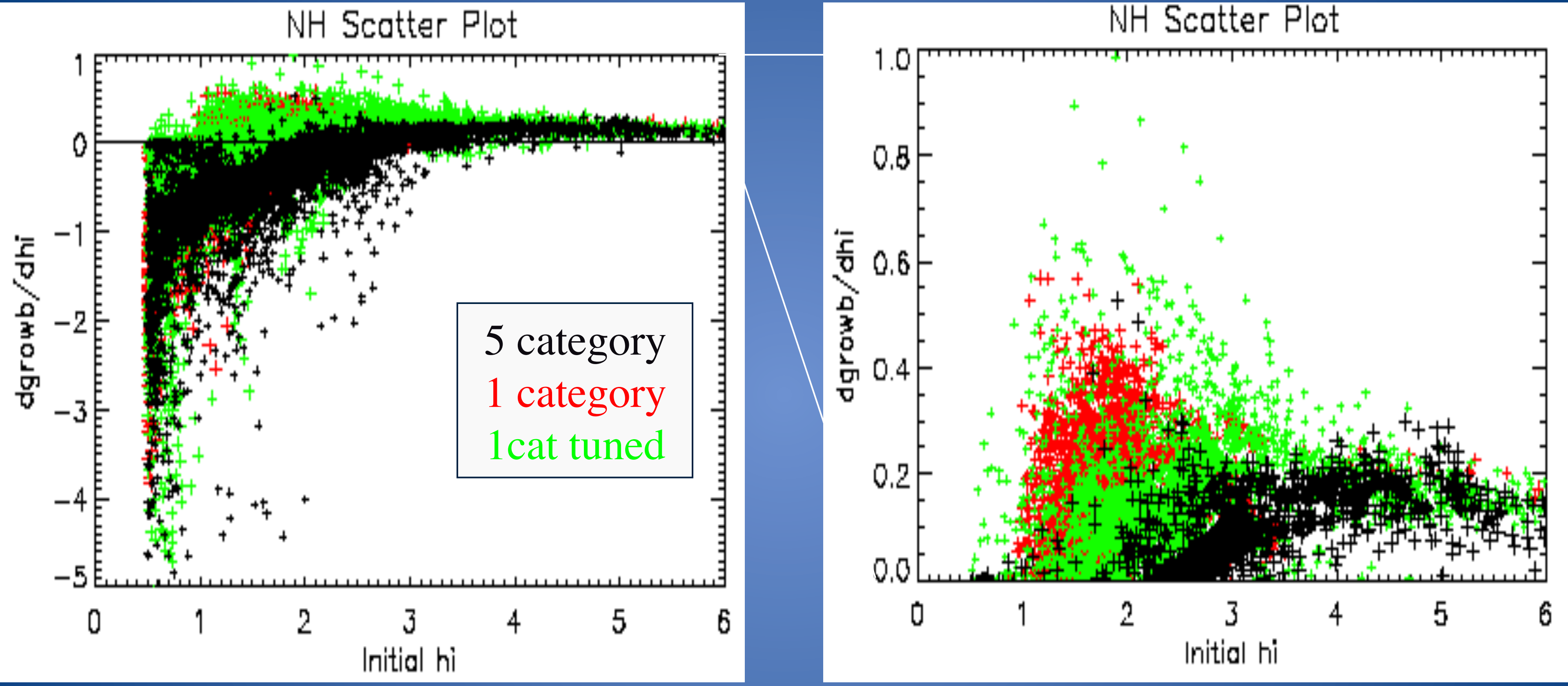


ITD (5 cat)
1 cat.
1cat tuned

Larger albedo change per temperature change for thinner initial ice
With ITD have larger a change for ice with same initial thickness
Suggests surface albedo feedback enhanced in ITD run

