Sea Ice Modeling in the CESM

CESM 2022 tutorial

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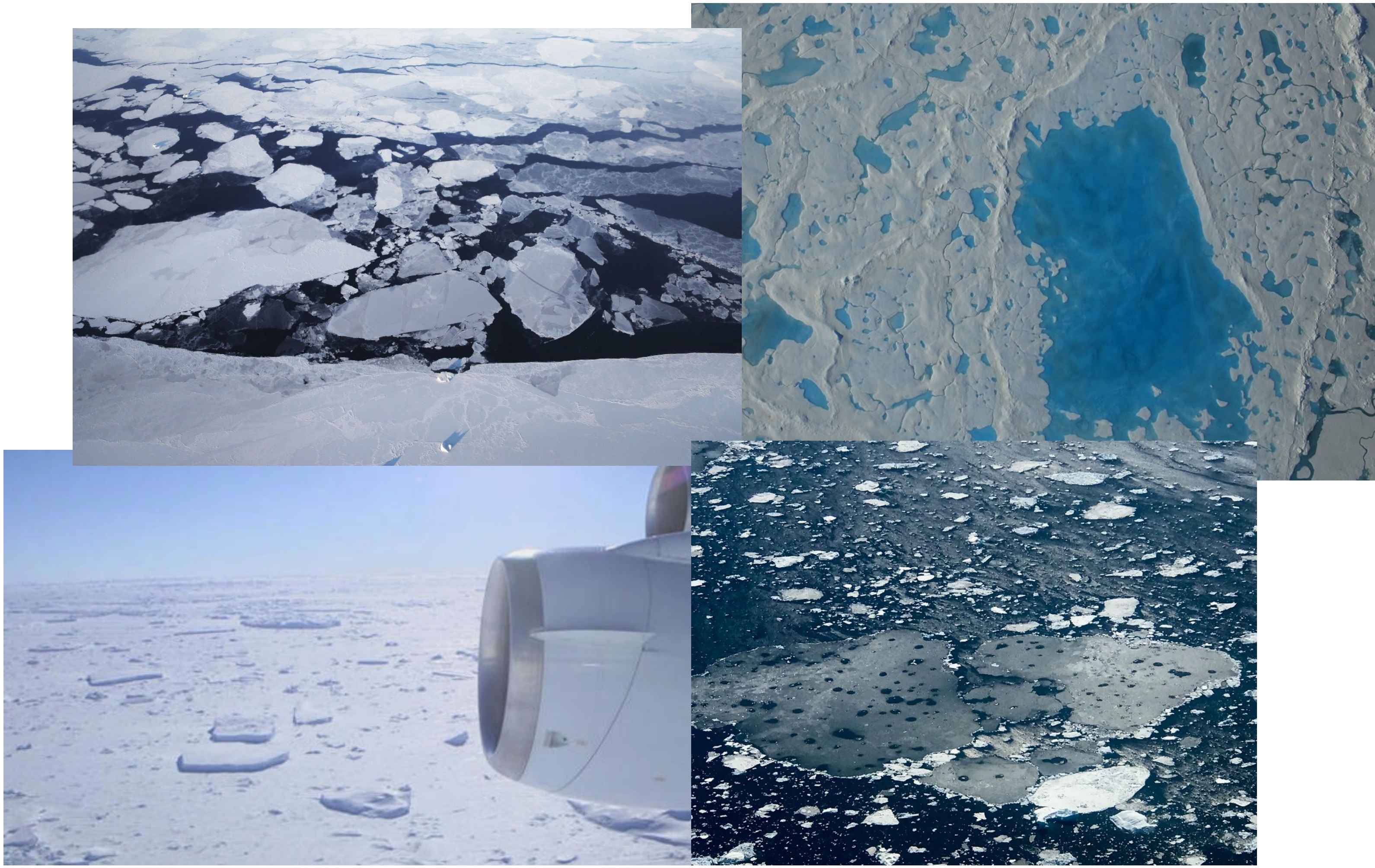
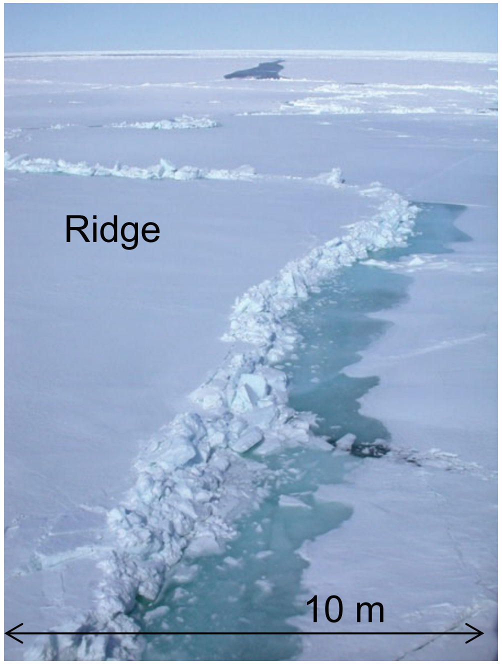
What is Sea Ice?

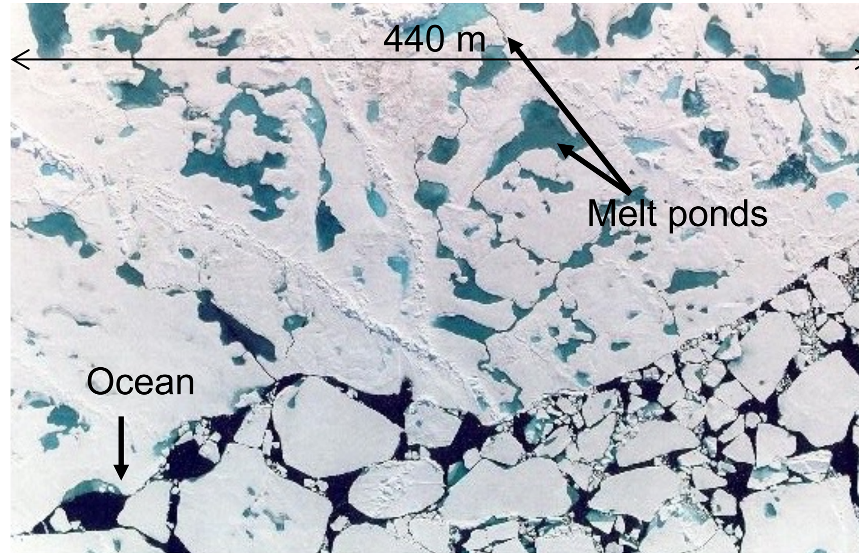
Sea Ice is <u>frozen sea water</u> that forms seasonally



Photos from NASA Operation IceBridge

Sea ice Cover





← Photos from Feltham, 2008 by Hajo Eicken

↑ Photo from Don Perovich

- Heterogeneous – lots of subgridscale variability
    - Leads, ridges, melt ponds, floes, albedo, snow cover, etc.
- Individual floes of varying size can form a continuous cover
- Thickness on the order of meters

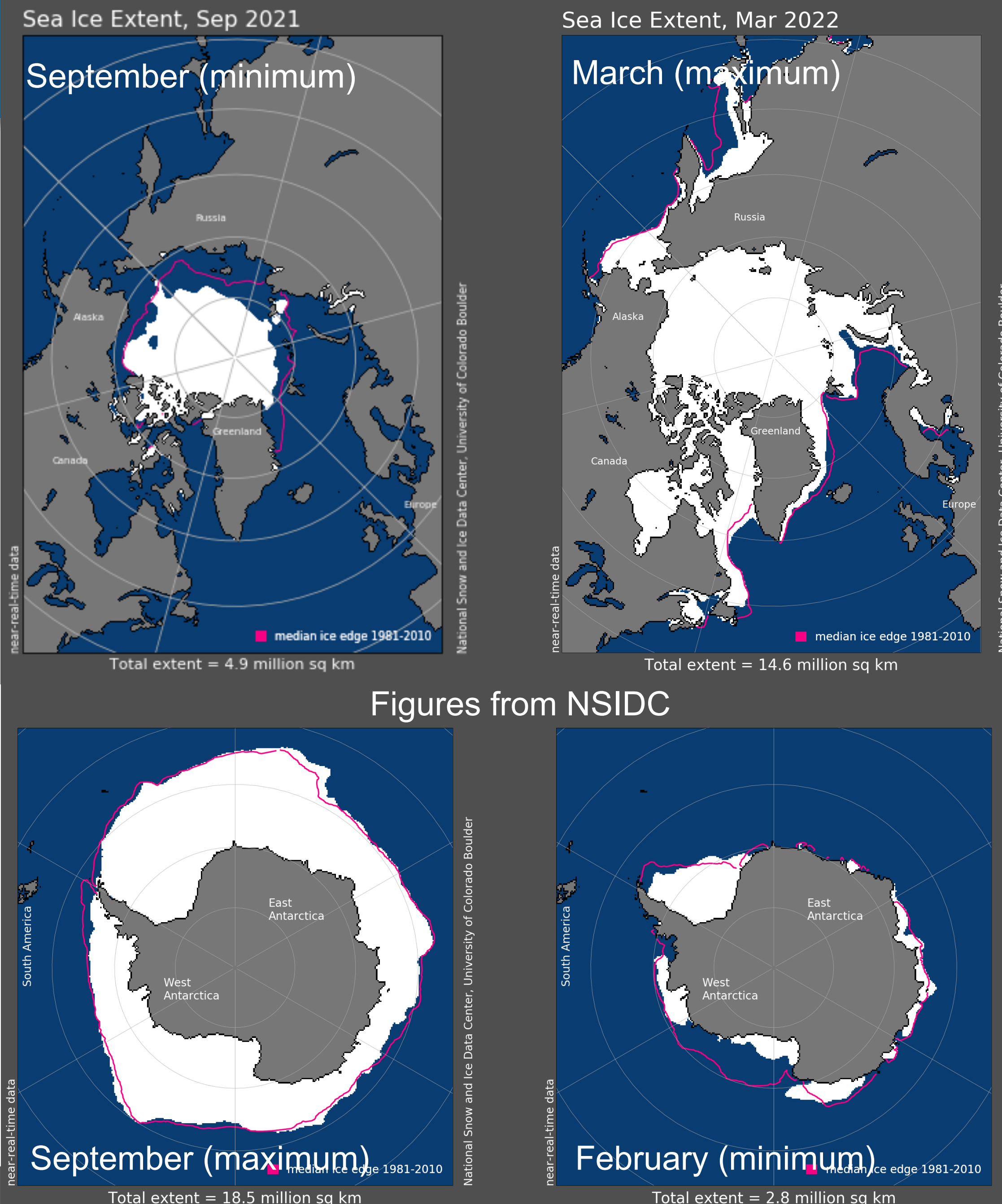
Arctic vs. Antarctic

Arctic

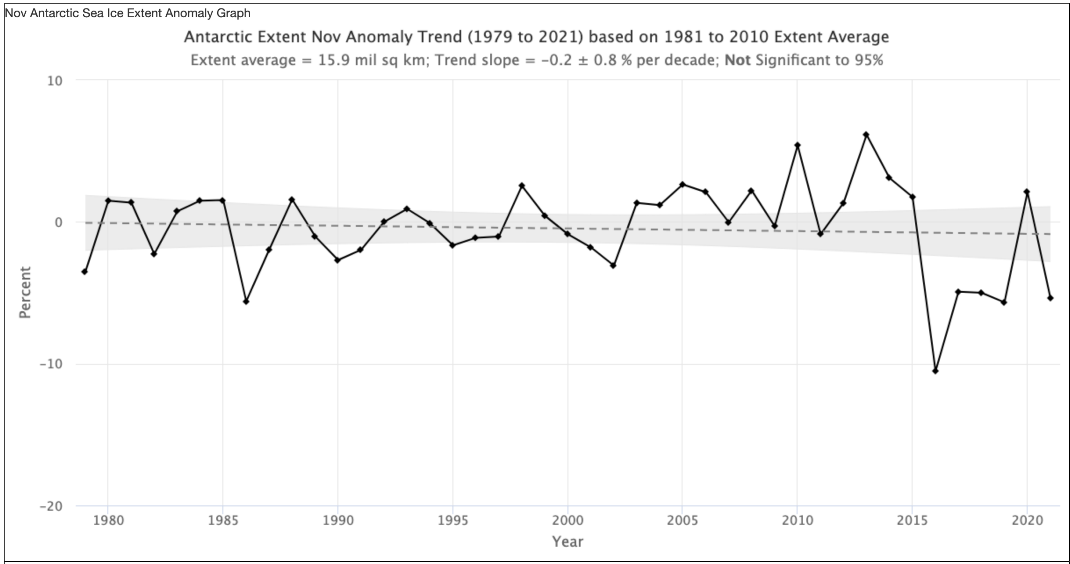
- Ocean bounded by land → ice converges at land, thick!
- Extent seasonal cycle: ~ 5→12 x10^6 km^2
- Land boundaries & ocean heat determine winter extent

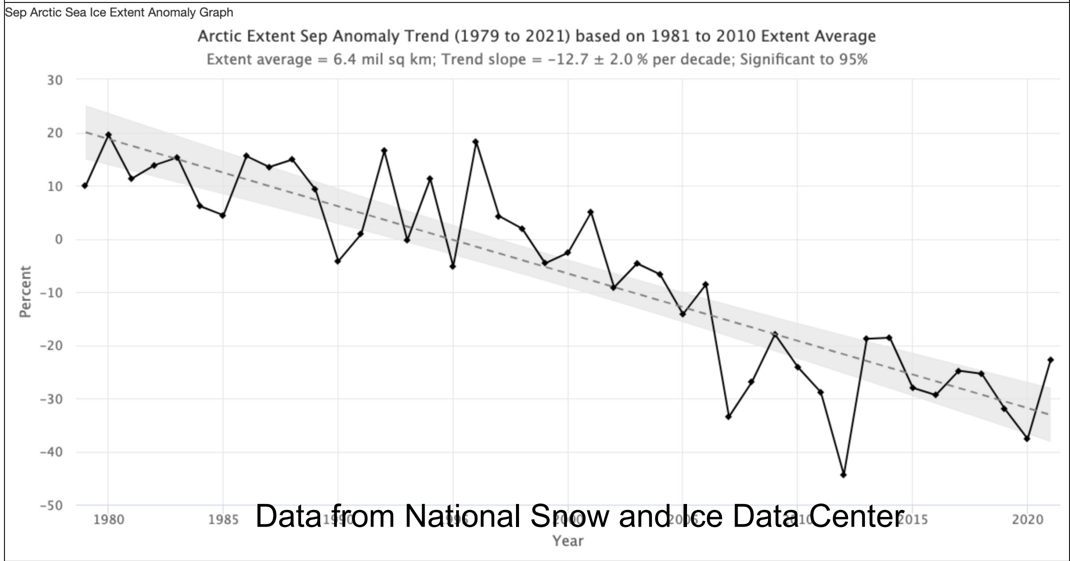
Antarctic

- Unbounded → ice in free drift
- Extent seasonal cycle: ~ 2→15 x10^6 km^2
- Ocean heat determines winter extent



