Sea Ice Modeling in the CESM

CSU Visit – September 19, 2024

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With MANY contributions from: David Bailey (NCAR), Marika Holland (NCAR), and the Polar Climate Working Group (PCWG)

NCAR | CLIMATE & GLOBAL DYNAMICS

NSF

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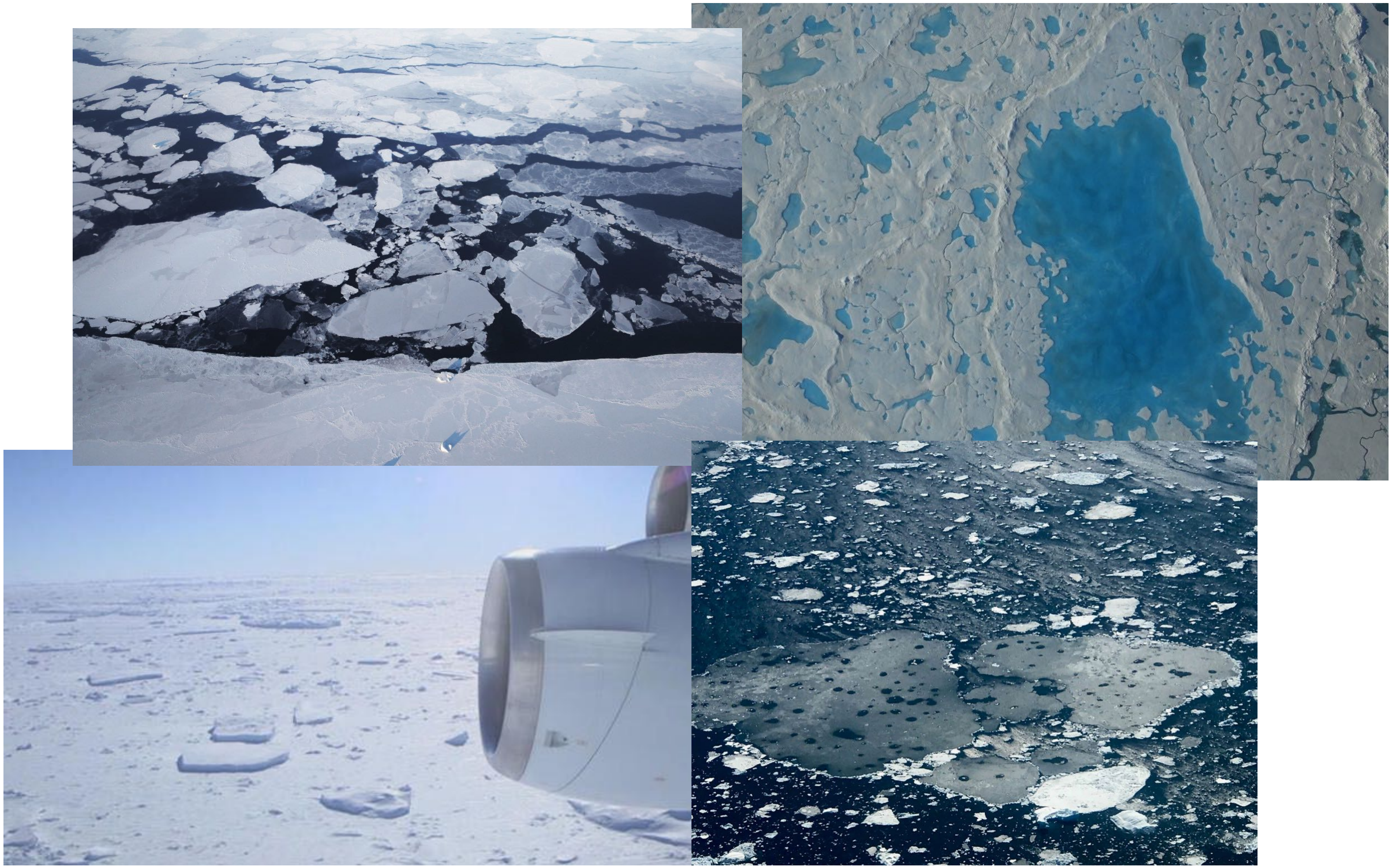
What is Sea Ice?

Sea Ice is frozen sea water that forms seasonally



Photos from NASA Operation IceBridge

Arctic vs. Antarctic

Arctic

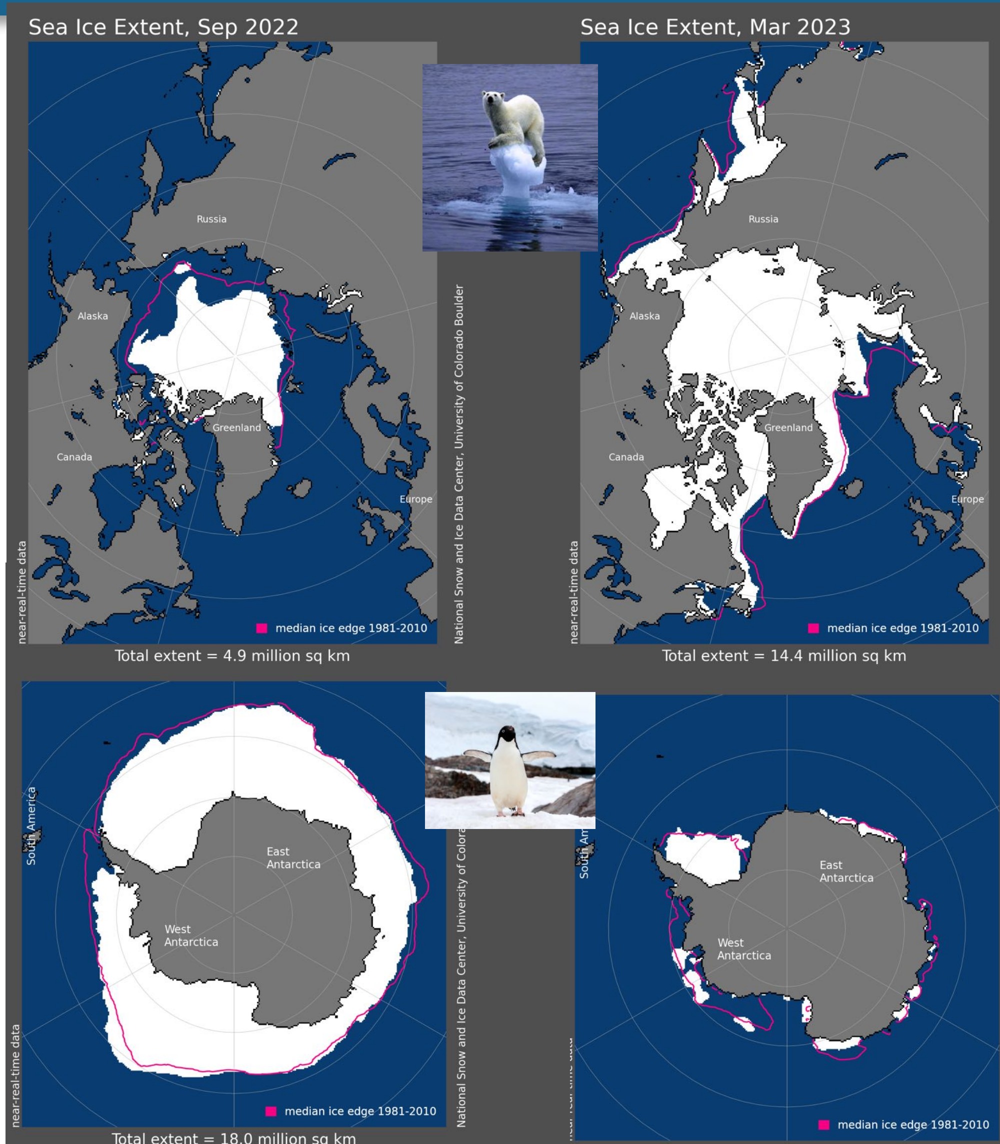
- Ocean bounded by land → ice converges at land, thick!
- Extent seasonal cycle: ~ 5→12 x10^6 km^2
- Land boundaries & ocean heat determine winter extent

Antarctic

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

September (minimum)

March (maximum)