Holland et al., 2006

Model parameterizations modify ice growth rate feedback



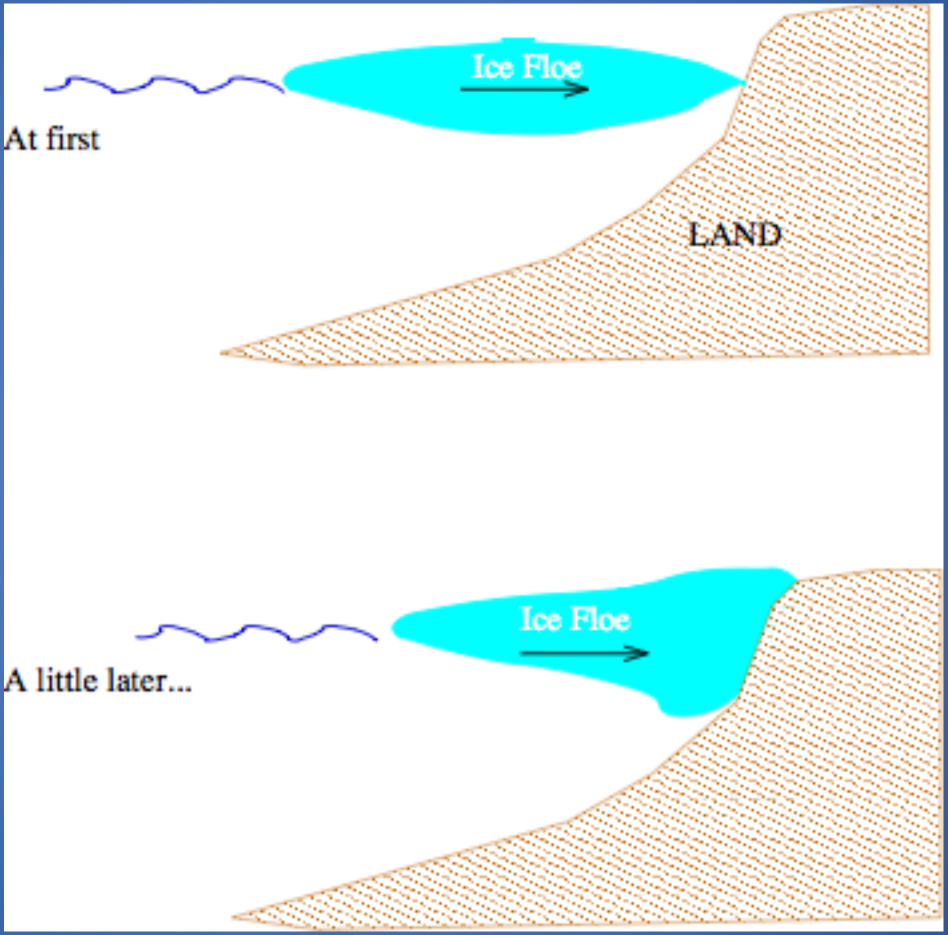
For ice of the same mean thickness,

- The ITD has fewer locations with increased ice growth.
- This suggests a reduced negative feedback on ice thickness

Challenges in Modeling Sea Ice in a Changing Environment

- So, is it all hopeless?
- Recent studies providing insight on what is needed if we are to accurately simulate sea ice change:
  - present day ice conditions, including extent and the spatial distribution of ice thickness;
  - the evolving surface energy budget
- To achieve this involves numerous and interacting factors across the coupled ice-ocean-atmosphere system
- Models are continuously improving and have provided considerable insight into the functioning of sea ice and its role in the climate system

Sea Ice Dynamics in climate models



Past ad hoc method was to stop ice from moving at a critical thickness, sometimes called stoppage.

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

1 2 3 4 5

1. Lagrangian time derivative of g following "parcel"
2. Convergence of parcel
3. Ψ = Mechanical redistribution
4. Ice growth/melt results in "advection of g in thickness space"
5. $\mathcal{L}$ = Reduction of g from lateral melt

h = ice thickness

$\mathbf{u}$ = ice velocity

f = growth rate

Heat Equation used to find temperature T

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z} + \kappa I_0 e^{-\kappa z},$$

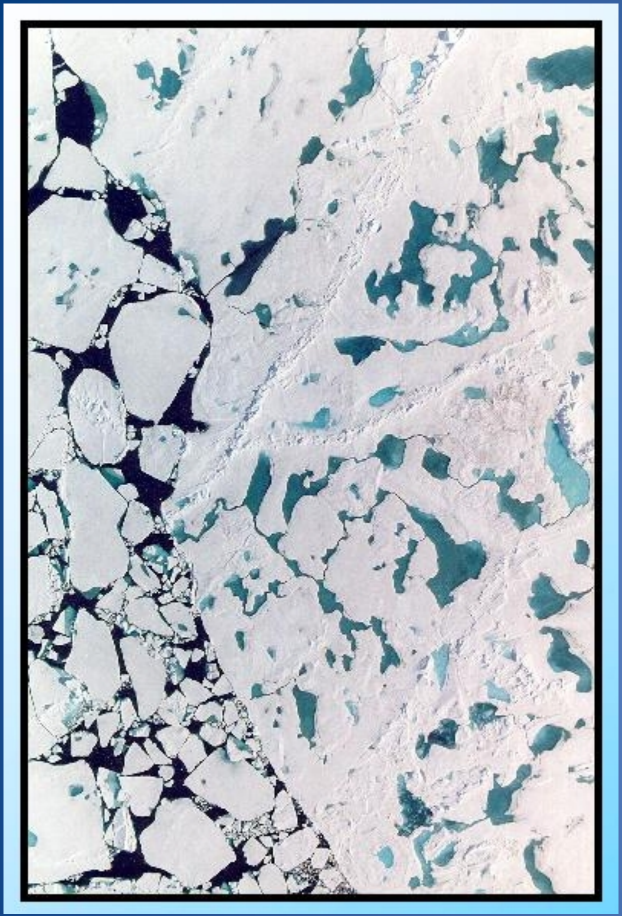
Untersteiner (1961) suggested the heat capacity of sea ice is