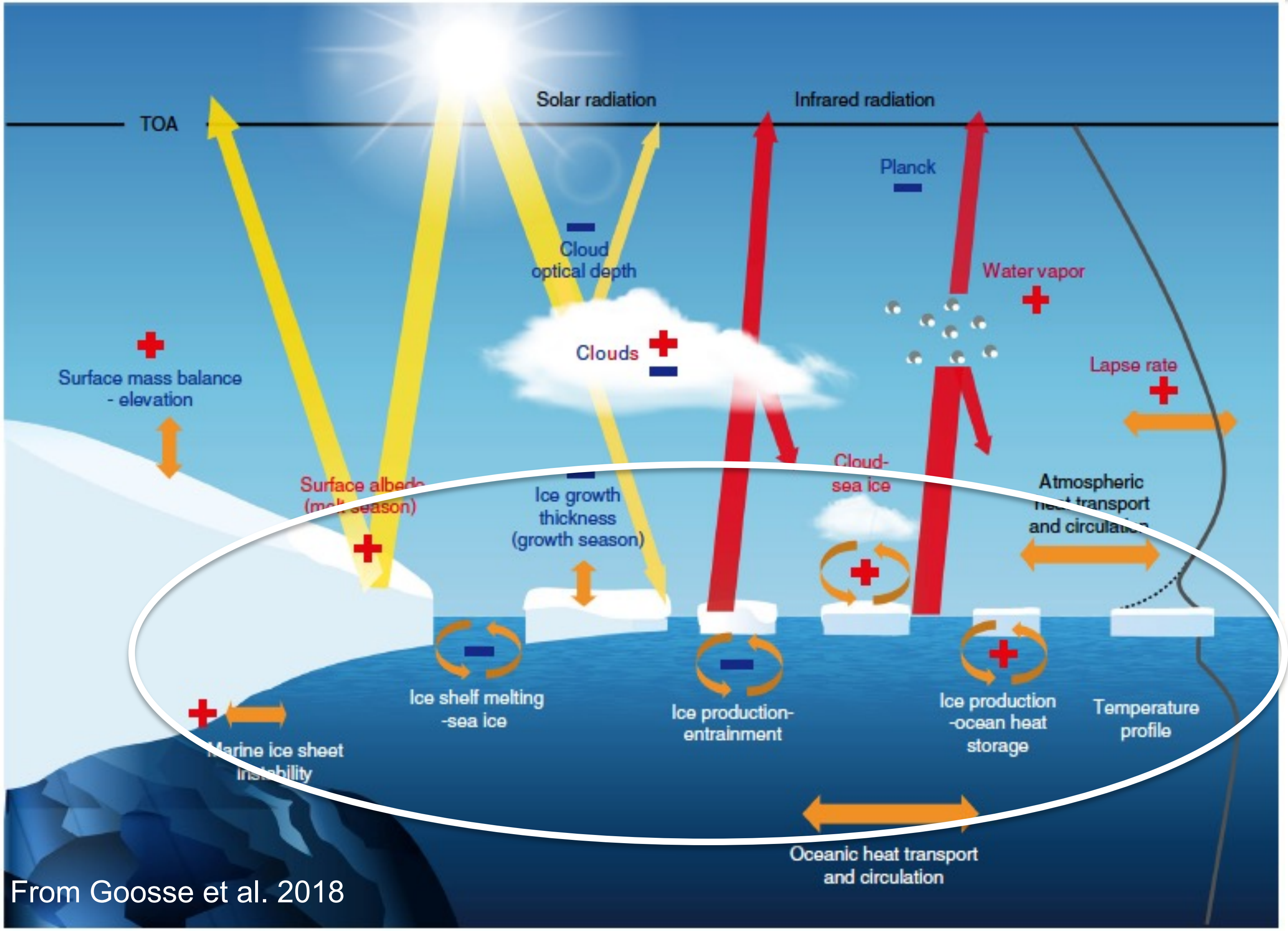
Why do we care about sea ice? (in climate models)





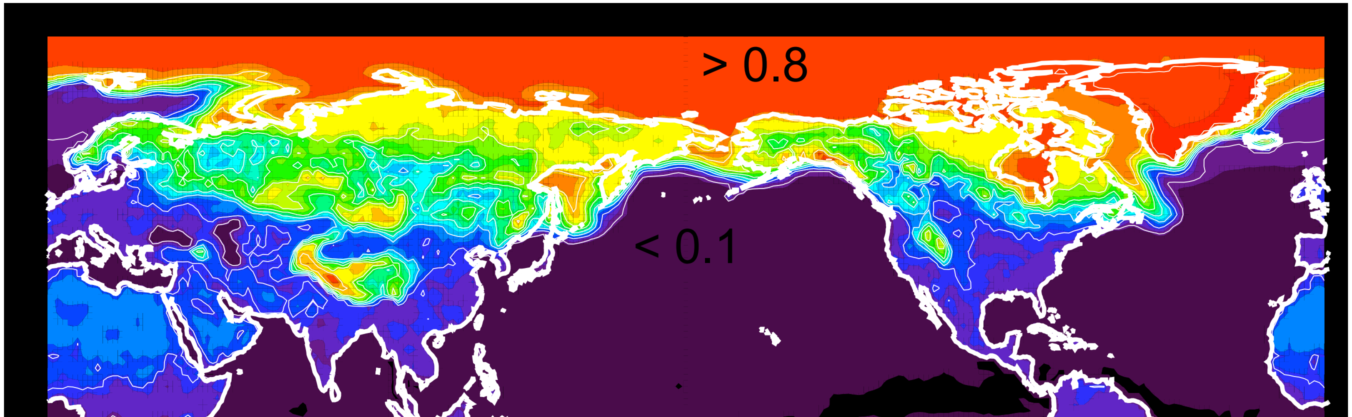
SIAT v2.2.2

Why sea ice matters: Climate Feedbacks

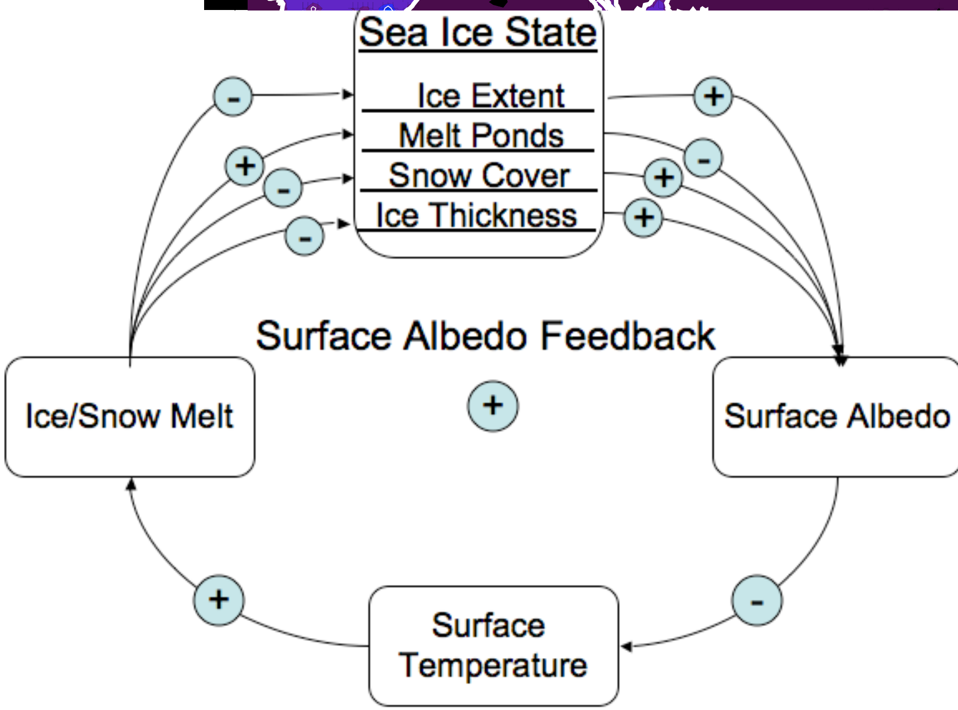


From Goosse et al. 2018

Why sea ice matters: Surface energy budget

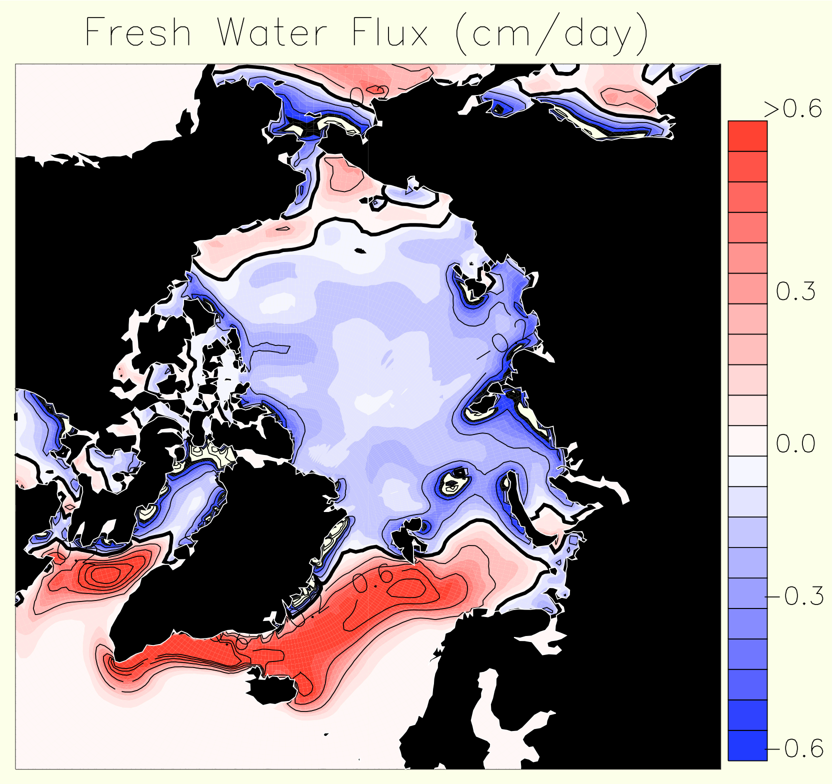


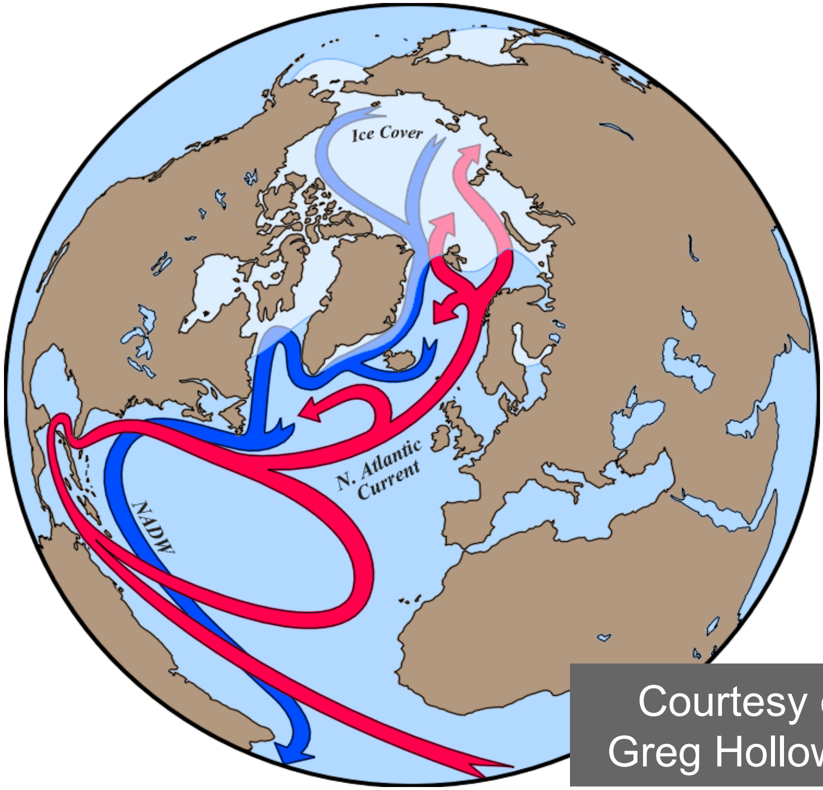
March Mean Surface albedo



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

Why sea ice matters: Hydrological Cycle





Courtesy of Greg Holloway

- Ice formation leads to salt flux to ocean and relatively fresh ice
- Ice melt releases freshwater back to the ocean
- Can modify ocean circulation

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

Sea Ice models used in climate simulations

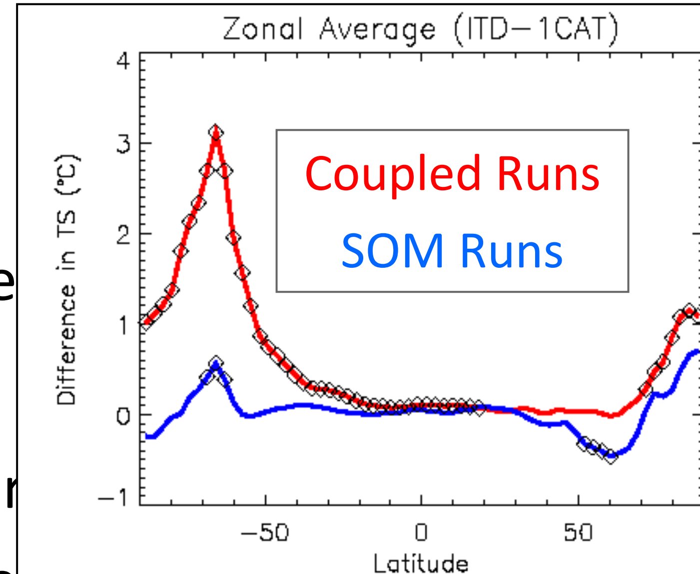
Two primary components

- Dynamics
  - Solves force balance to determine sea ice motion
- Thermodynamics
  - Solves for vertical ice temperature profile
  - Vertical/lateral melt and growth rates

Sea Ice models used in climate simulations

Two primary components

- Dynamics
  - Solves force balance to determine se
- Thermodynamics
  - Solves for vertical ice temperature pr
  - Vertical/lateral melt and growth rates
- Ice Thickness Distribution (some models)
  - Sub-gridscale parameterization
  - Accounts for high spatial heterogeneity in ice



(Holland et al., 2006)

CICE (pronounced "s-ice"): the Los Alamos Sea Ice Model

- CESM2 uses the CICE V5.1.2 (Hunke et al.)
  - Full documentation available online: http://www.cesm.ucar.edu/models/cesm2.0/sea-ice/
- Current CICE development is through the international CICE Consortium
  - https://github.com/CICE-Consortium/

Dynamics

Sea Ice Model - Dynamics

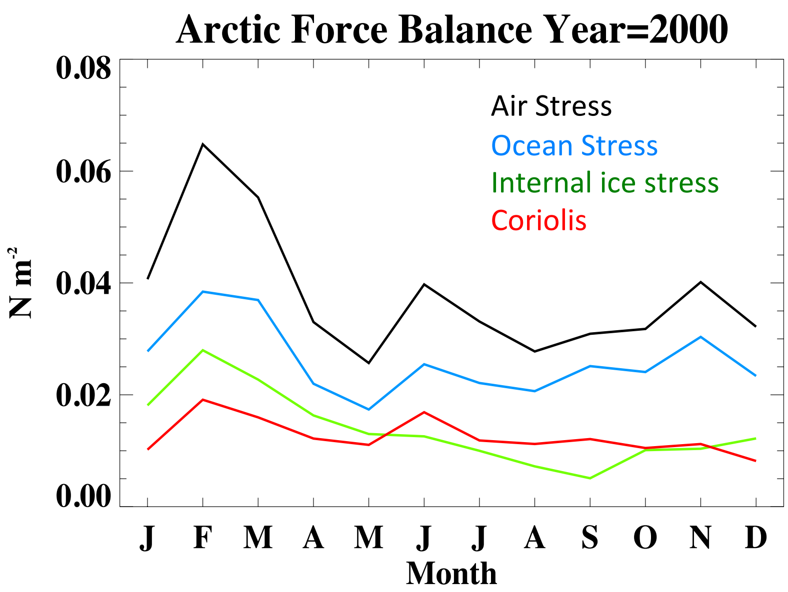
- Force balance between wind stress, water stress, internal ice stress, Coriolis and stress associated with sea surface slope
- Ice treated as a continuum with an effective large-scale rheology describing the relationship between stress and deformation
- Ice freely diverges (no tensile strength)
- Ice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