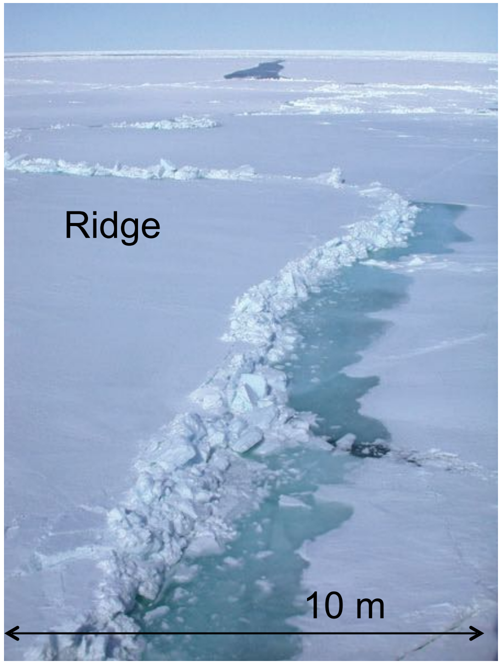


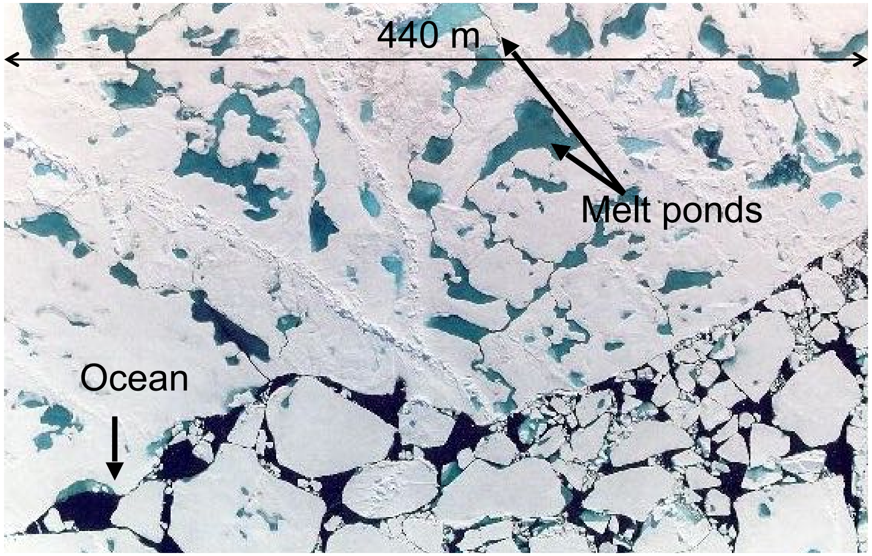
September (maximum)

February (minimum)

Figures from NSIDC

Sea ice Cover



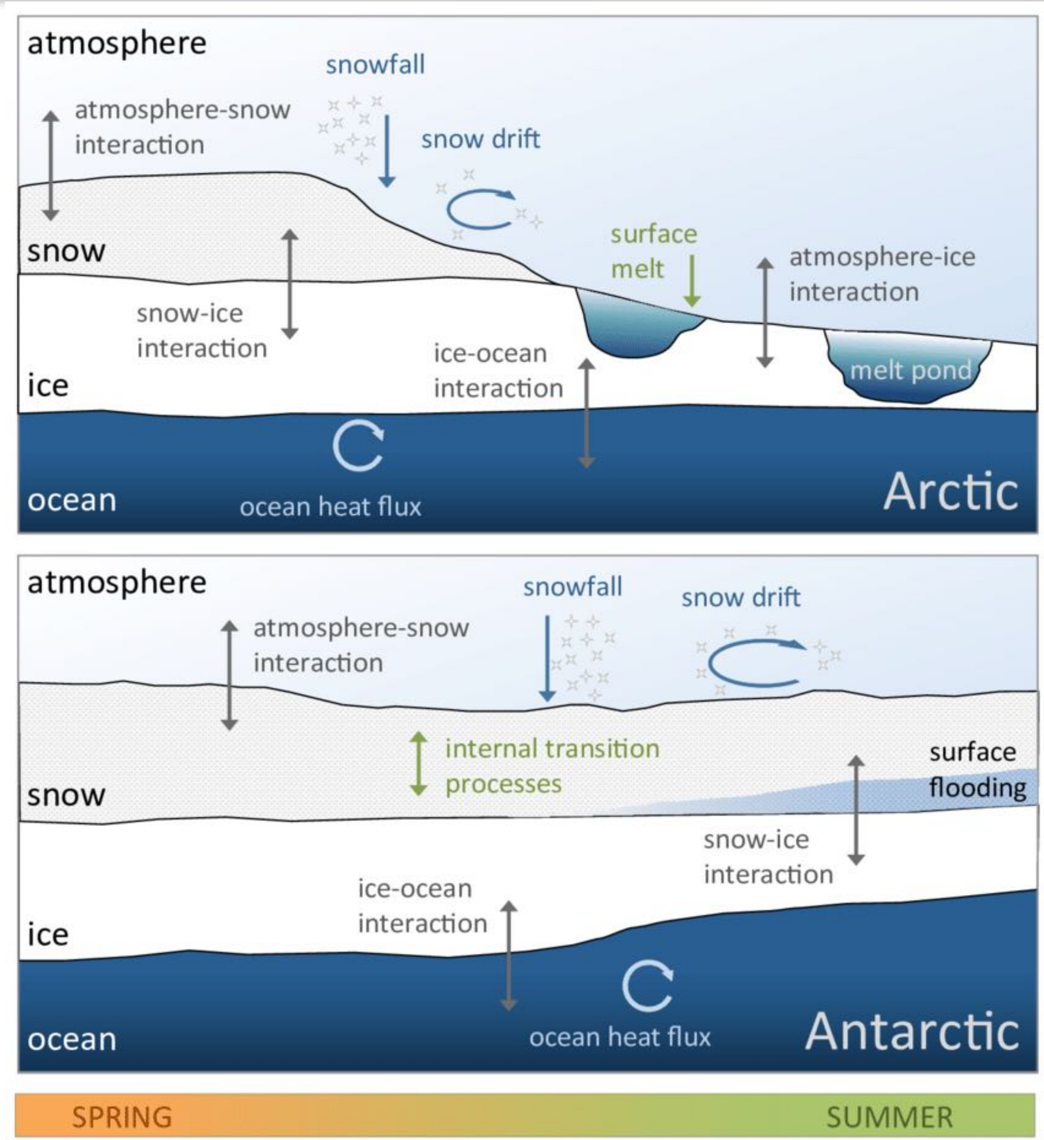


← Photos from Feltham, 2008 by Hajo Eicken

↑ Photo from Don Perovich

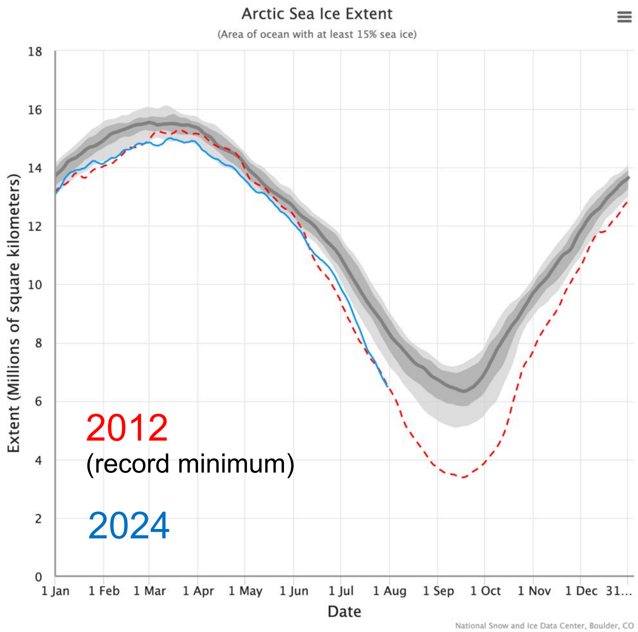
- Heterogeneous – lots of subgridscale variability
  - Leads, ridges, melt ponds, floes, albedo, snow cover, etc.
- Individual floes of varying size can form a continuous cover
- Thickness on the order of meters

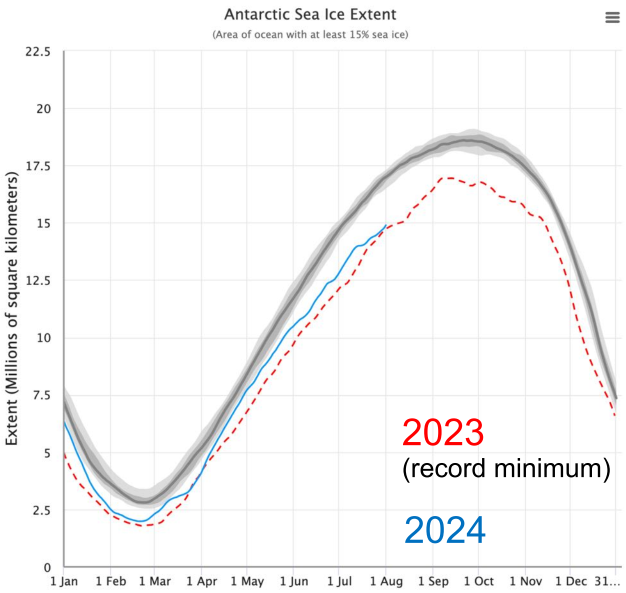
Arctic vs. Antarctic – seasonal evolution