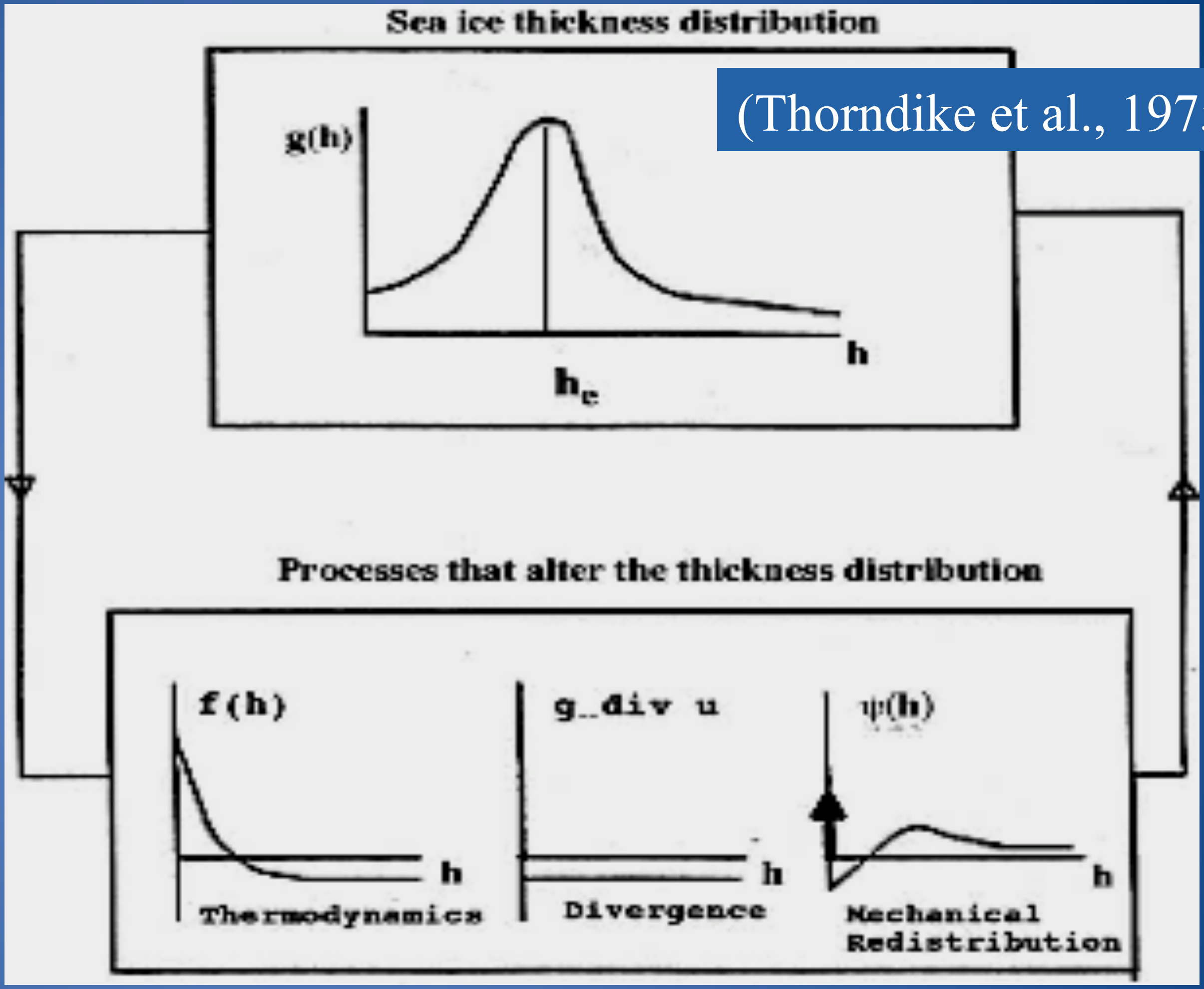
$$c(T, S) = c_o + \frac{\gamma S}{T^2}$$

where T is in Celsius,

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

Ice Thickness Distribution





$$\frac{Dg}{Dt} = -\frac{\partial}{\partial h}(fg) + L(g) - \nabla \bullet (\vec{v}g) + \Psi(h,g,\vec{v})$$

Evolution depends on: Ice growth, lateral melt, ice divergence, and mechanical redistribution (riding/rafting)