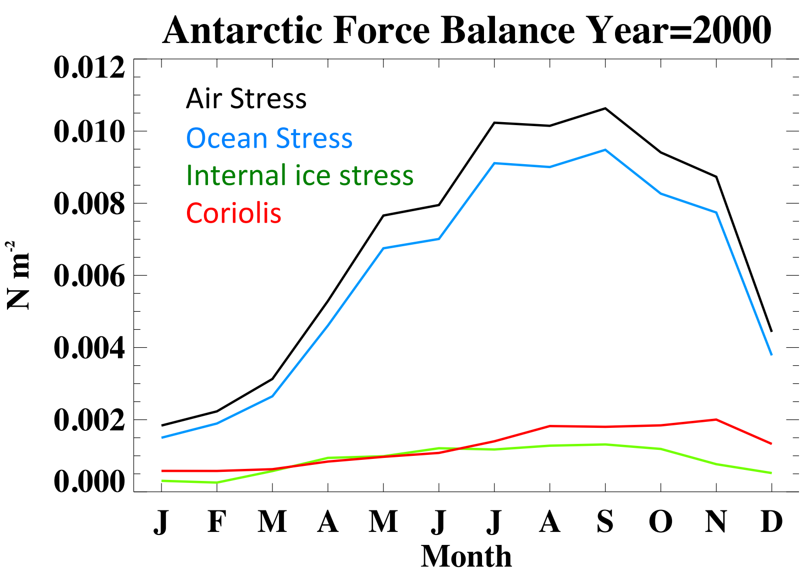
(e.g. Hibler, 1979)

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

Simulated Force Balance

- Arctic: Air stress largely balanced by ocean stress. Internal ice stress has smaller role
- Antarctic: Ice in nearly free drift - weak internal ice stress





Air-Ice and Ocean-Ice Stress

Air-Ice Stress

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

Ocean-Ice Stress

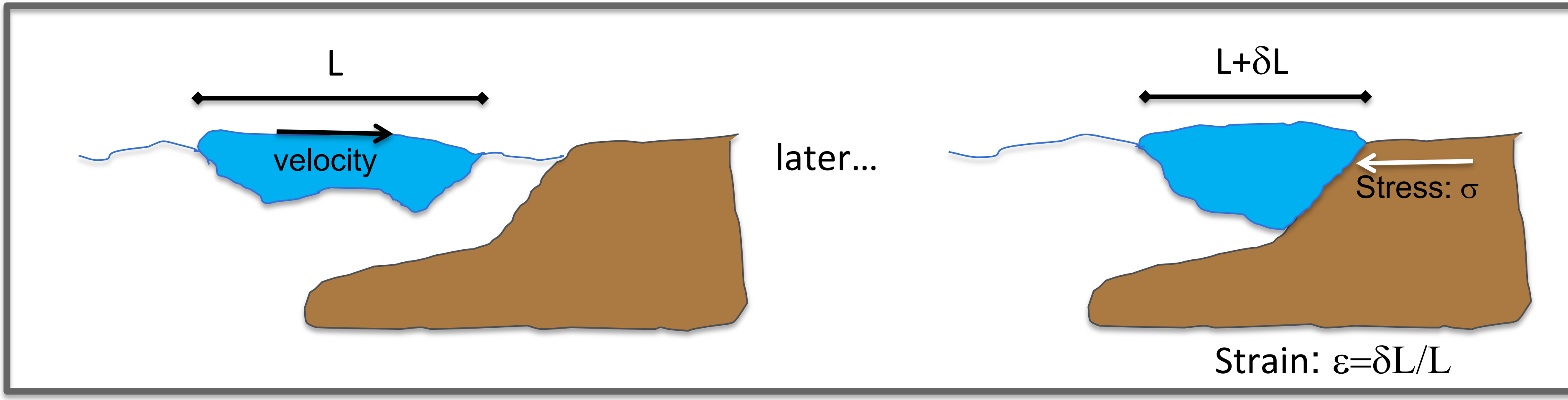
$$\vec{\tau}_w = c_w \rho_w \left|\vec{U}_w - \vec{u}\right| \left[\left(\vec{U}_w - \vec{u}\right)\cos\theta + \hat{k} \times \left(\vec{U}_w - \vec{u}\right)\sin\theta\right]$$

(e.g. Hibler, 1979)

$$\mathrm{m}\frac{\mathrm{Du}}{\mathrm{Dt}} = -\mathrm{mf}\mathbf{k} \times \mathbf{u} + \boldsymbol{\tau}_{\mathrm{a}} + \boldsymbol{\tau}_{\mathrm{w}} - \mathrm{mg_r}\nabla\mathrm{Y} + \nabla\cdot\sigma$$

Total derivative | Coriolis | Air stress | Ocean stress | Sea Surface Slope | Internal Ice Stress

Internal Ice stress



– Stress causes ice to deform, but volume is conserved.

– Need to relate ice stress (σ) to ice strain rate (ε) → area of active research.

(e.g. Hibler, 1979)

$$m\frac{D\mathbf{u}}{Dt} = -mf\mathbf{k}\times\mathbf{u} + \boldsymbol{\tau}_{\mathrm{a}} + \boldsymbol{\tau}_{\mathrm{w}} - mg_{\mathrm{r}}\nabla Y + \nabla\cdot\sigma$$

Total derivative | Coriolis | Air stress | Ocean stress | Sea Surface Slope | Internal Ice Stress

Dynamics used in CESM

CESM uses Elastic Viscous Plastic Model (Hunke and Dukowicz, 1997)

- Ice has no tensile strength but resists convergence and shear with strength dependent on ice state.
- Treats ice as a continuum, based on Viscous-Plastic Rheology (Hibler, 1979)

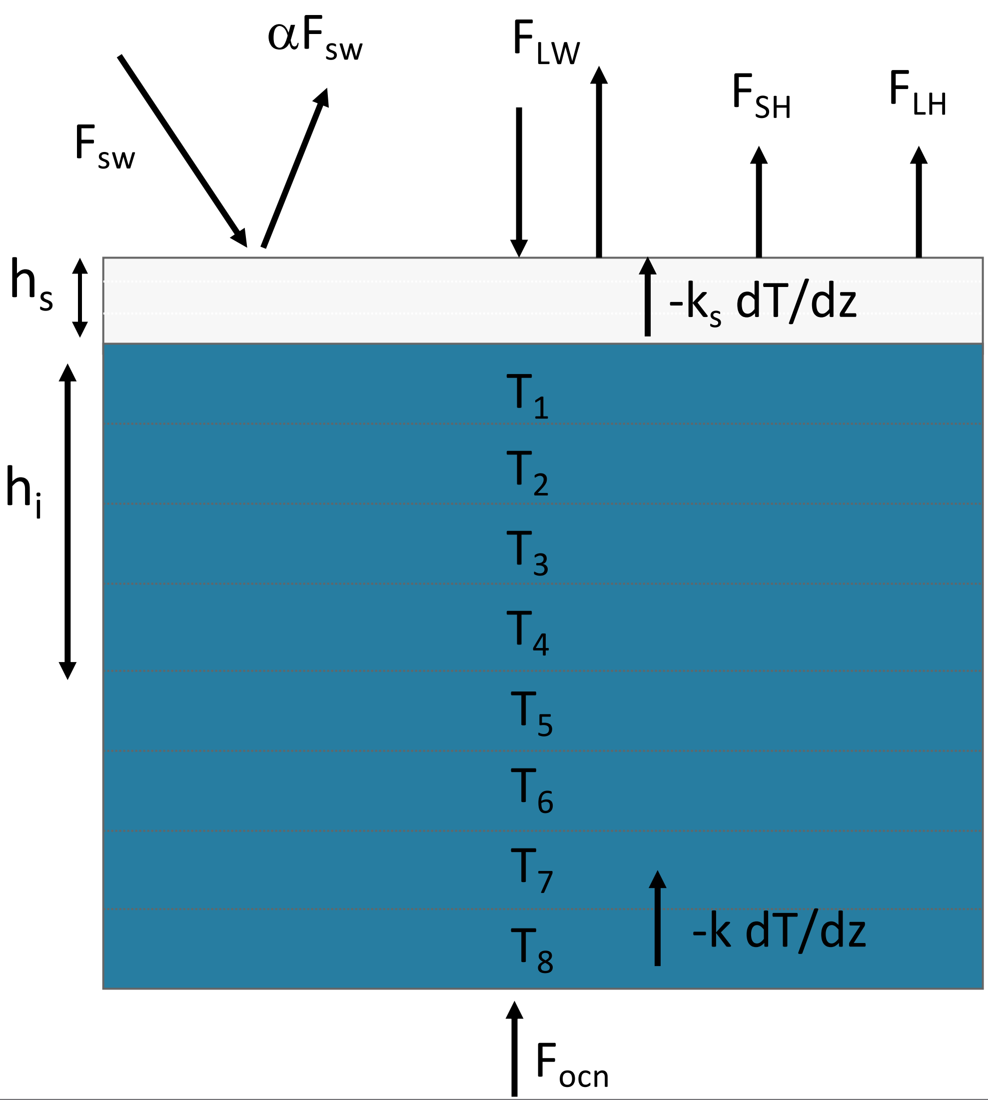
    →Plastic at normal strain rates and viscous at very small strain rates.

    →A viscous-plastic material creeps along but responds to stresses and strains.

- EVP adds in non-physical elasticity as numerical device for solving equations.

Thermodynamics

Sea ice thermodynamics



- Calculate top and basal growth/melt
- CESM 2: 8 sea ice thickness categories and 3 snow layers. (CESM1: 4 and 1 respectively)

Top surface flux balance

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

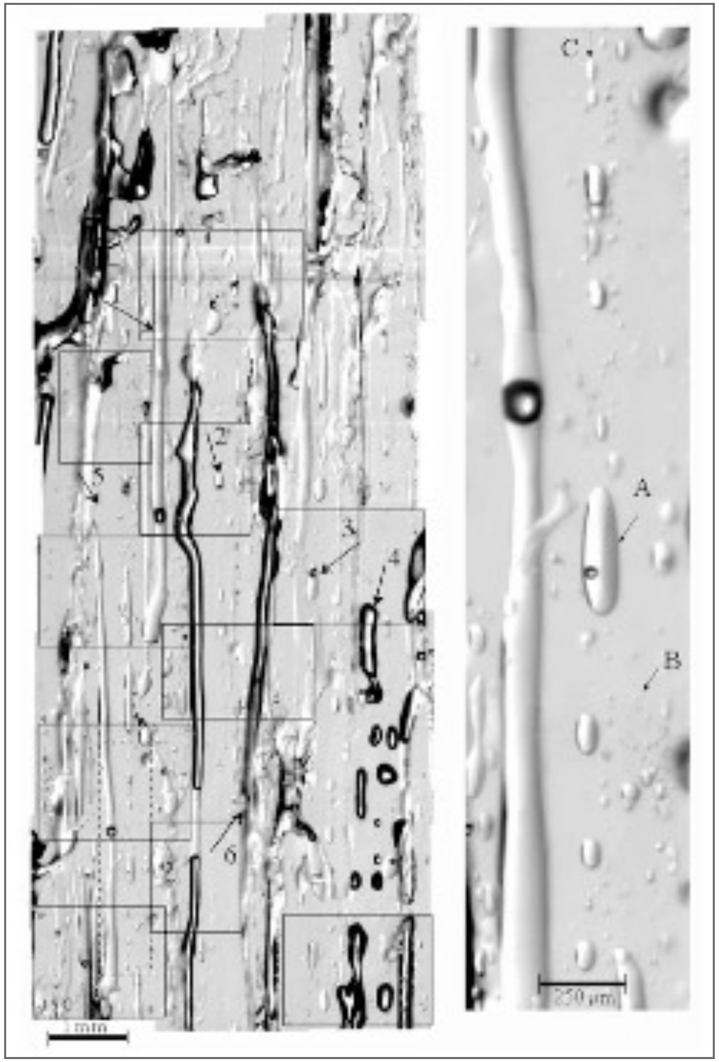
Vertical heat transfer (conduction)

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

Bottom surface flux balance

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

Thermodynamics: Vertical Heat Transfer

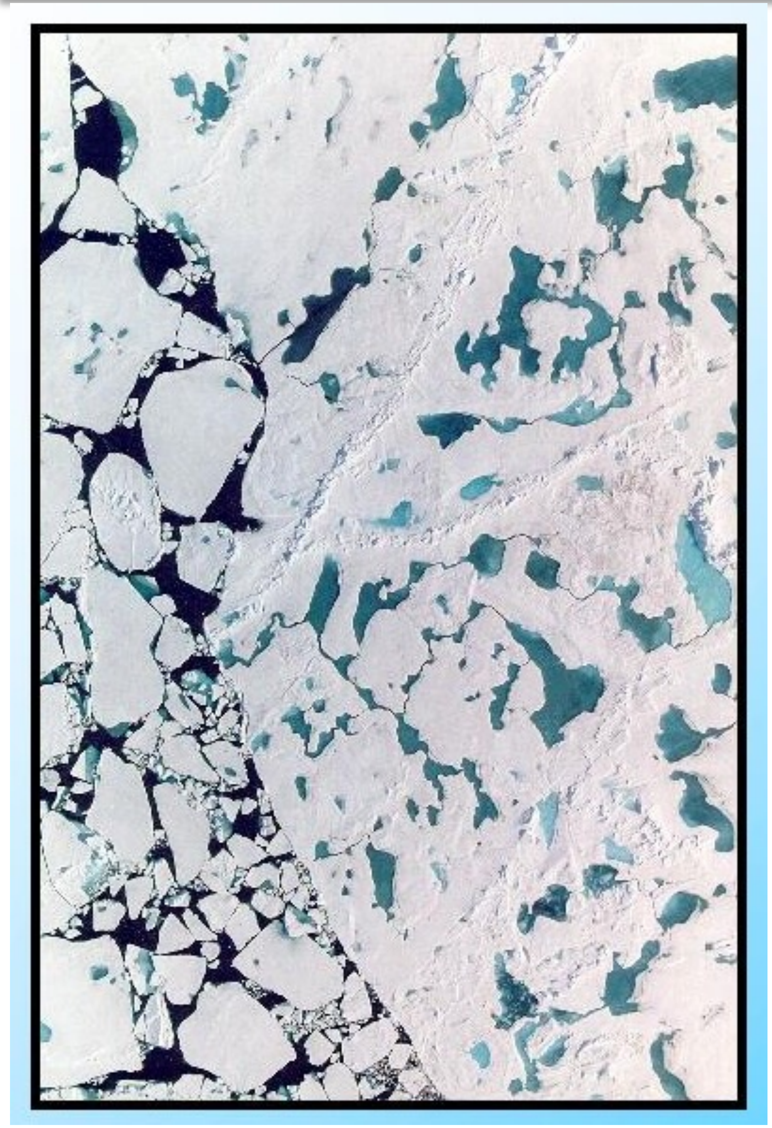


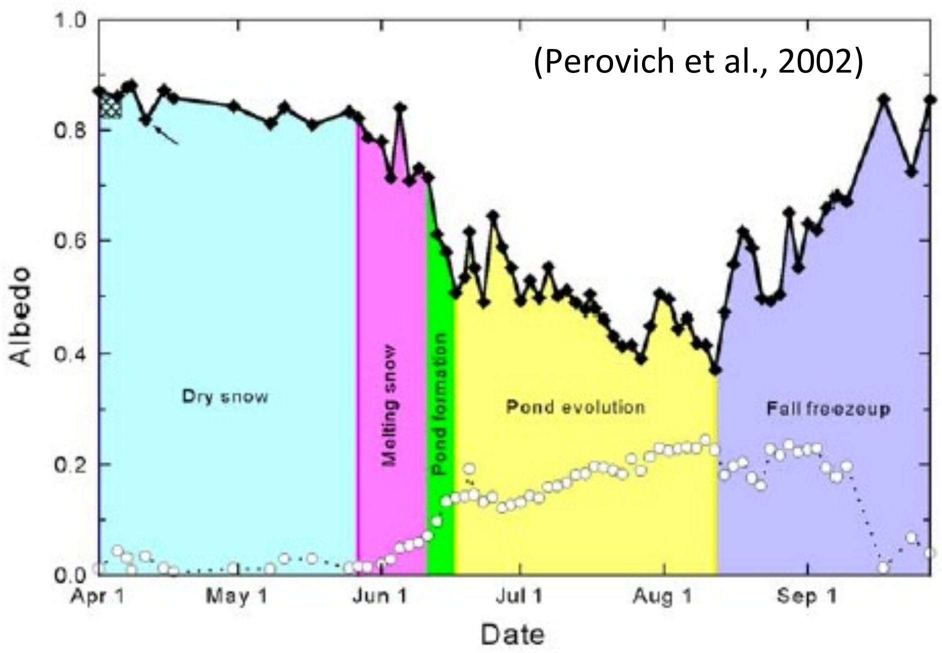
(from Light, Maykut, Grenfell, 2003)