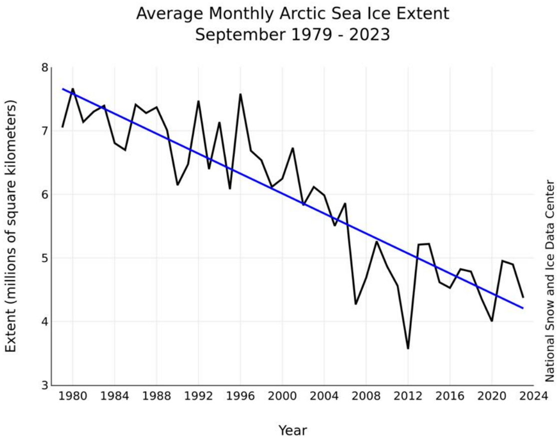


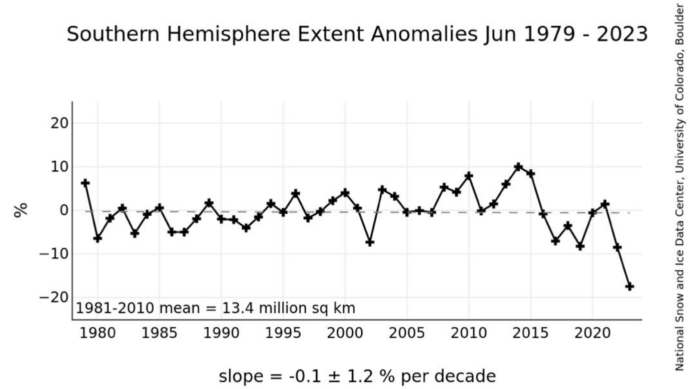
Arndt et al. 2017

Why do we care about sea ice in climate models?