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

- Heat capacity and conductivity are functions of T/S of ice
- Solve to get temperature **<u>and</u>** salinity profiles using mushy layer thermodynamics (Turner and Hunke 2015; new in CESM2)
- Assume pockets/channels are brine filled and they are in thermal equilibrium with ice
- Assume non-varying ice density

Albedo

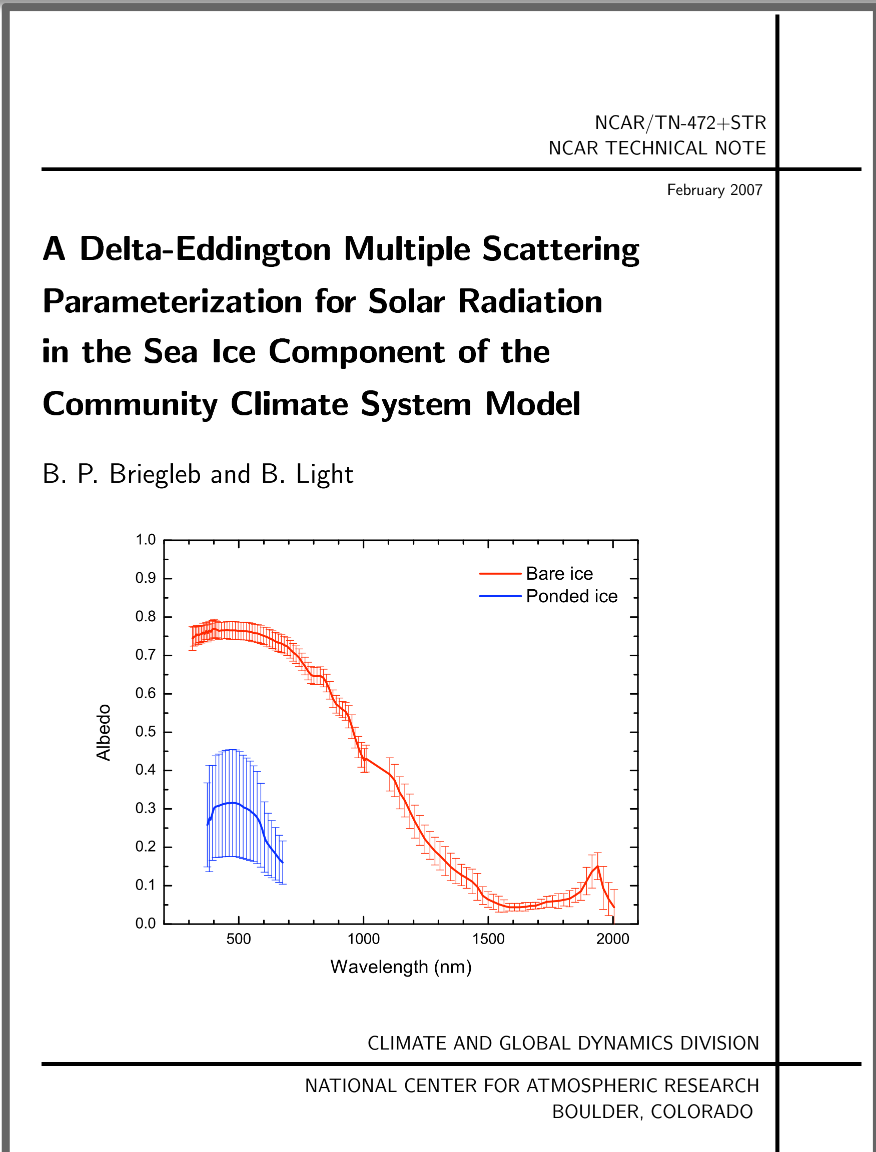




Often the parameterized sea ice albedo depends on characteristics of surface state (snow, temp, ponding, h_i).

Surface ice albedo is only for fraction of gridcell covered by ice.

Delta Eddington Solar Radiation parameterization



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

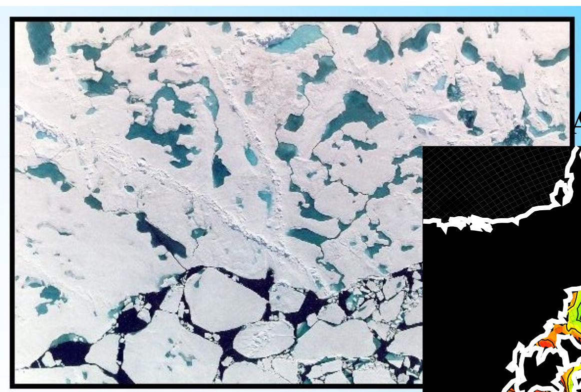
CLIMATE AND GLOBAL DYNAMICS DIVISION

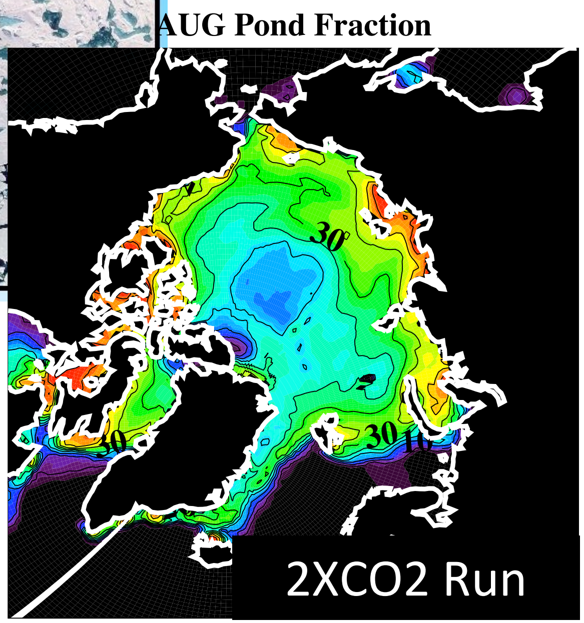
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

- Inherent optical properties define scattering and absorption properties for snow, sea ice, and absorbers.
- Calculate base albedo and then modify.
- Explicitly allows for included absorbers (e.g. algae, carbon, sediment) in sea ice
- Accounts for melt ponds, snow grain sizes, etc.
- Used in CESM1 and CESM2

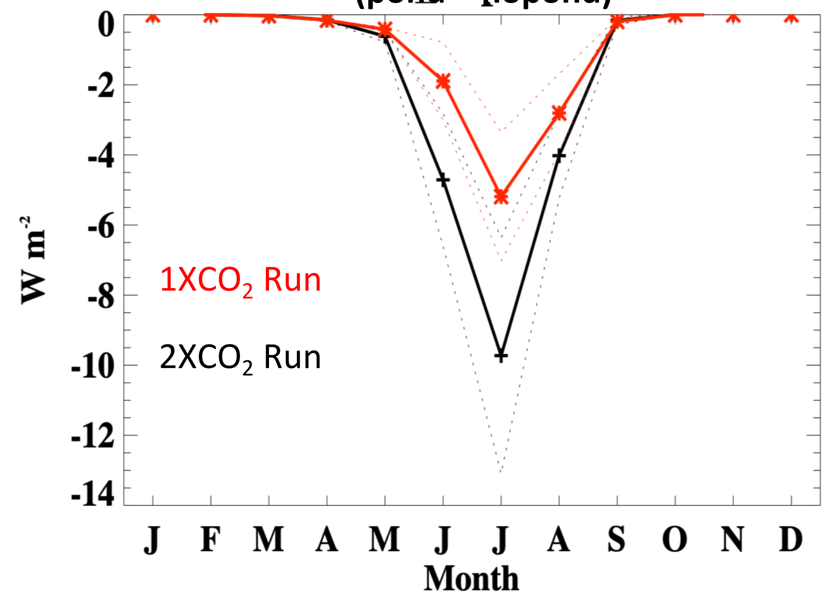
Melt Pond Parameterization

- Only influences radiation and has big influence on surface forcing
- Ponds evolve over time and are carried as tracers on the ice
- CESM2 pond evolution takes into account if sea ice is deformed (level ponds)





Arctic Basin Average SW flux (pond – nopond)

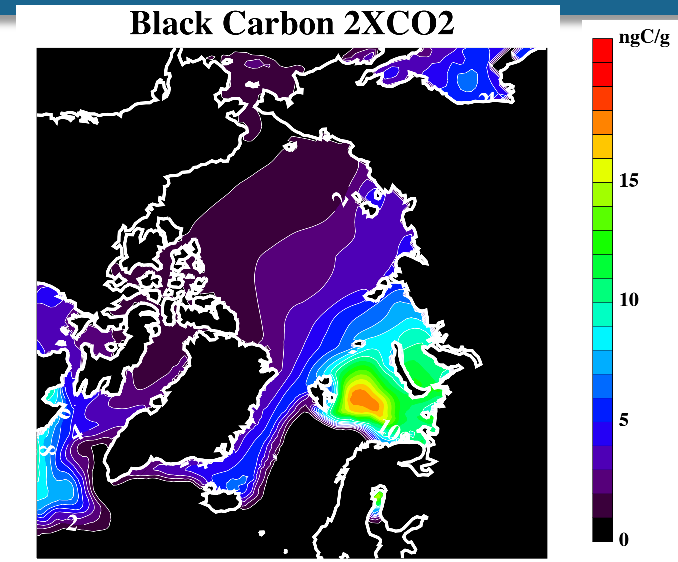


Holland, M. M., et al. 2012: Improved sea ice shortwave radiation physics in CCSM4

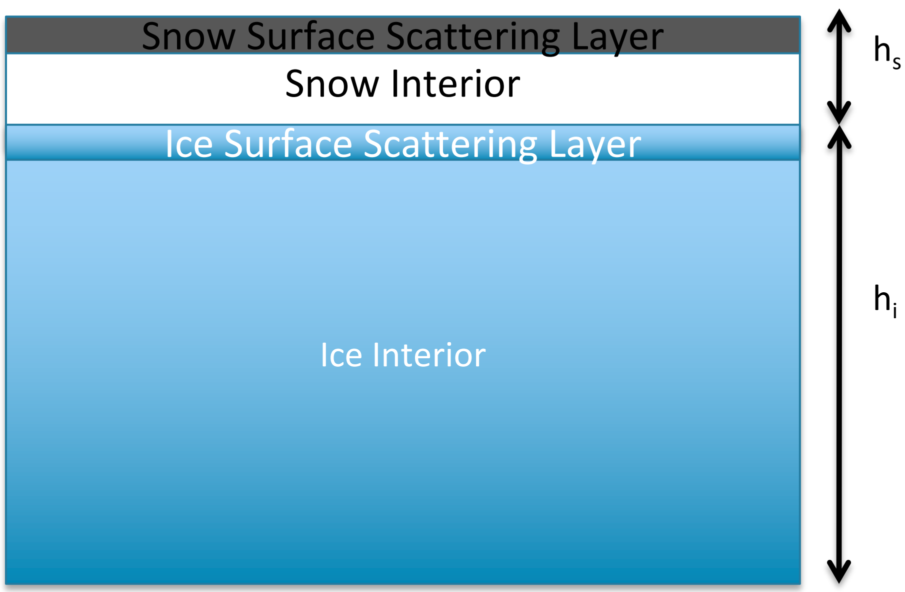
Aerosol deposition and cycling

- Aerosol (e.g. dust, black carbon) deposition and cycling now included.
- These are deposited from the atmosphere and modified by melt and transport
- ~10% of the impact of melt ponds