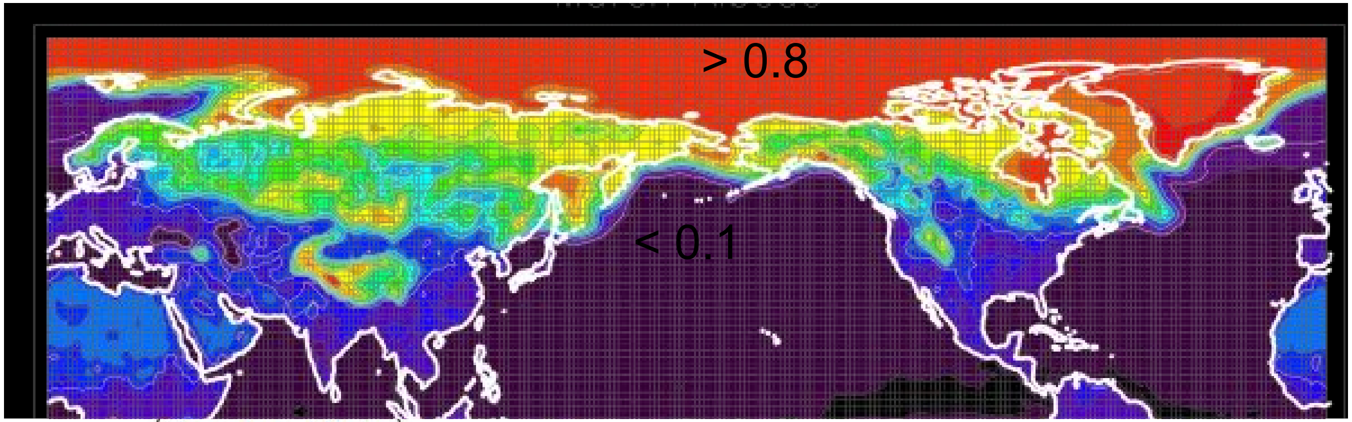




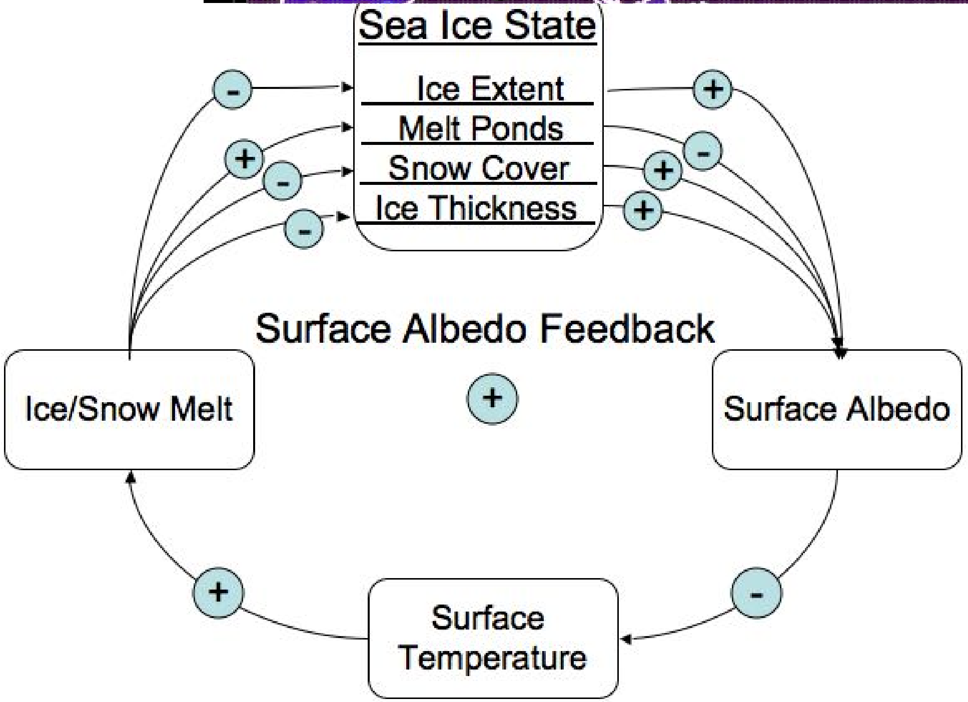




Why sea ice matters: Surface energy budget

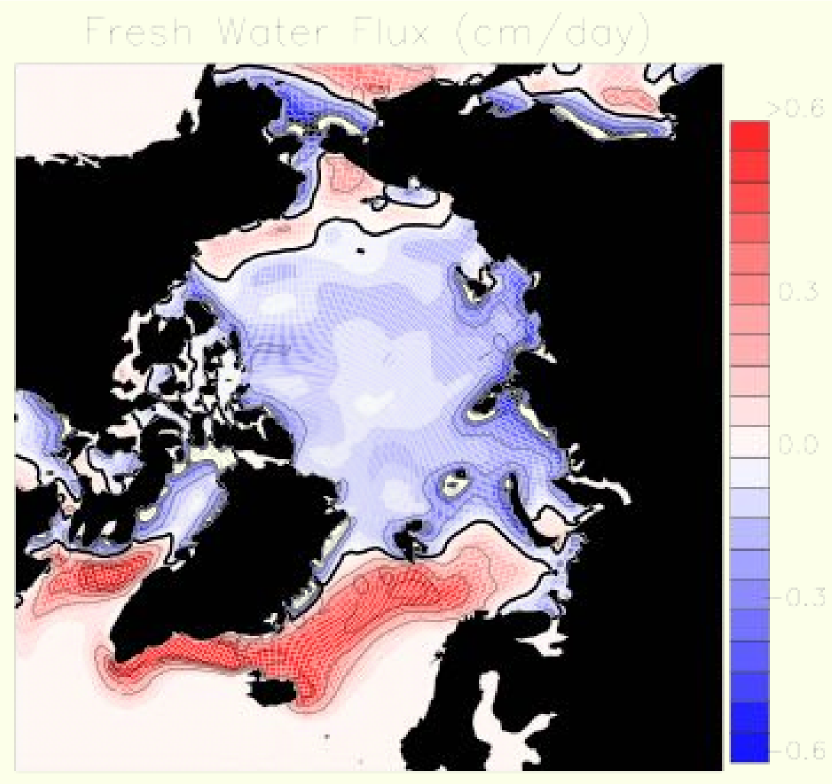


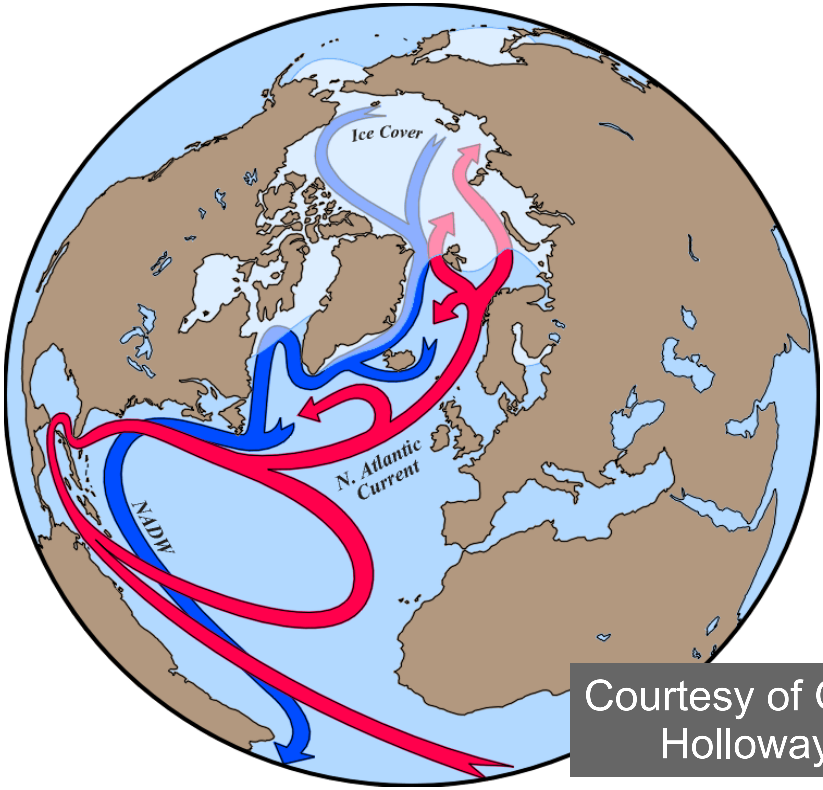
March Mean Surface albedo



- 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

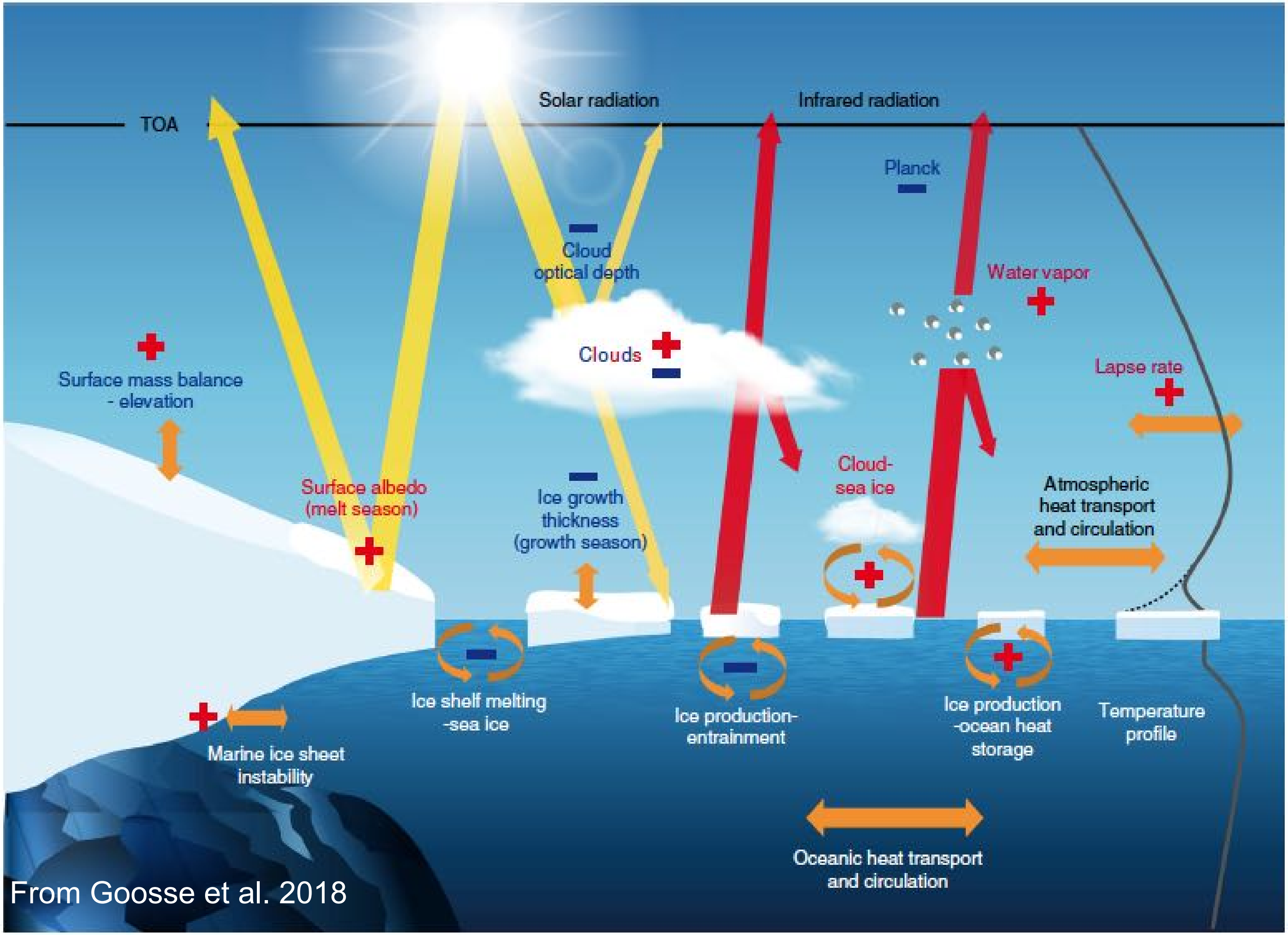




Courtesy of Greg Holloway

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

Why sea ice matters: Climate Feedbacks



Select key sea ice related Climate Feedbacks

Feedback	Sign	Description
Surface Albedo	+	Sea ice melts → exposes ocean and lowers surface albedo → increased SW surface absorption → increased warming → more ice melt
Water Vapor	+	Sea ice melts → more water available → more water vapor in atmosphere → more greenhouse warming → more ice melt
Cloud – sea ice	+	Sea ice melts → more water available → more cloud cover → more LW down (non-summer) → more ice melt
Cloud optical depth	-	Sea ice melts → more water available → higher cloud albedo → less SW reaches surface (summer) → less ice melt
Ice production/ entrainment	-	Sea ice forms → brine rejected → ocean mixed layer deepens → entrain heat from depth → more ice melt
Ice growth/ thickness	-	Thick sea ice → has lower heat conduction (than thin ice) → relatively less ice bottom growth
Sea ice/ ice shelf	-	Ice shelf melt → releases freshwater into ocean → stable and fresher upper ocean → sea ice growth → reduces ocean warming
Sea ice/ surface wind	+/-	Sea ice melts → more momentum to ocean → affects ocean circulation strength and heat transport → multiple effects

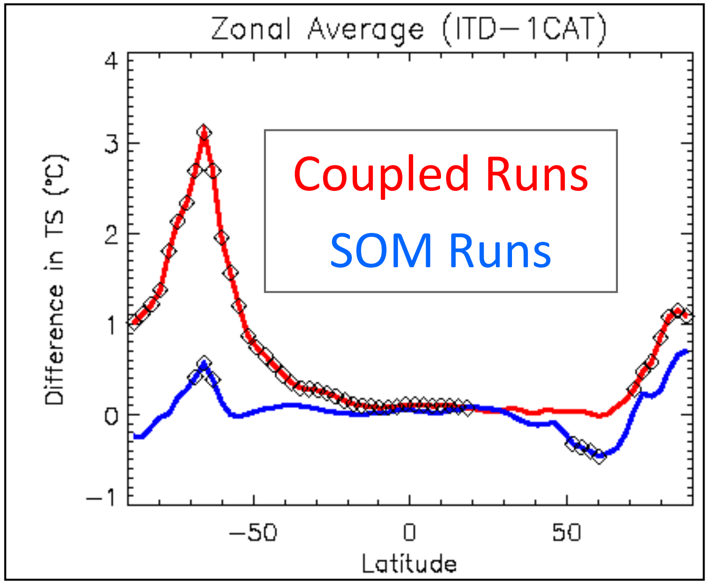
What do we need in a sea ice model for climate applications?

- 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 motion
- Thermodynamics
  - Solves for vertical ice temperature
  - 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 "sice"): The CICE Consortium 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/

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

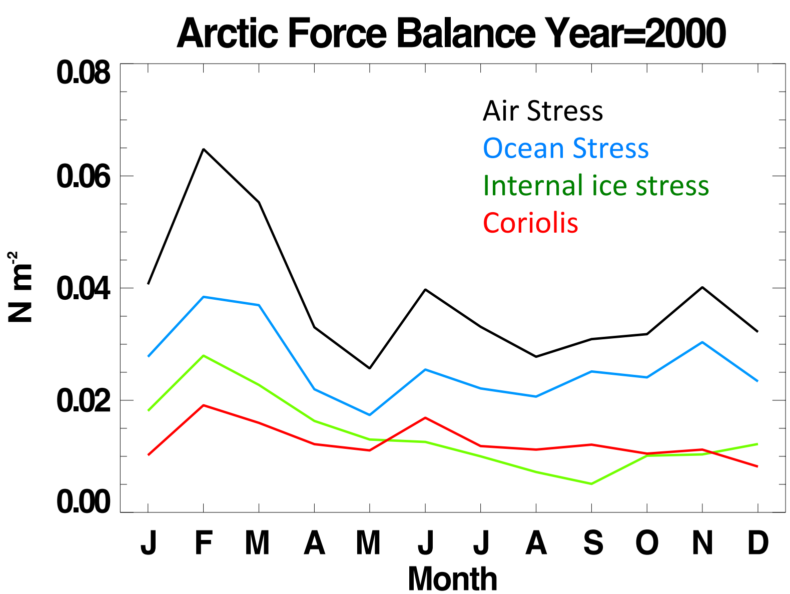
(e.g. Hibler, 1979)