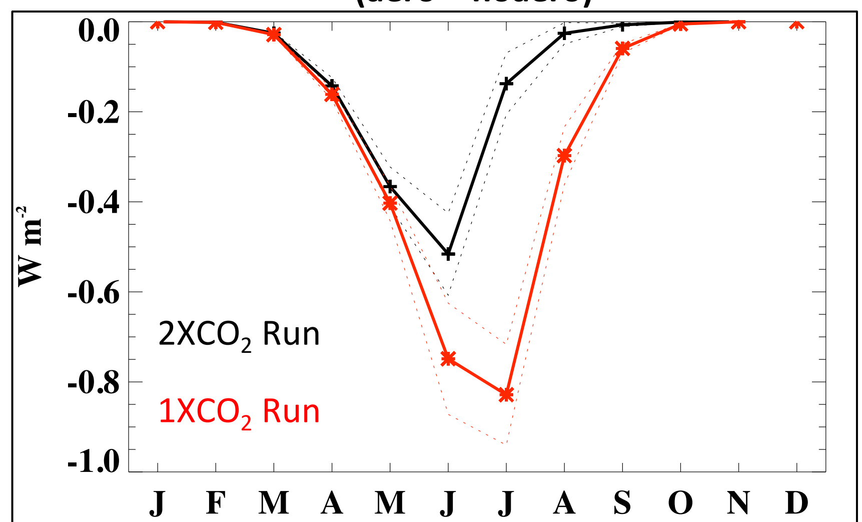
With 1850 Aerosol Deposition



Arctic Basin Average

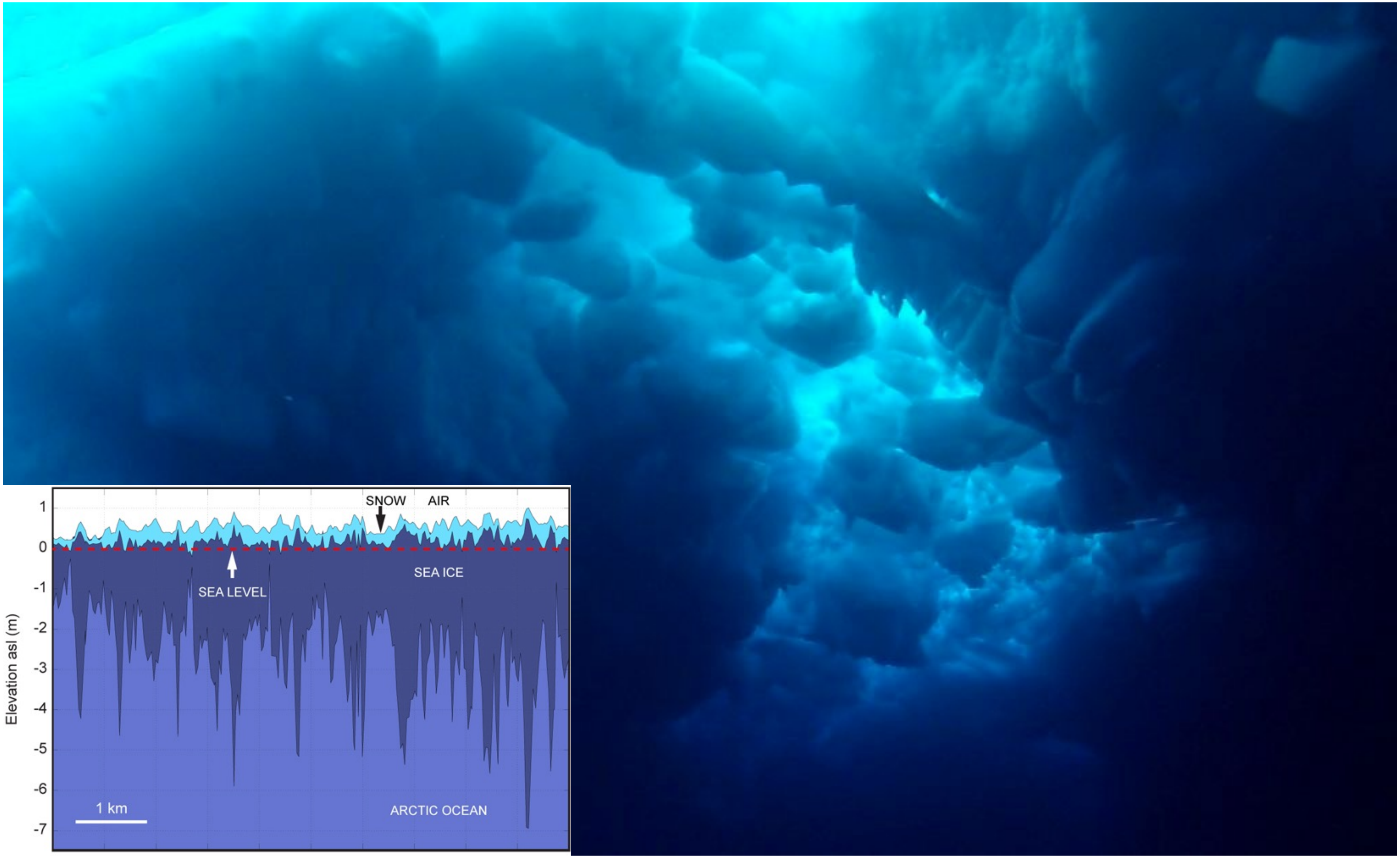


Arctic Basin Average SW flux (aero – noaero)



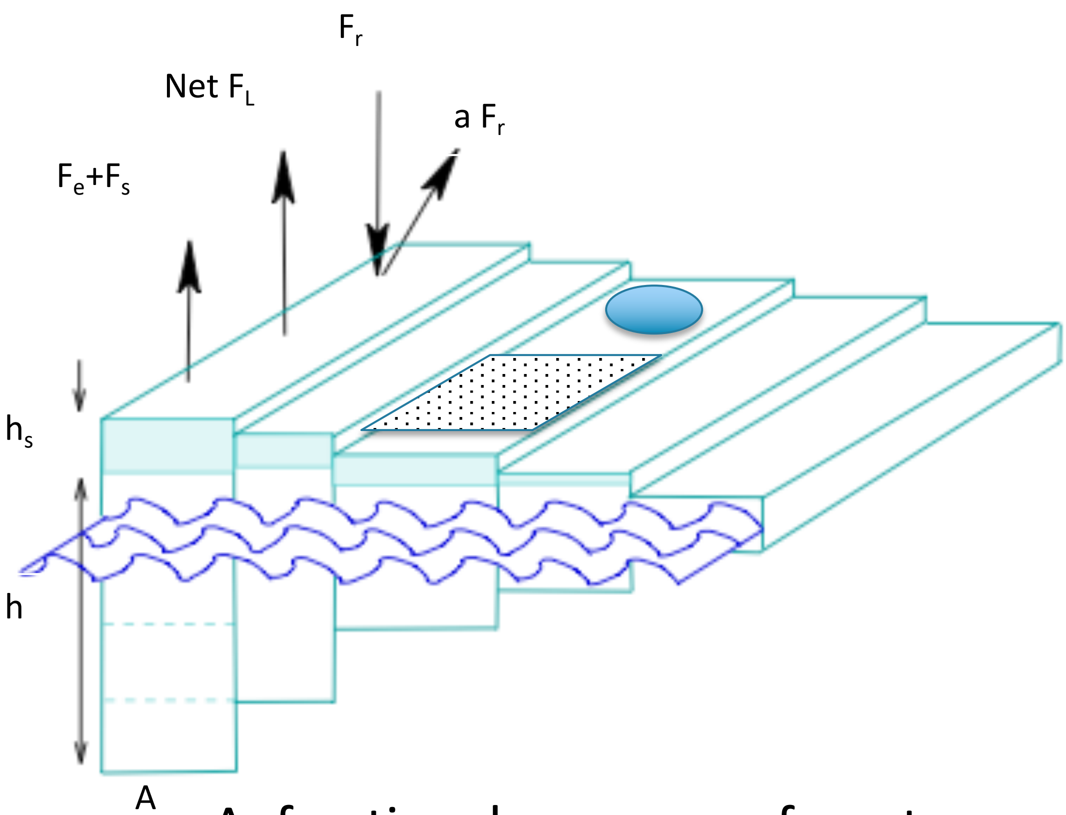
Holland, M. M., et al. 2012: Improved sea ice shortwave radiation physics in CCSM4

Ice Thickness Distribution



Ice Thickness Distribution

- Represents high spatial heterogeneity of sea ice
- CESM uses five ice "categories"



A=fractional coverage of a category

For each category, keep track of:

- Fractional area per grid cell
- Volume per grid cell
- Enthalpy per grid cell
- Surface temperature
- Snow and melt pond areas
- Aerosol contents
- Etc.

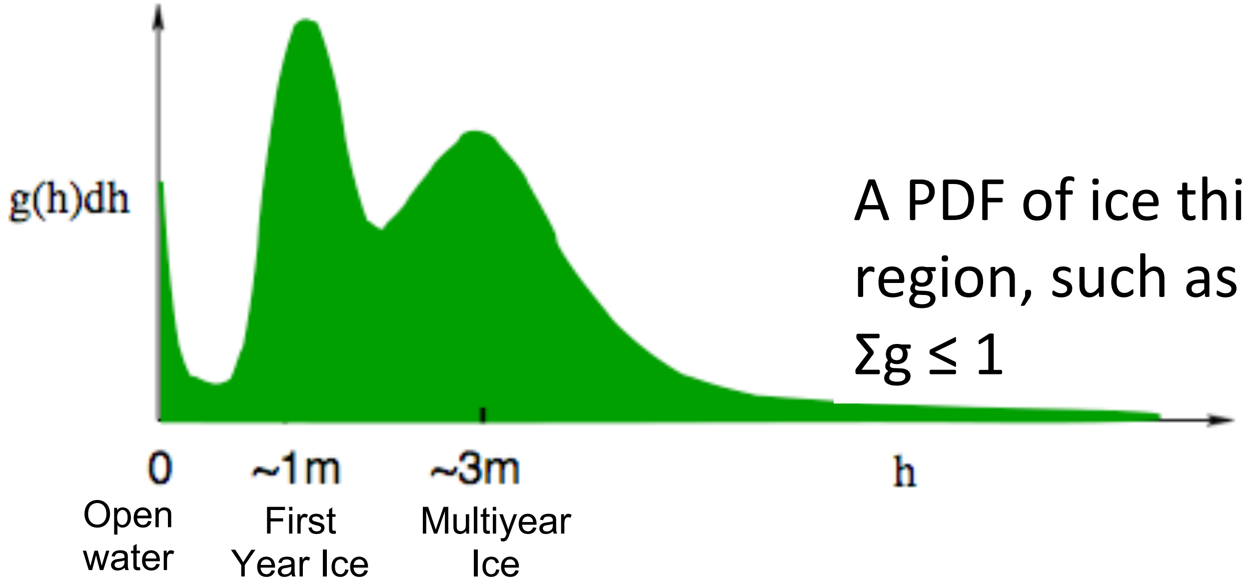
Ice Thickness Distribution

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

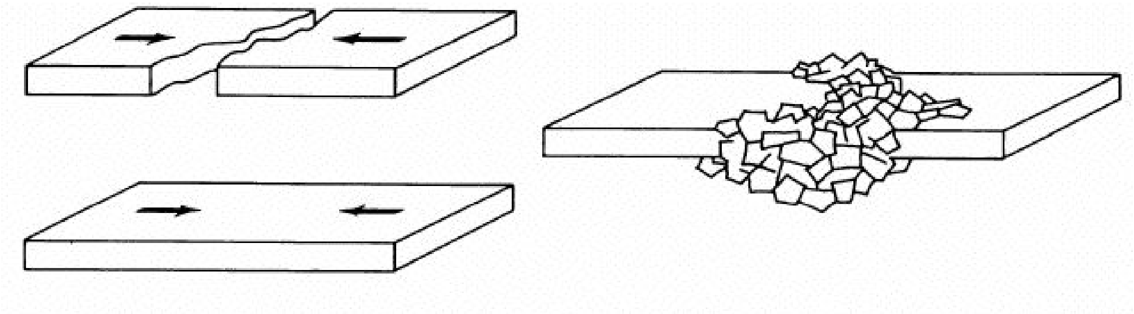
g(h)dh is the fractional area covered by ice of thickness h to h+dh

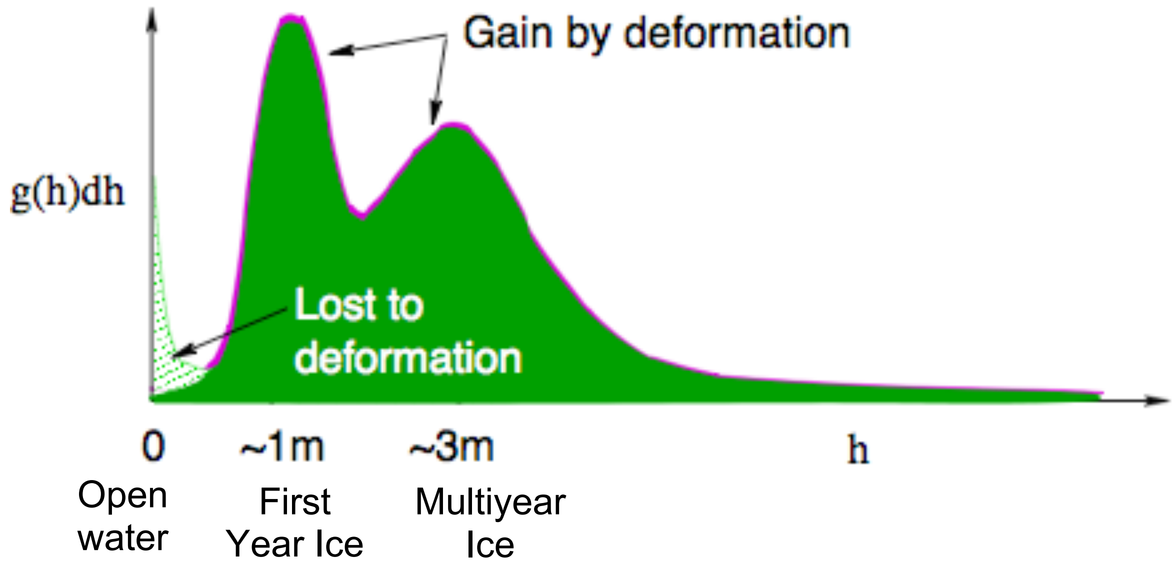


A PDF of ice thickness h in a region, such as a grid cell. $0 \leq \Sigma g \leq 1$

Ice Thickness Distribution: impact of convergence

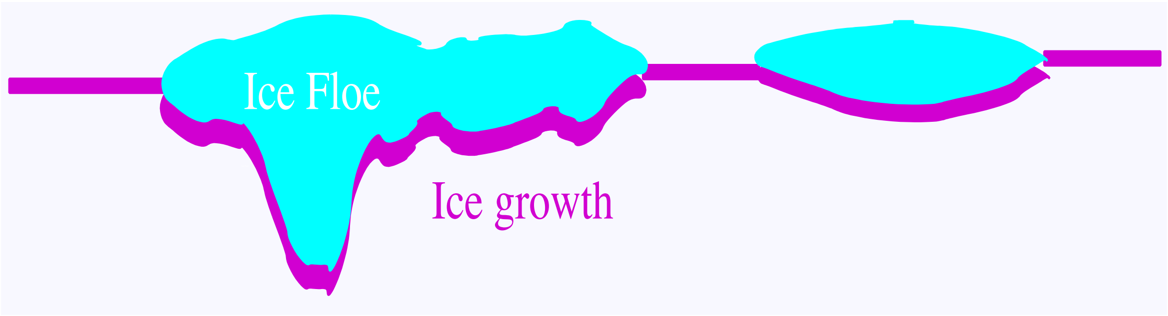
Mechanical redistribution: Transfer ice from thin part of distribution to thicker categories

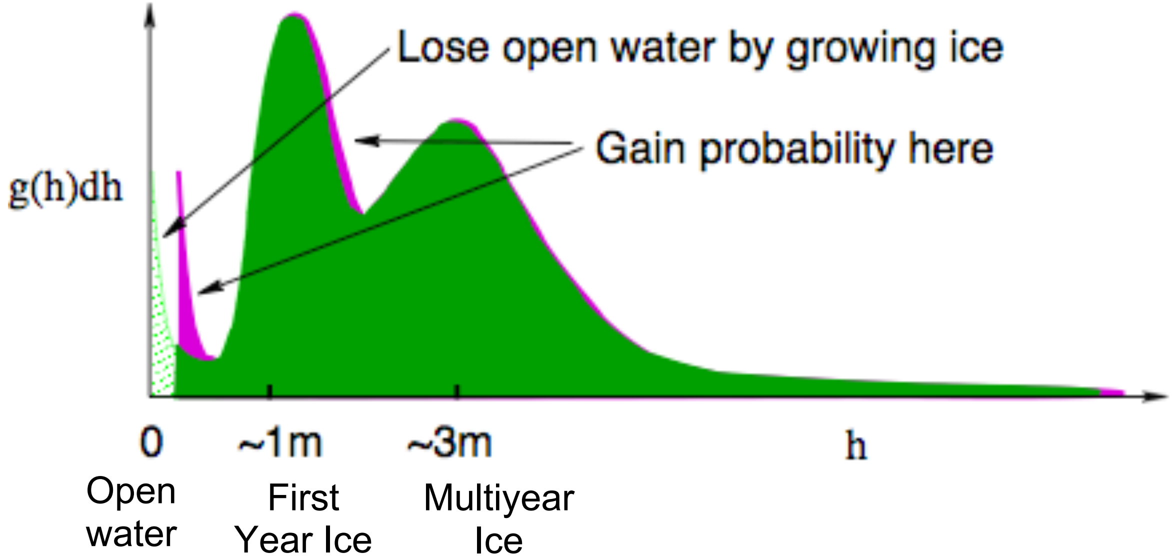




Ice Thickness Distribution: impact of ice growth

Lose open water, gain probability of both thin ice and thicker ice





Summary

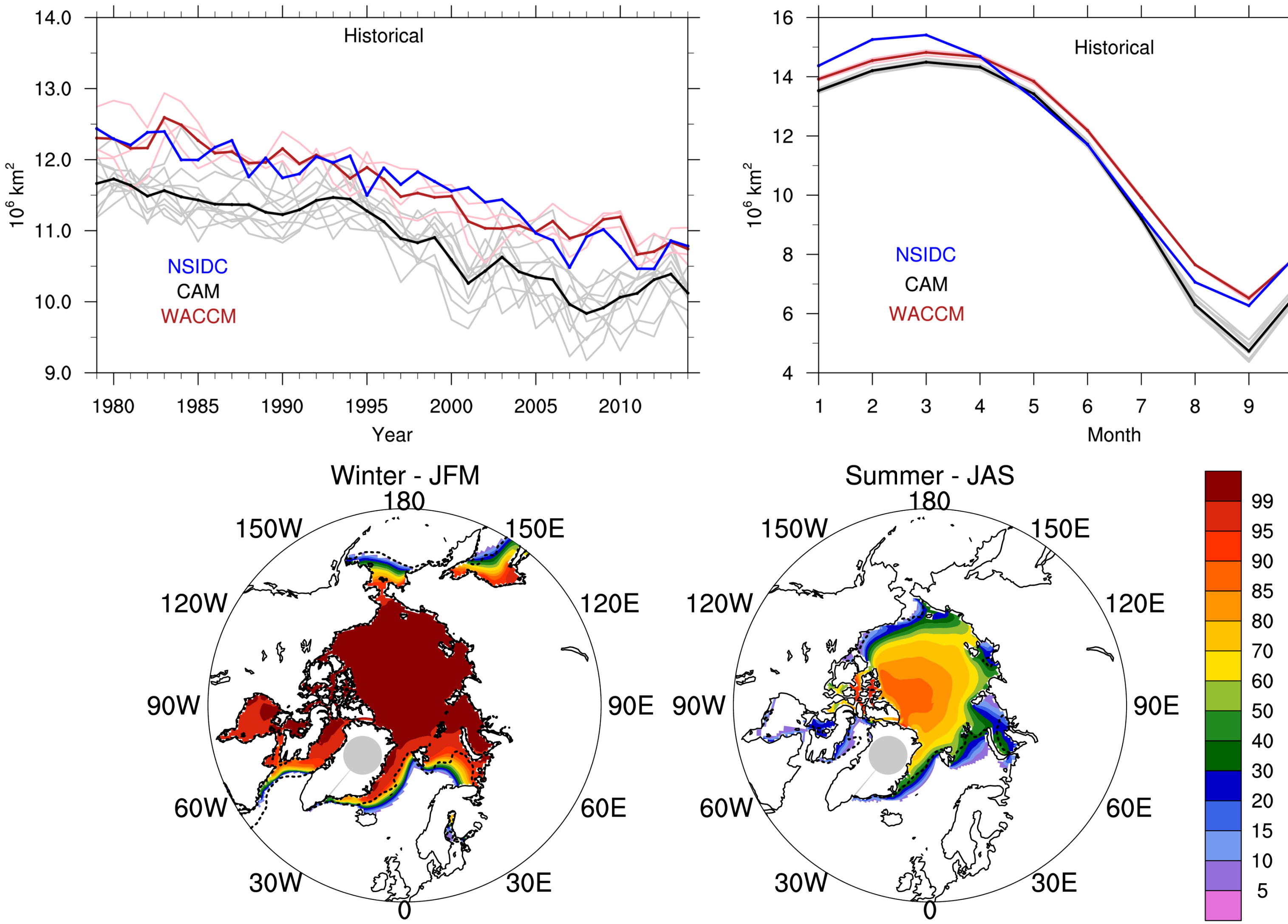
- CICE in CESM2
  - EVP dynamics
  - Sophisticated mushy layer thermodynamics (Turner and Hunke 2015)
  - 8 sea ice vertical levels (was 4); 3 snow vertical levels (was 1)
  - Sub-gridscale ice thickness distribution – 5 categories
  - Level ice ponds (Hunke et al. 2013)
  - Salinity dependent freezing point

- In development:
  - Biogeochemistry, Water isotopes, Floe size distribution, Snow model changes, Satellite simulators, Data assimilation

Science Highlights

- CESM2 simulated sea ice compared to obs
  - Two configurations submitted to CMIP6: CAM and WACCM. Both use identical sea ice physics.
- Impact of sea ice physics changes in CESM2 vs. CESM1
- Using the model to understand future Arctic ice loss
- Changes to Antarctic sea ice variability in CESM2 vs. CESM1