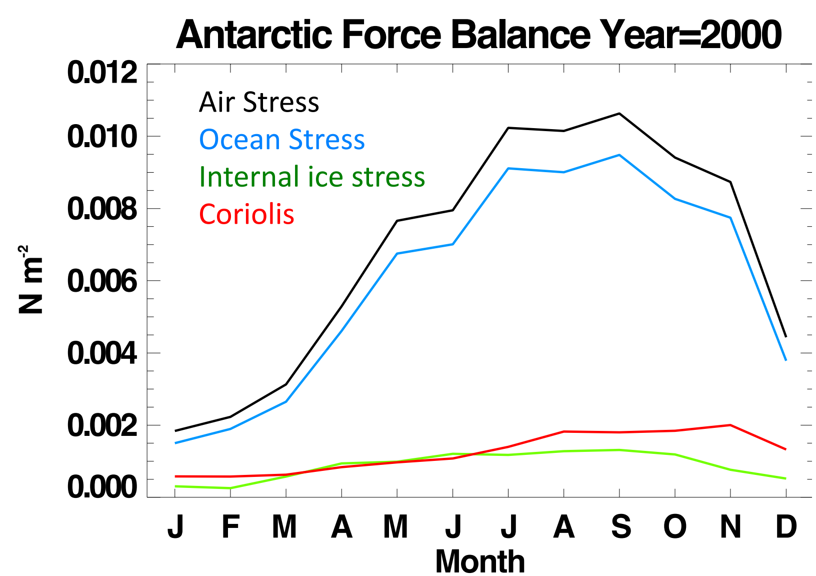
$$m\frac{D\mathbf{u}}{Dt} = -mf\mathbf{k}\times\mathbf{u} + \boldsymbol{\tau}_a + \boldsymbol{\tau}_w - mg_r\nabla Y + \nabla\cdot\sigma$$

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

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





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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)

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

Total derivative

Coriolis

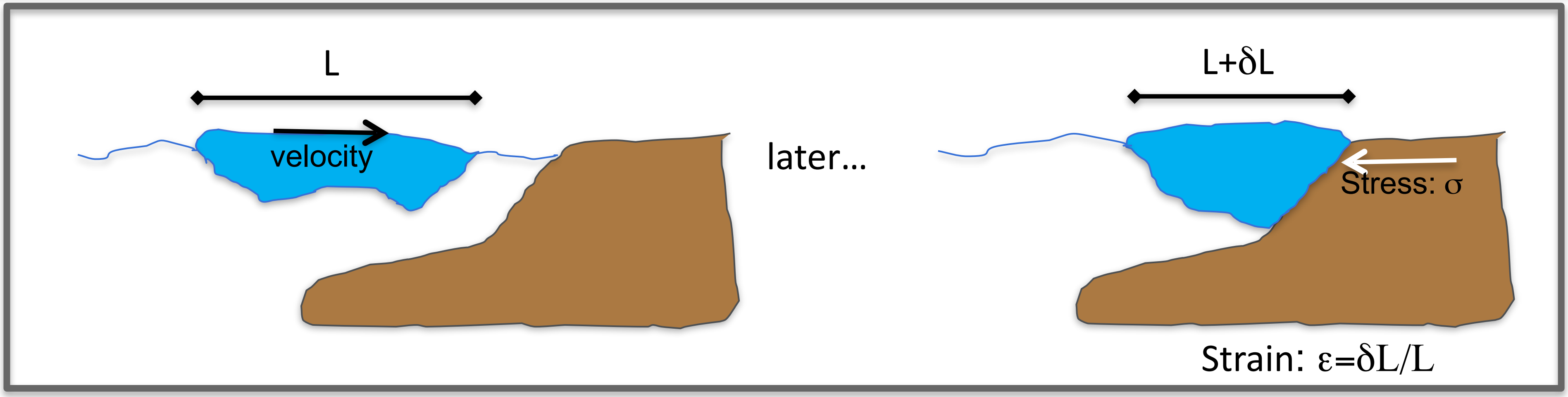
Air stress

Ocean stress

Sea Surface Slope

Internal Ice Stress

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)

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

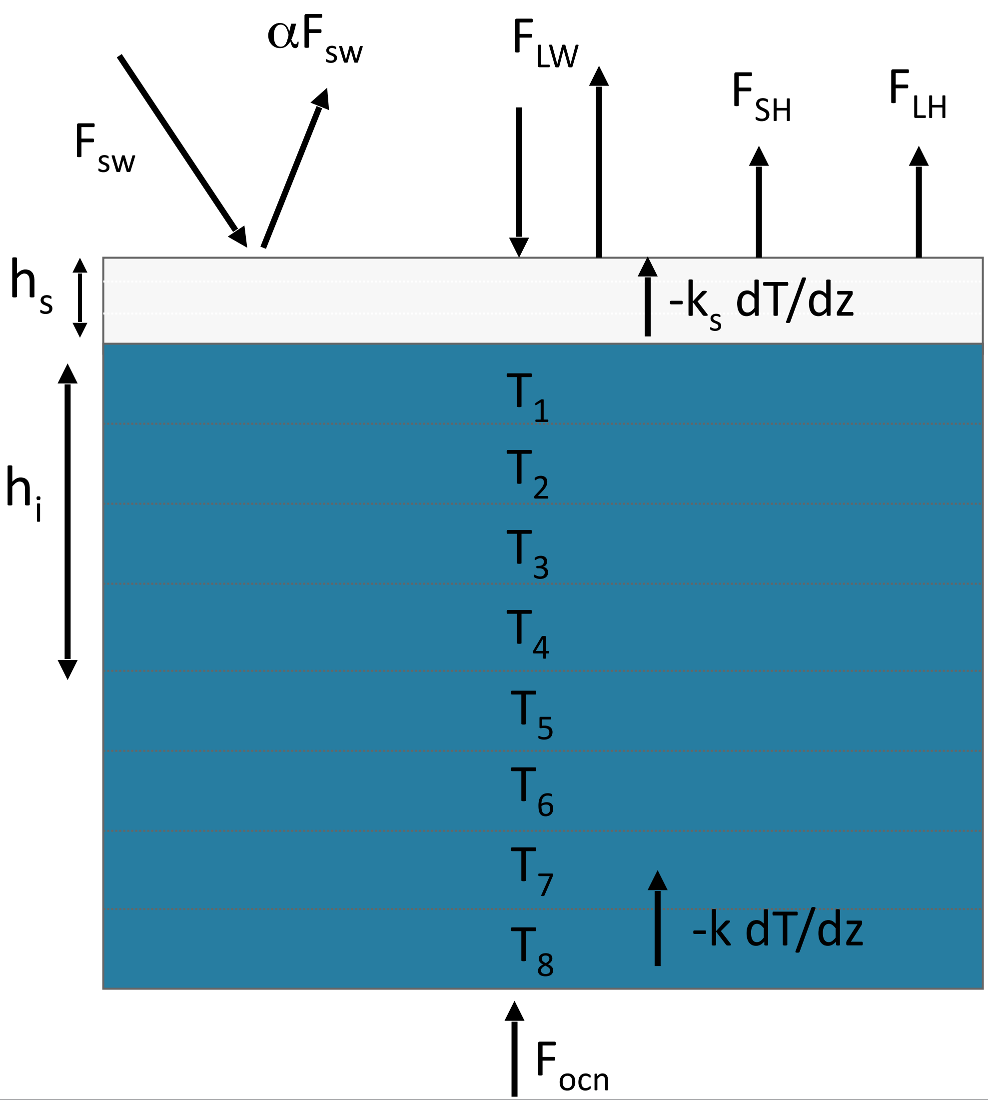
Total derivative; Coriolis; Air stress; Ocean stress; Sea Surface Slope; Internal Ice Stress

Thermodynamics

Sea ice thermodynamics

- Main CICE thermodynamic budget terms:
  - melt_t – sea ice top melt
  - melt_b – sea ice bottom (basal) melt
  - melt_l – lateral sea ice melt
  - frazil – frazil (open water) ice growth
  - congel – congelation (bottom) ice growth
  - snoice – snow-ice formation
- If you add all these up, you get the thermodynamic volume tendency
  - dvidtt