CESM2 Arctic Sea Ice Extent



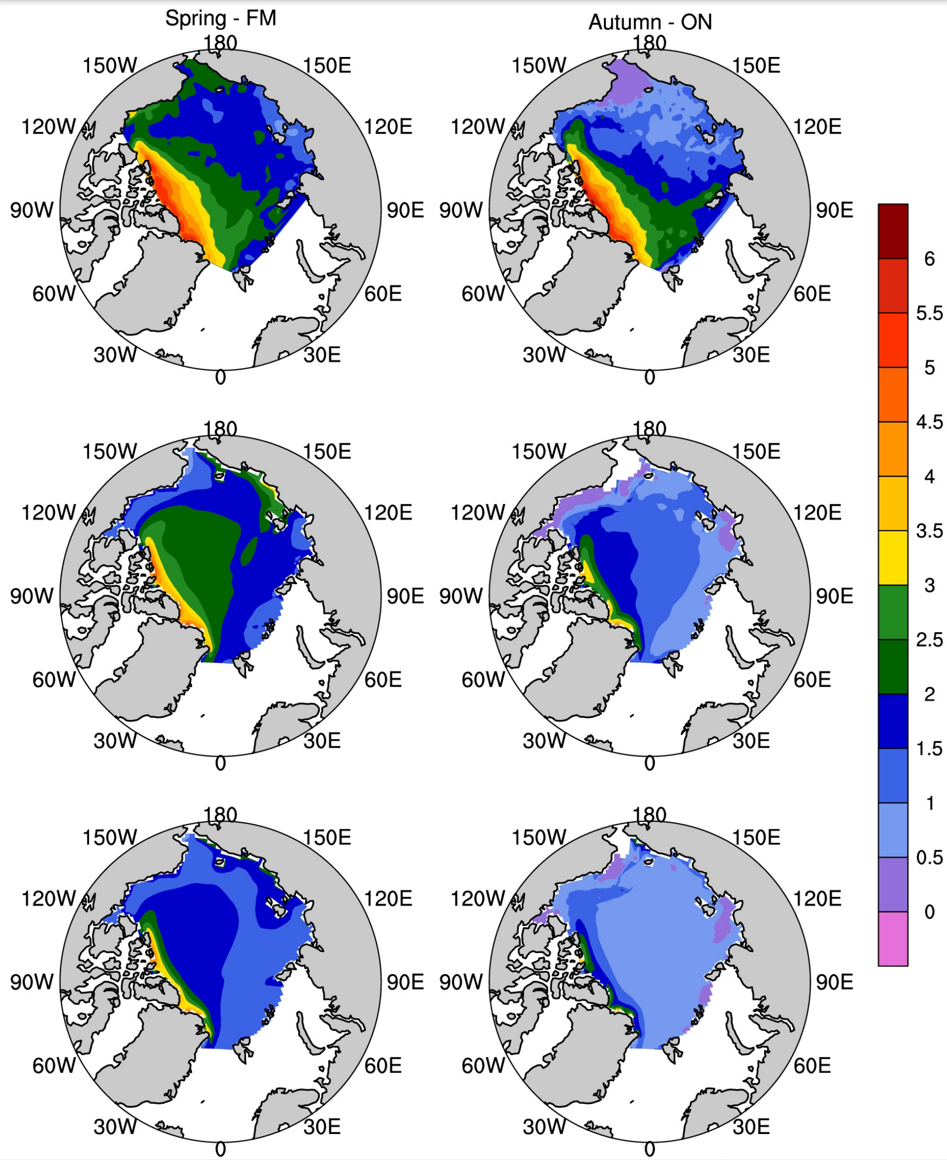
DuVivier et al. 2020

CESM2 Arctic Sea Ice Thickness

IceSat 2001-2005

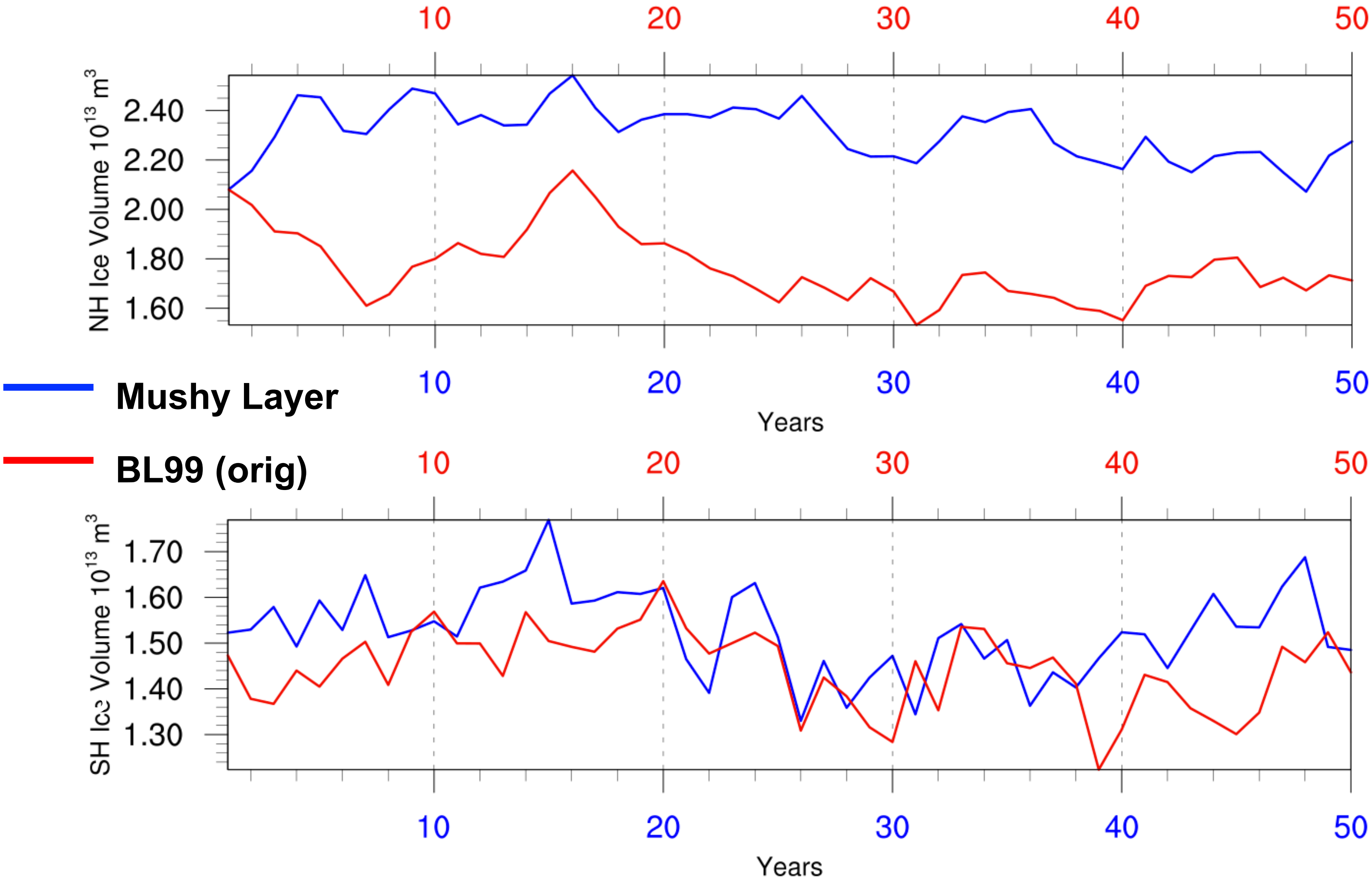
WACCM 2001-2005

CAM 2001-2005



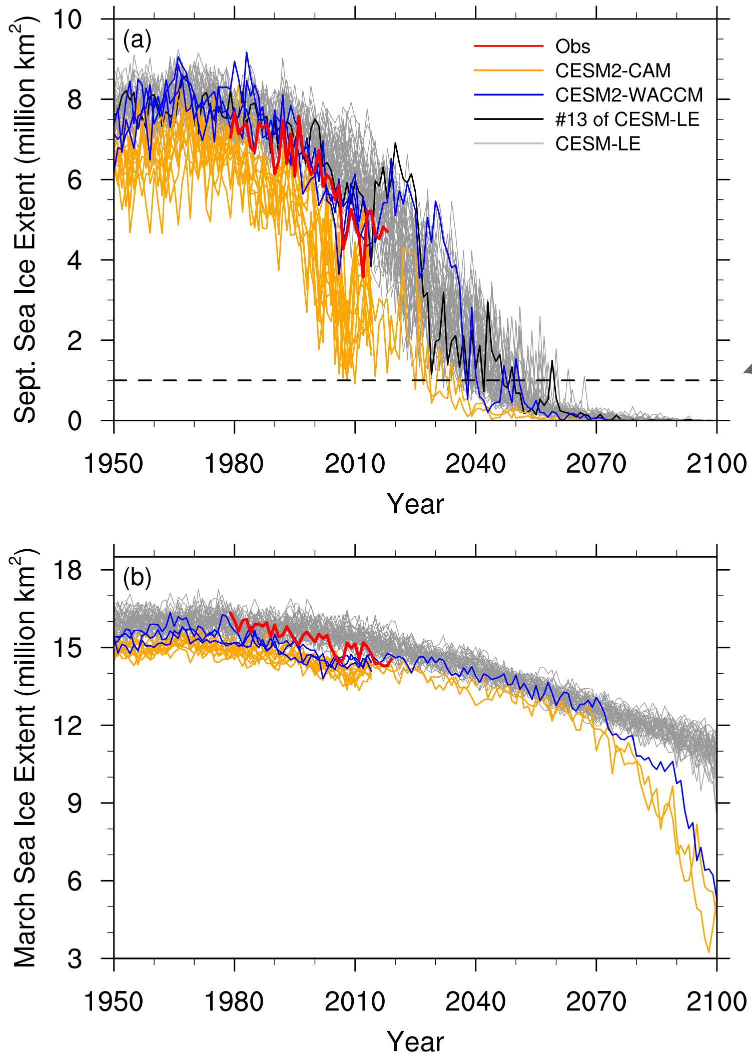
DuVivier et al. 2020

Mushy Layer Thermodynamics



Bailey et al. 2020

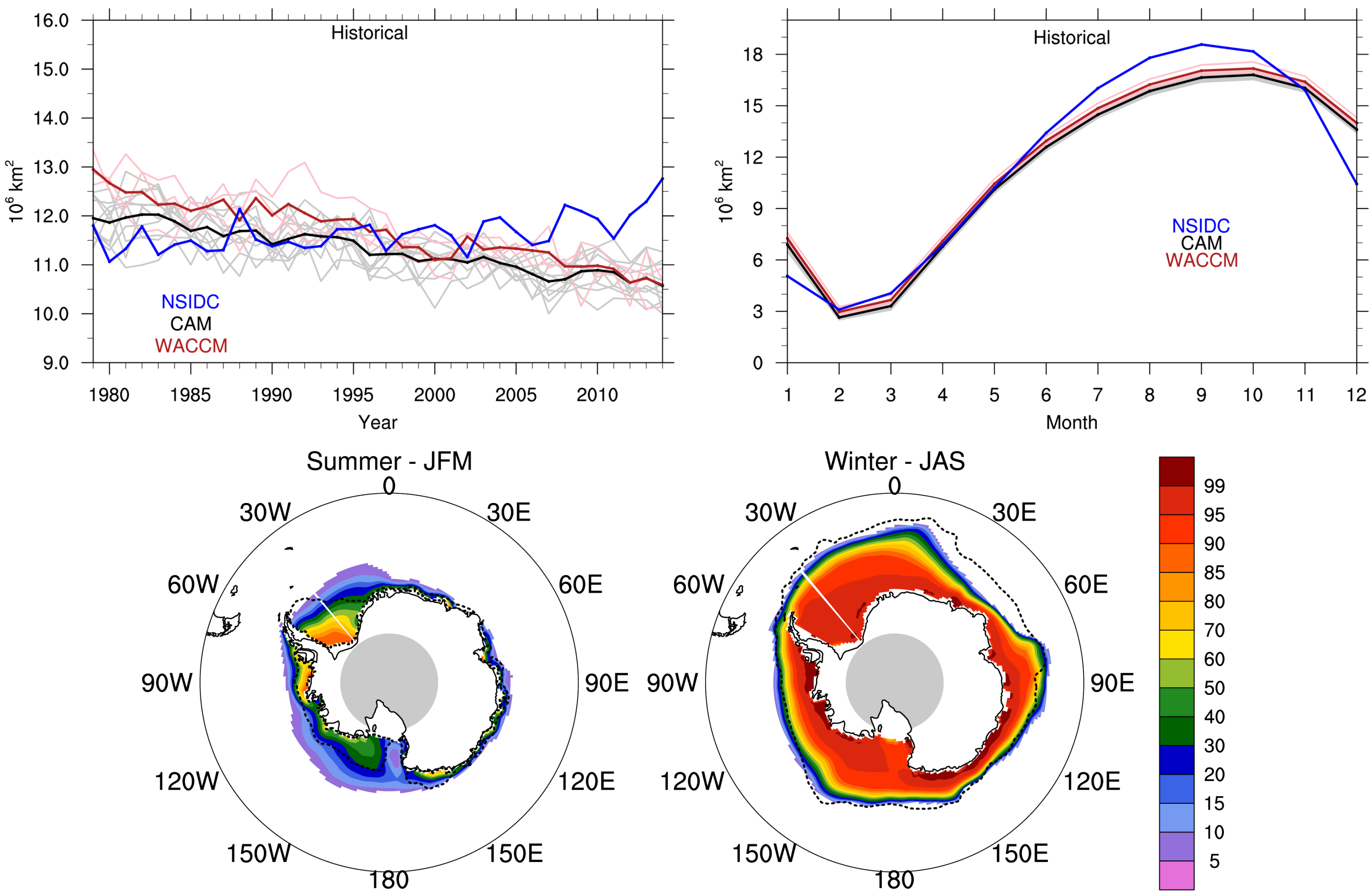
CESM2 Arctic Sea Ice Extent Projections



“Ice Free” Arctic

DeRepentigny et al. 2022

CESM2 Antarctic Sea Ice Extent

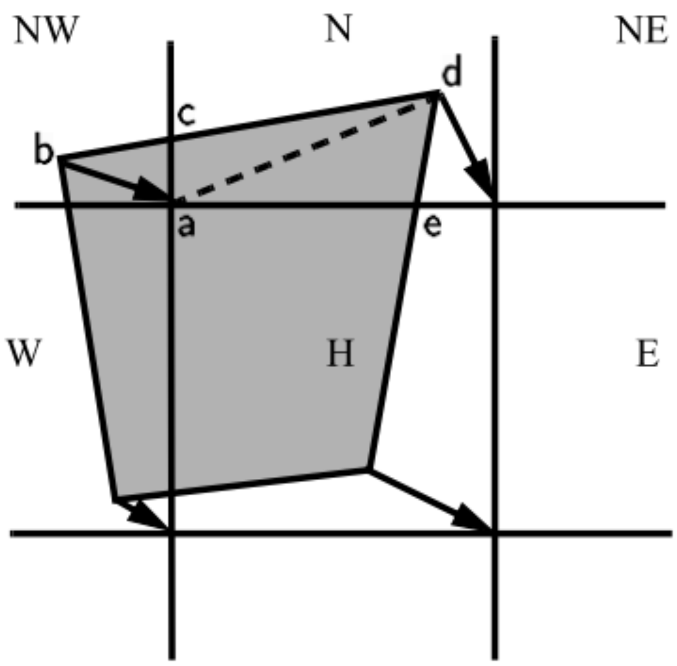


DuVivier et al. 2020

http://assets.nydailynews.com/polopoly_fs/1.17149.1313675705!/img/httpImage/image.jpg_gen/derivatives/gallery_635/gal-natures-best-08-jpg.jpg

Advection

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



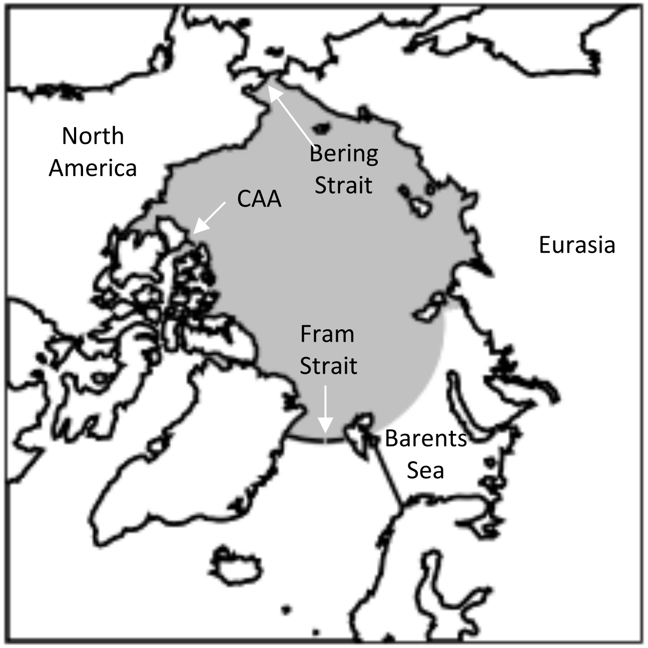
Conserved quantities are remapped from the shaded "departure region", which is computed from backward trajectories of the ice motion field.

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

$$\frac{d\bar{h}}{dt} = \Gamma_h - \nabla \bullet (\vec{u}h)$$

Ice volume change | Thermodynamic source | Divergence



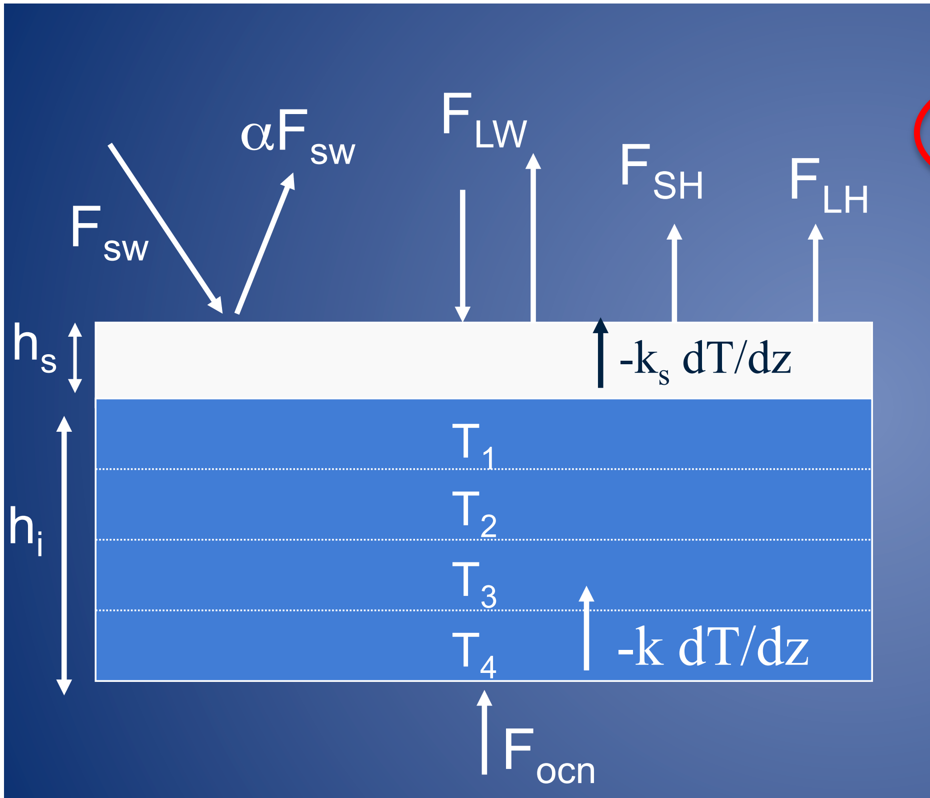
Climate model archive of monthly averaged ice thickness and velocity

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

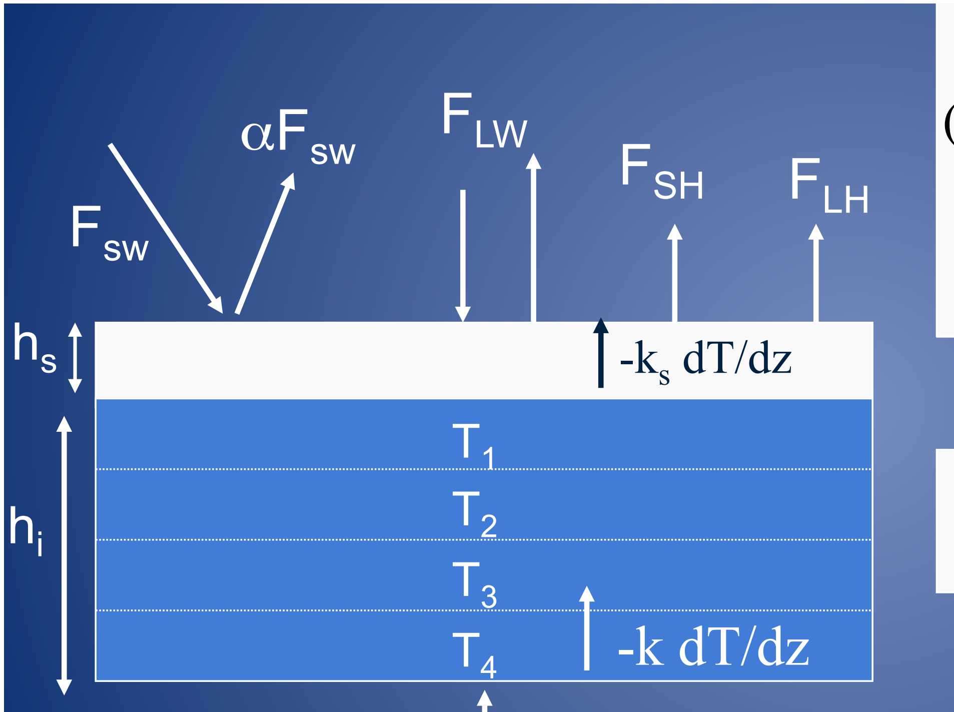
$$F_{ocn} - k\frac{\partial T}{\partial z} = -q\frac{dh}{dt}$$

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

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Vertical heat transfer (conduction, SW absorption)

Balance of fluxes at ice base

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

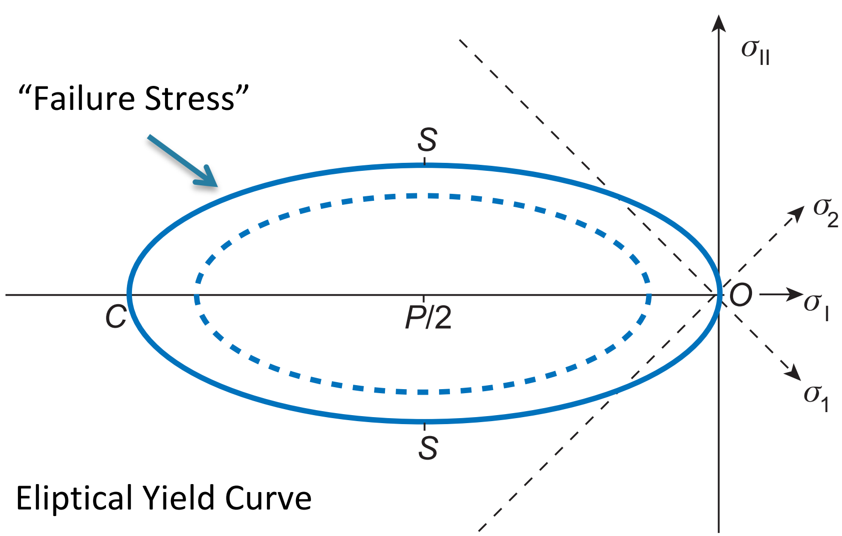
Heat conduction related to vertical temperature gradient

Causes ice growth to vary as 1/h

Has a stabilizing effect on ice thickness since thin ice grows more rapidly

Sea Ice Model - Dynamics

- 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

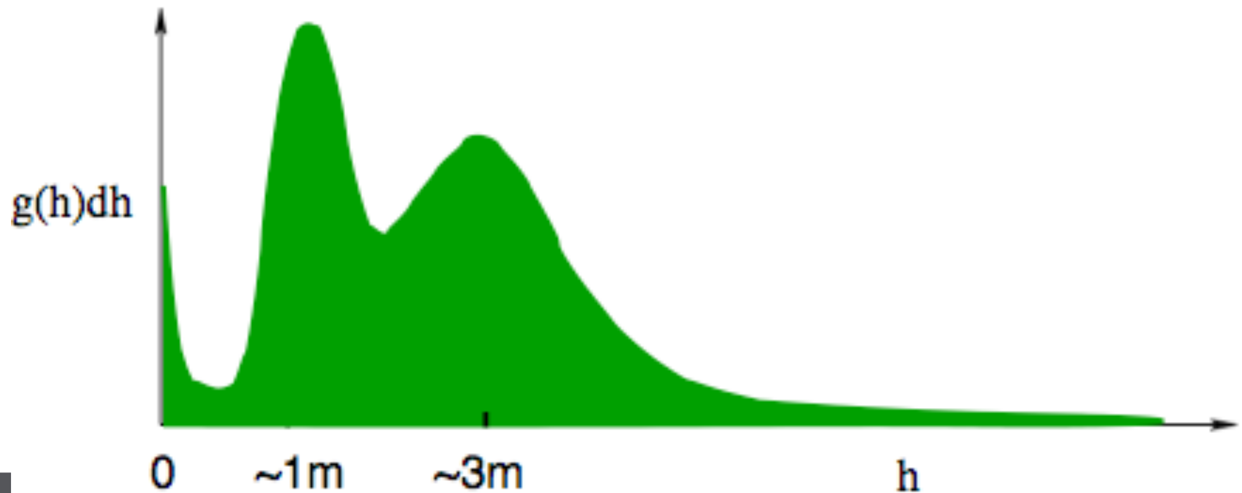
EVP model uses explicit time stepping by adding elastic waves to constitutive law (Hunke and Dukowicz, 1997)

Ice Thickness Distribution

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

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

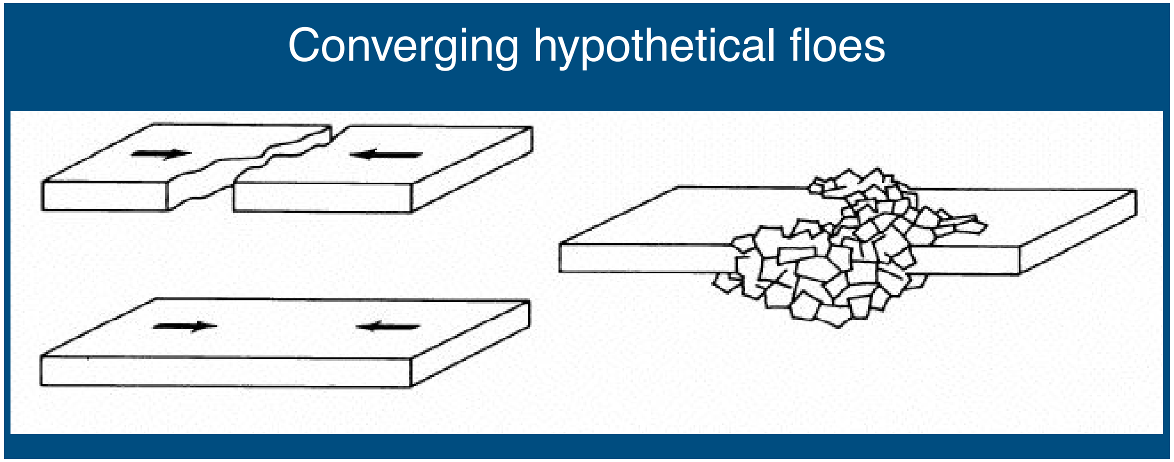
Ice Growth　Lateral Melt　Convergence　Mechanical Redistribution