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

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

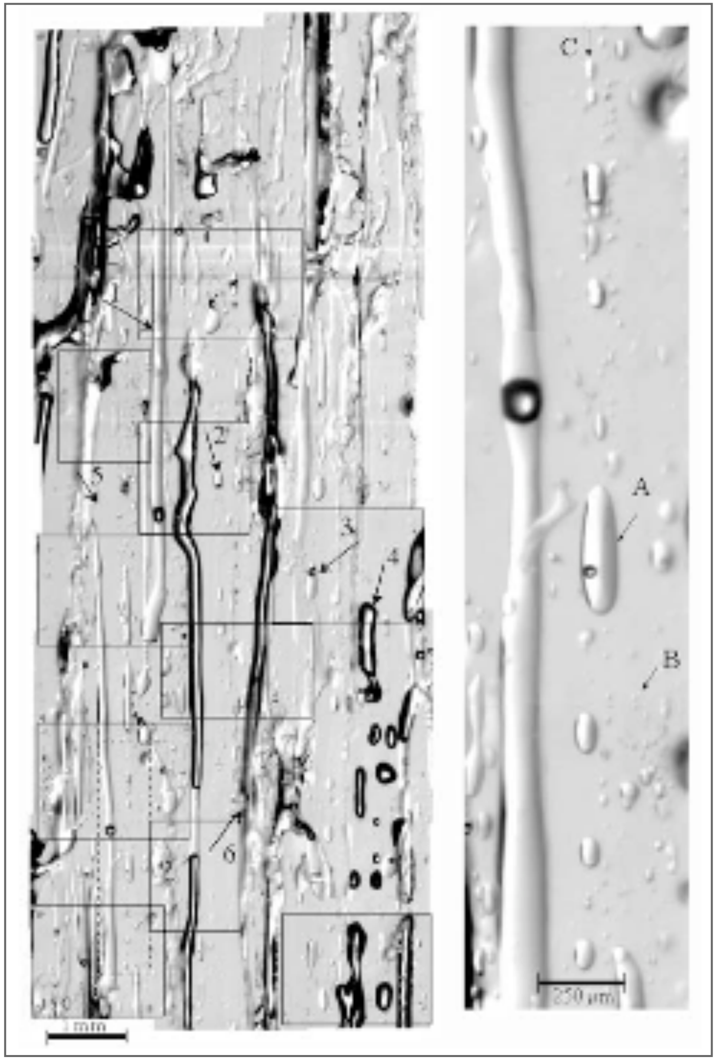
Vertical heat transfer (conduction)

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

Bottom surface flux balance

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

Thermodynamics: Vertical Heat Transfer

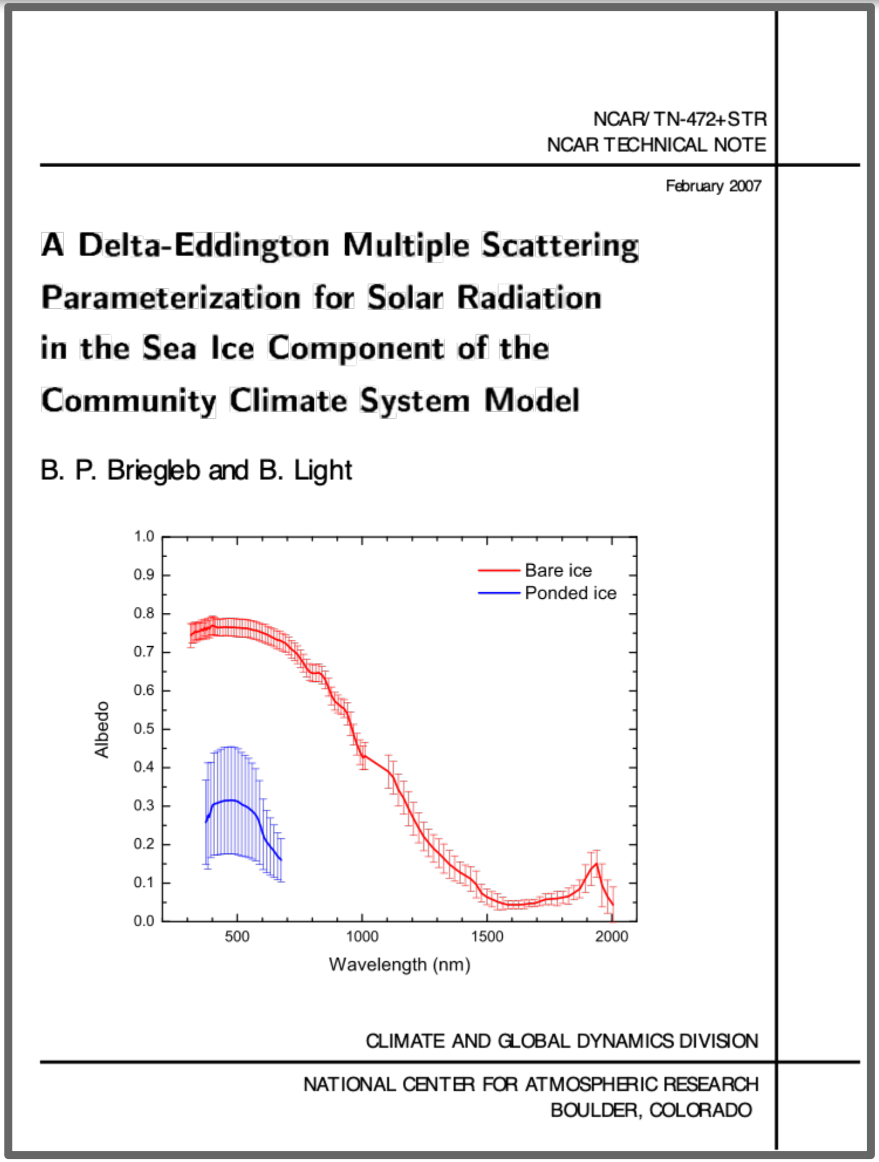


(from Light, Maykut, Grenfell, 2003)

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

- Assume salinity dependent freezing temperature
- Heat capacity and conductivity are functions of T/S of ice
- Solve to get temperature **and** 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

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

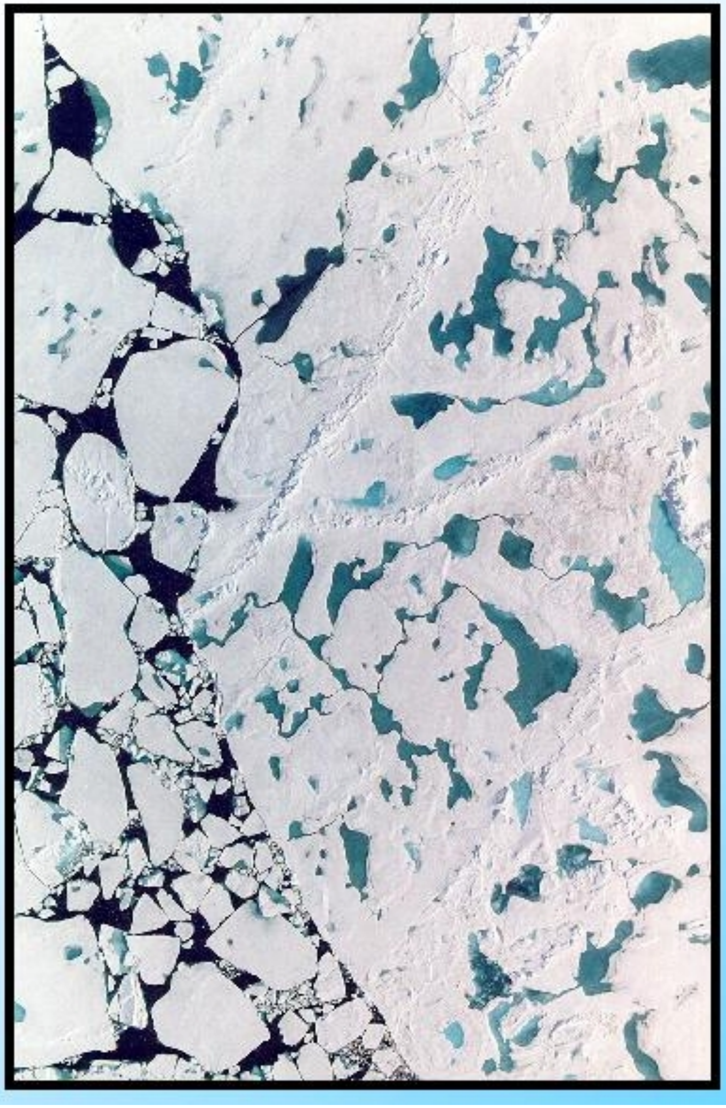
B. P. Briegleb and B. Light

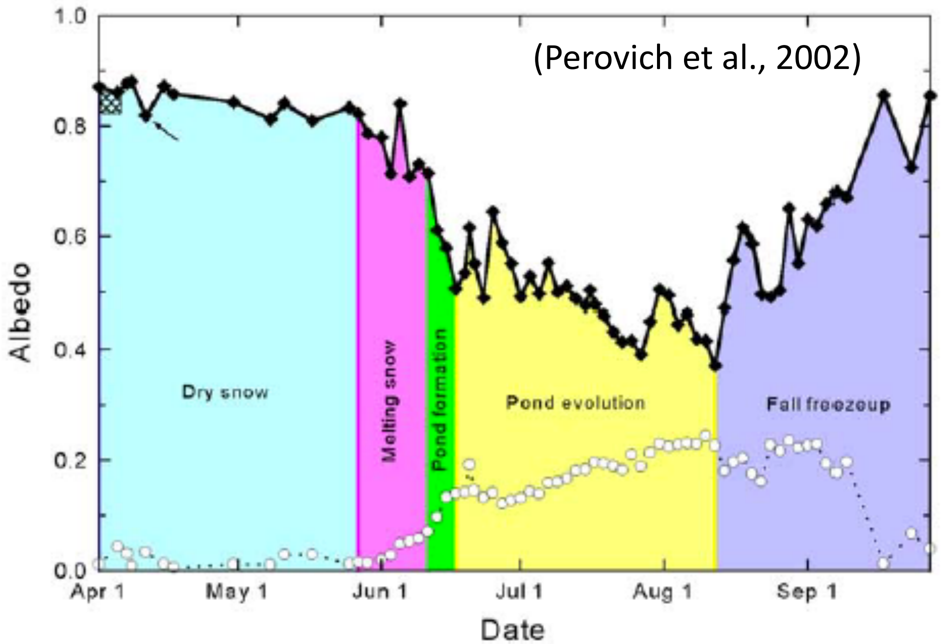
CLIMATE AND GLOBAL DYNAMICS DIVISION

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 <u>and</u> CESM2

Albedo



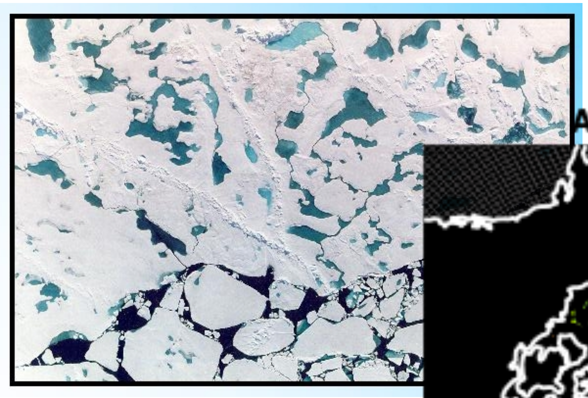


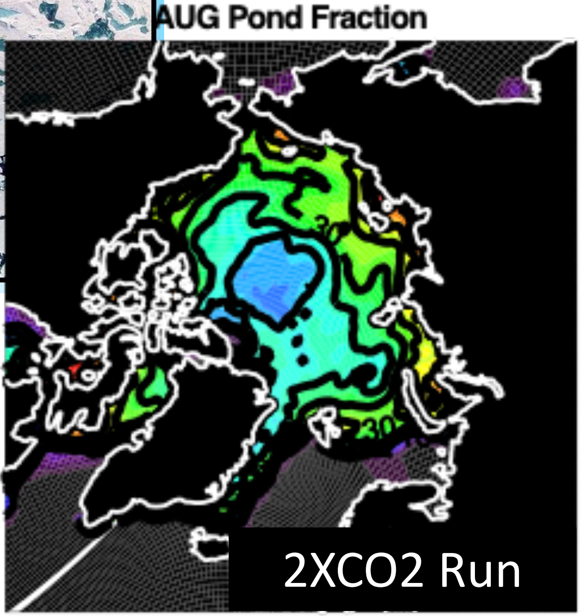
Often the parameterized sea ice albedo depends on characteristics of surface state (snow, temp, ponding, h_i).

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

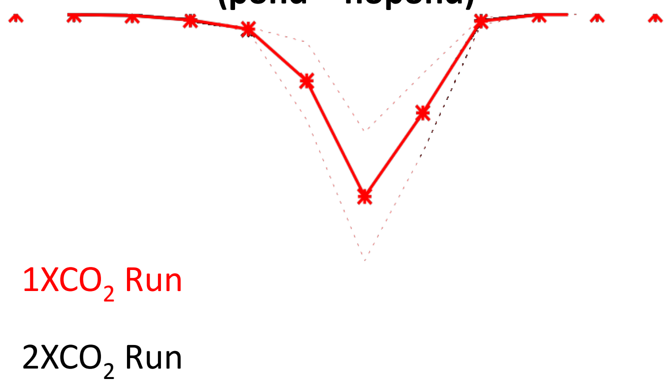
Melt Pond Parameterization

- 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)

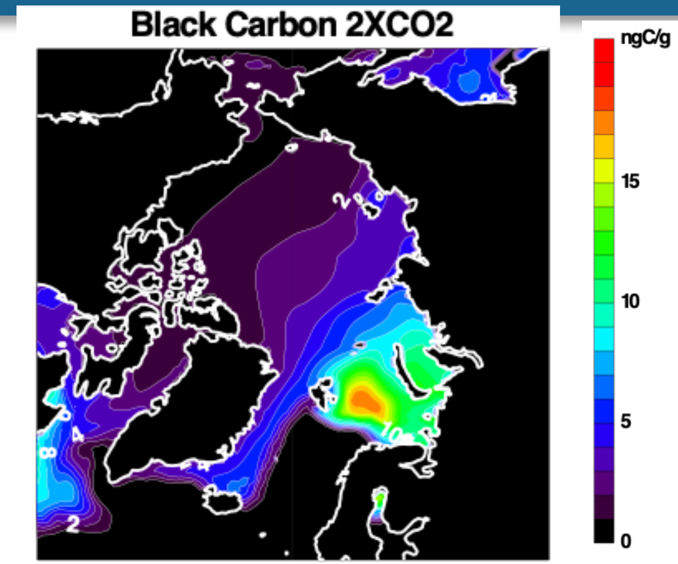


Holland, M. M., et al. 2012: Improved sea ice shortwave radiation physics in CCSM4