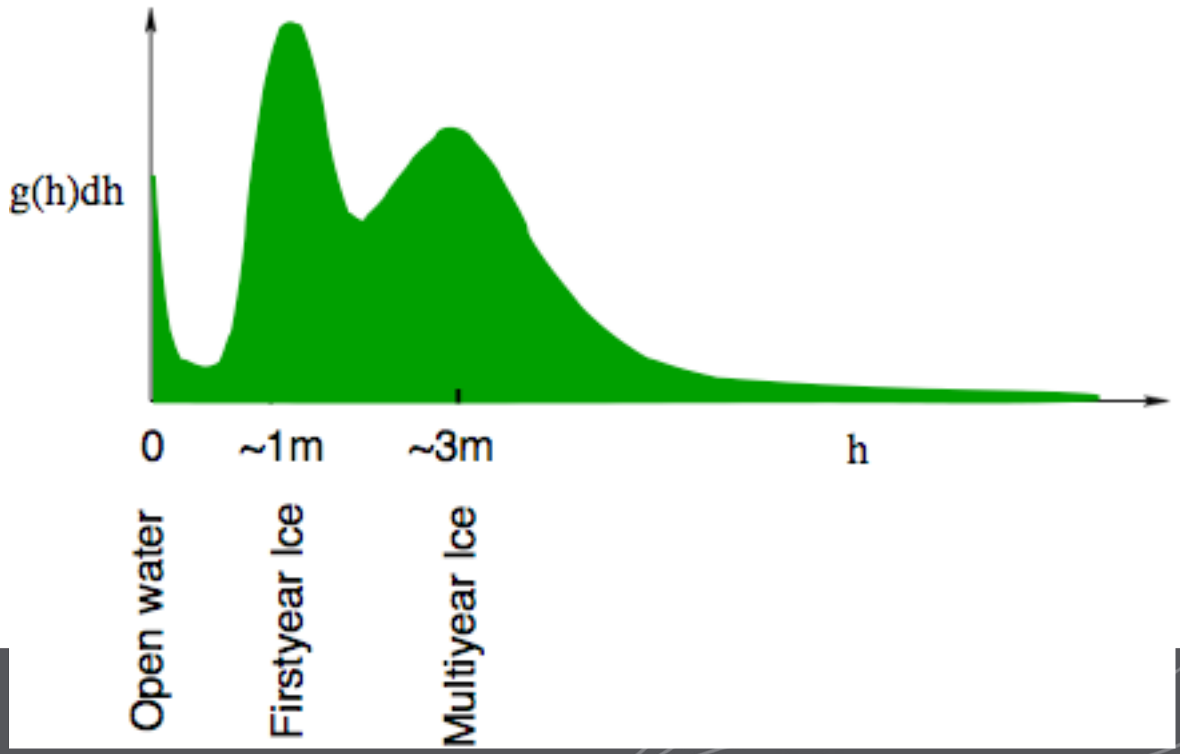


g(h)dh is the fractional area covered by ice of thickness h to h+dh

Y = Mechanical redistribution

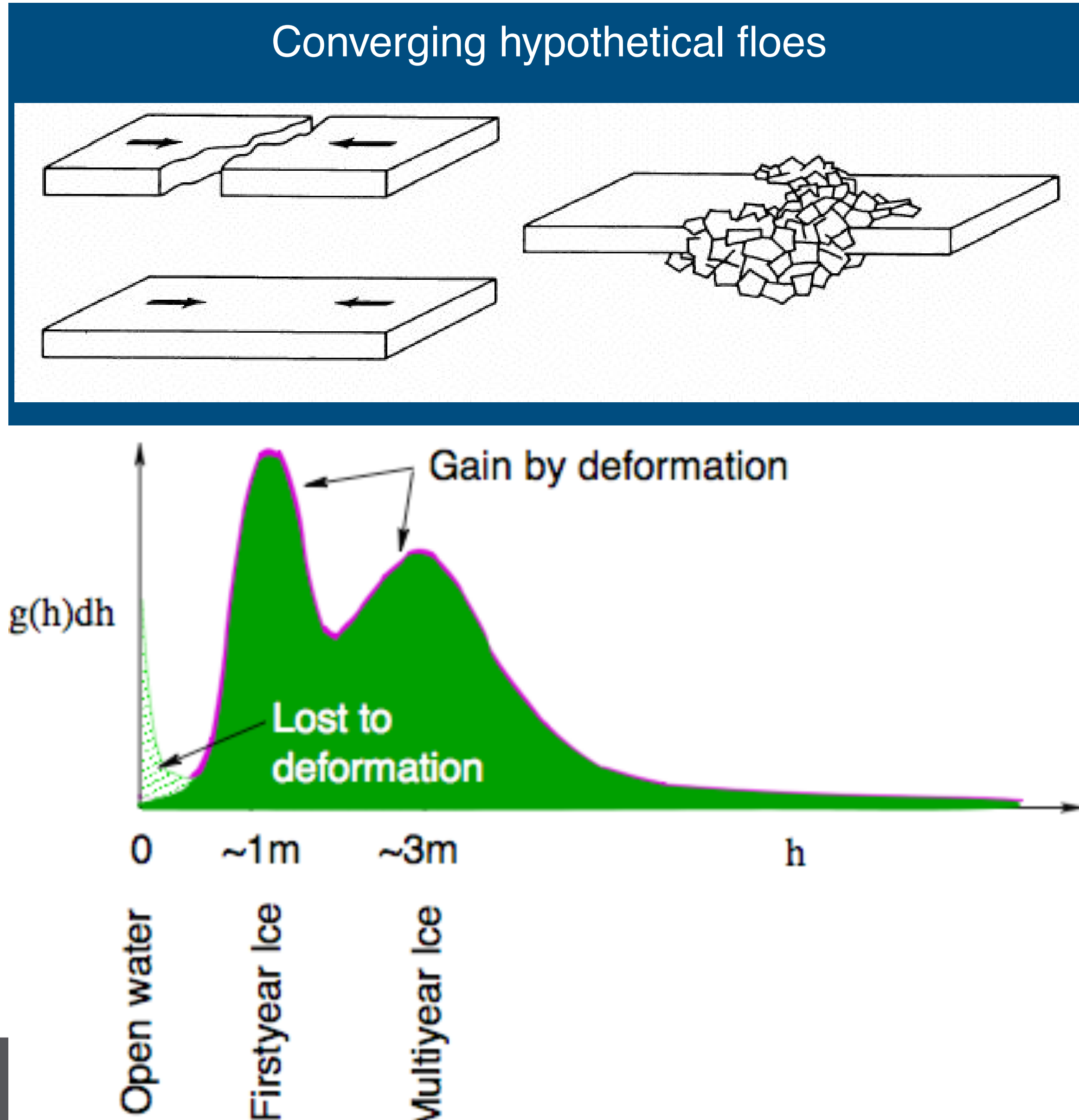
Transfers ice from thin part of distribution to thicker categories



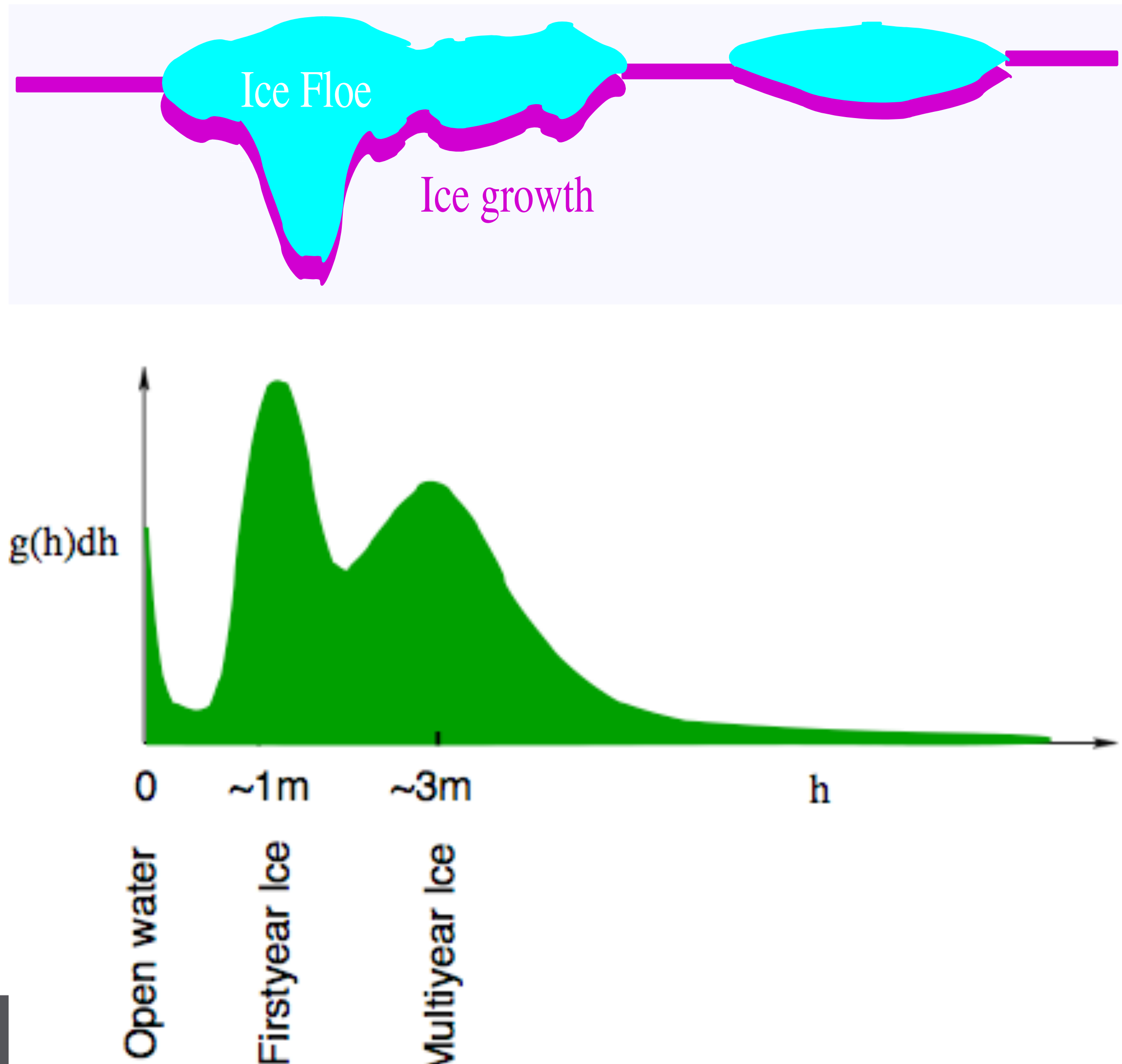


Y = Mechanical redistribution

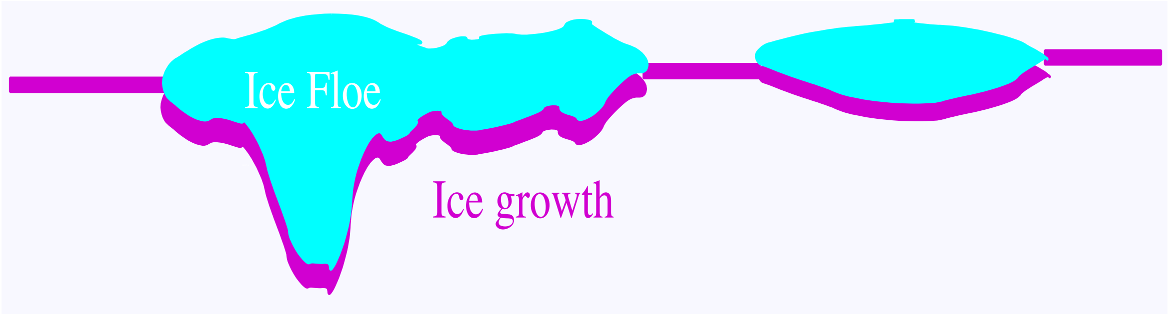
Transfers ice from thin part of distribution to thicker categories

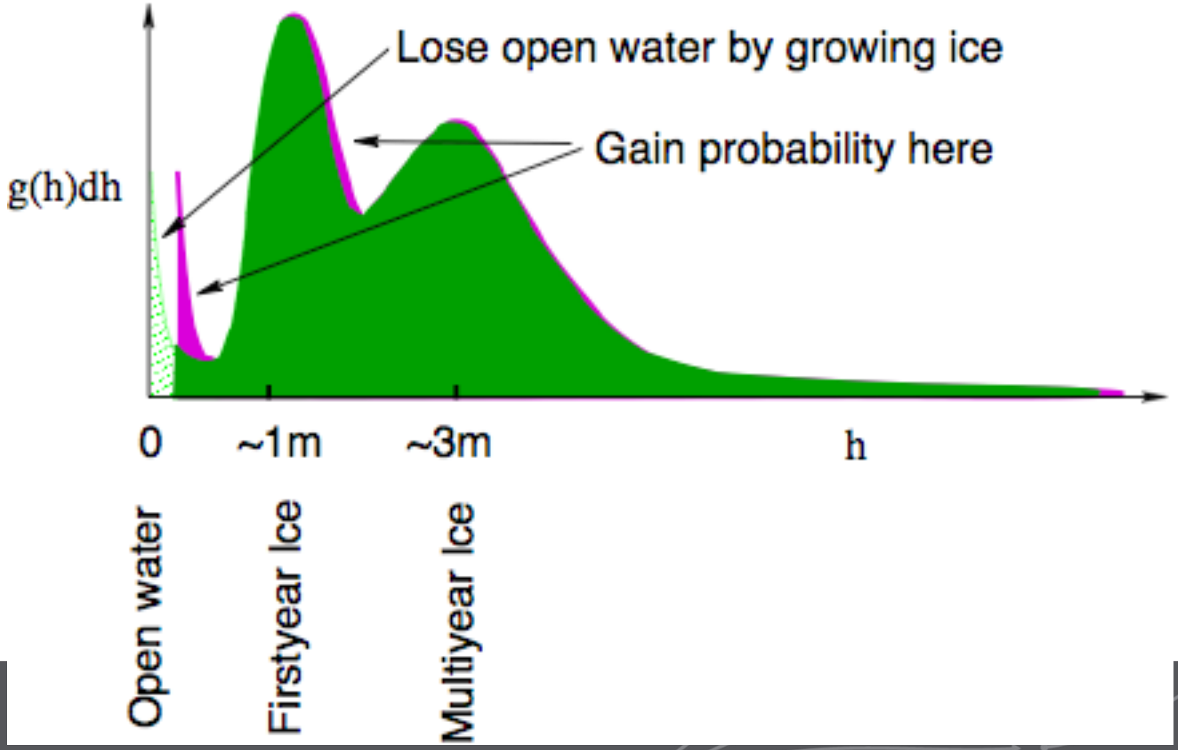


Ice growth:


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

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