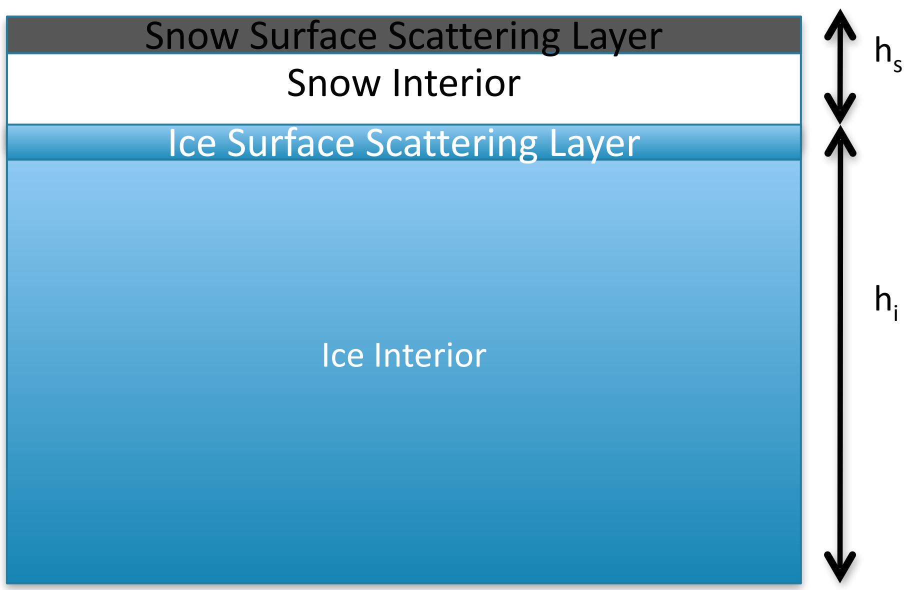
Aerosol deposition and cycling

- 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

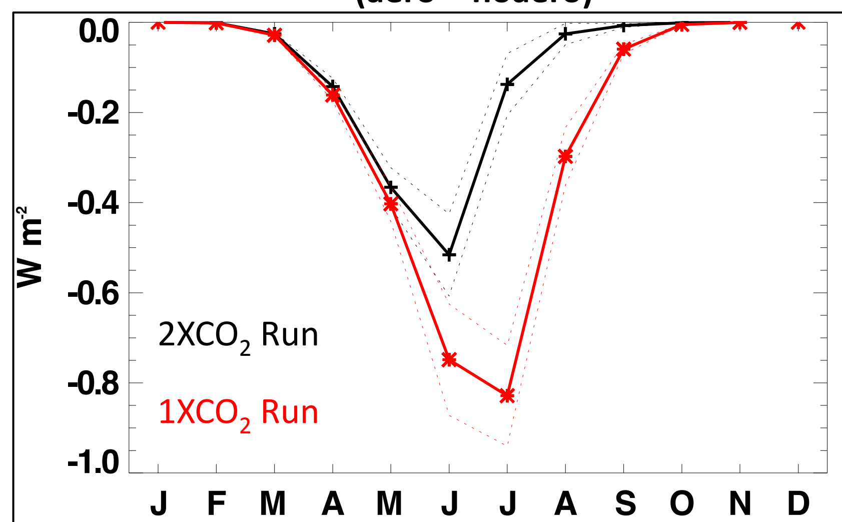
With 1850 Aerosol Deposition



Arctic Basin Average

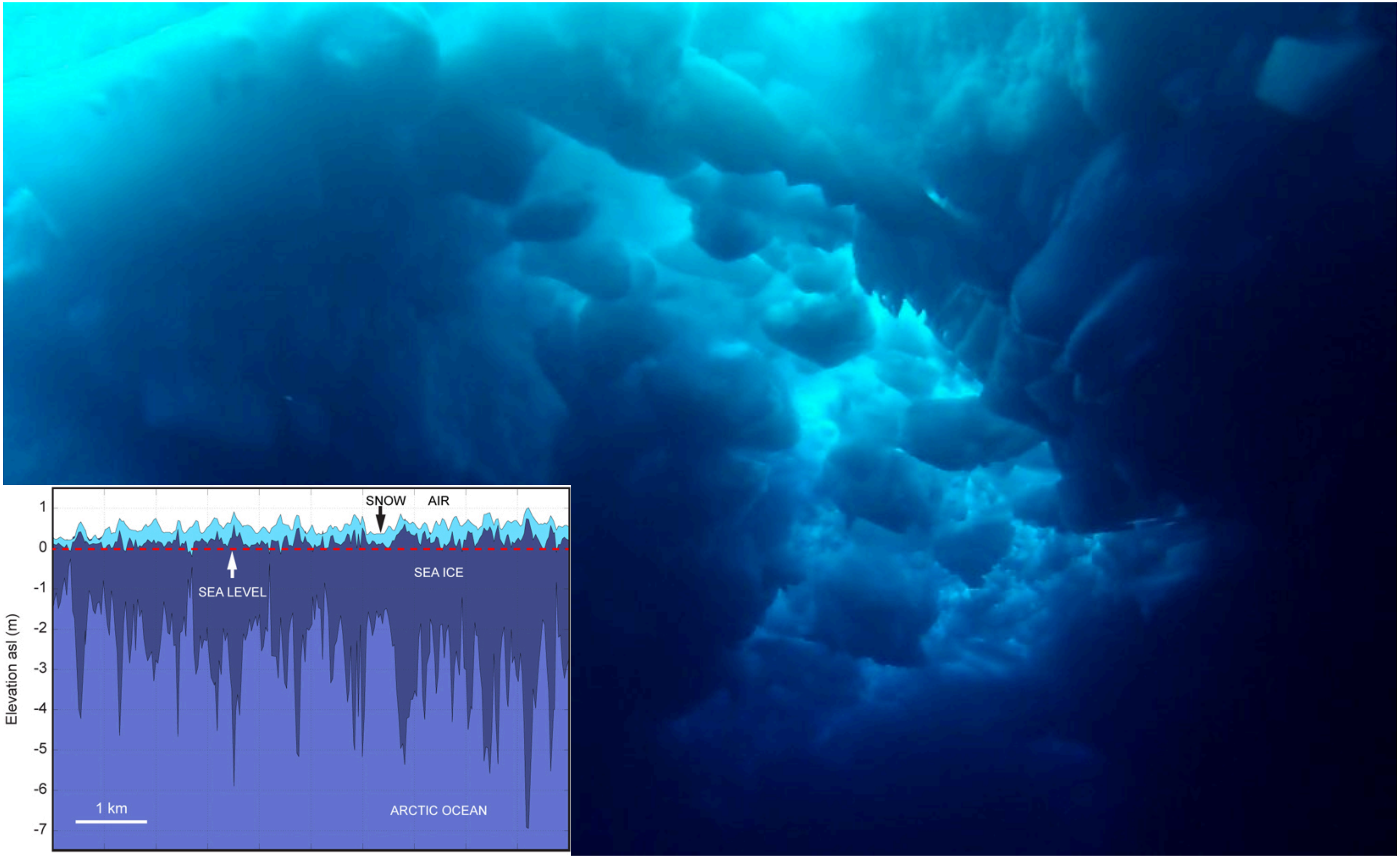


Arctic Basin Average SW flux (aero – noaero)



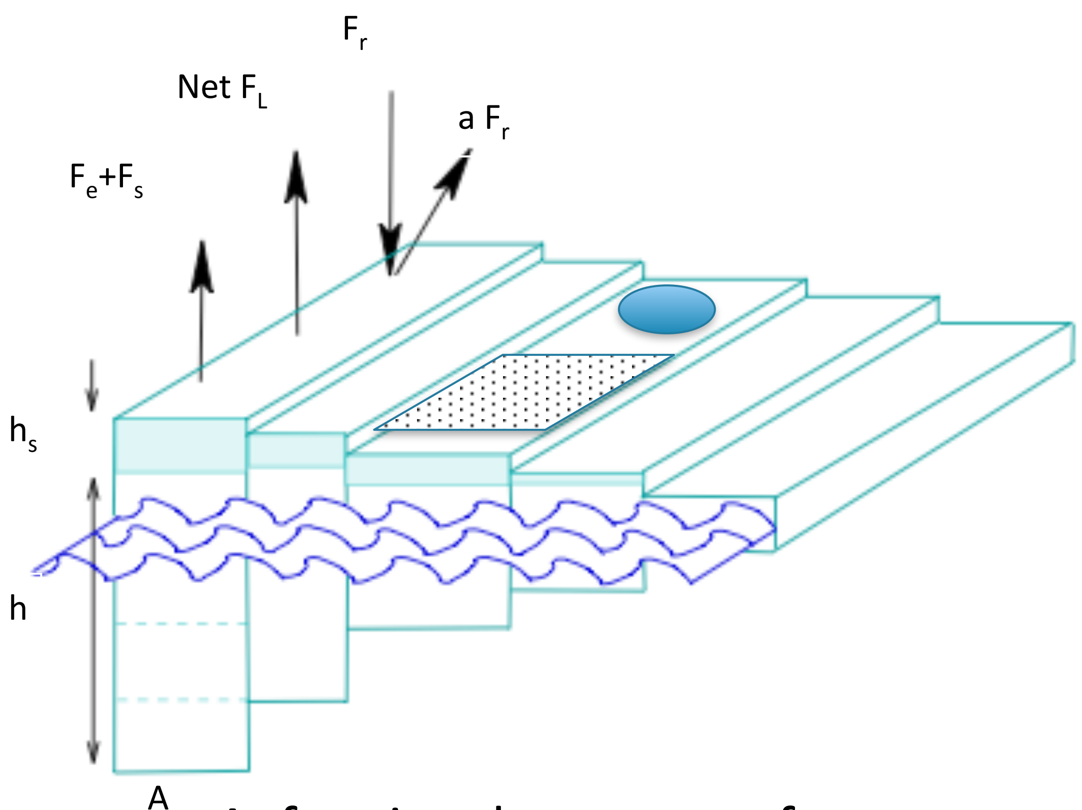
Holland, M. M., et al. 2012: Improved sea ice shortwave radiation physics in CCSM4

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.

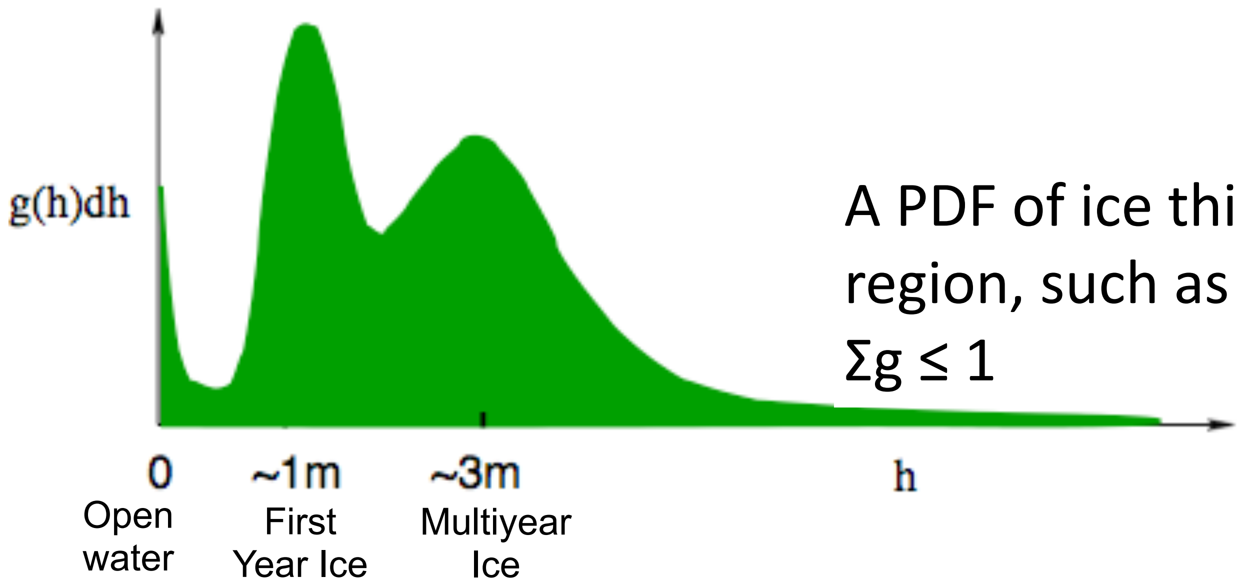
Ice Thickness Distribution

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

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

- $-\frac{\partial}{\partial h}(fg)$: Ice Growth
- $L(g)$: Lateral Melt
- $\nabla \bullet (\vec{v}g)$: Convergence
- $\Psi(h,g,\vec{v})$: Mechanical Redistribution

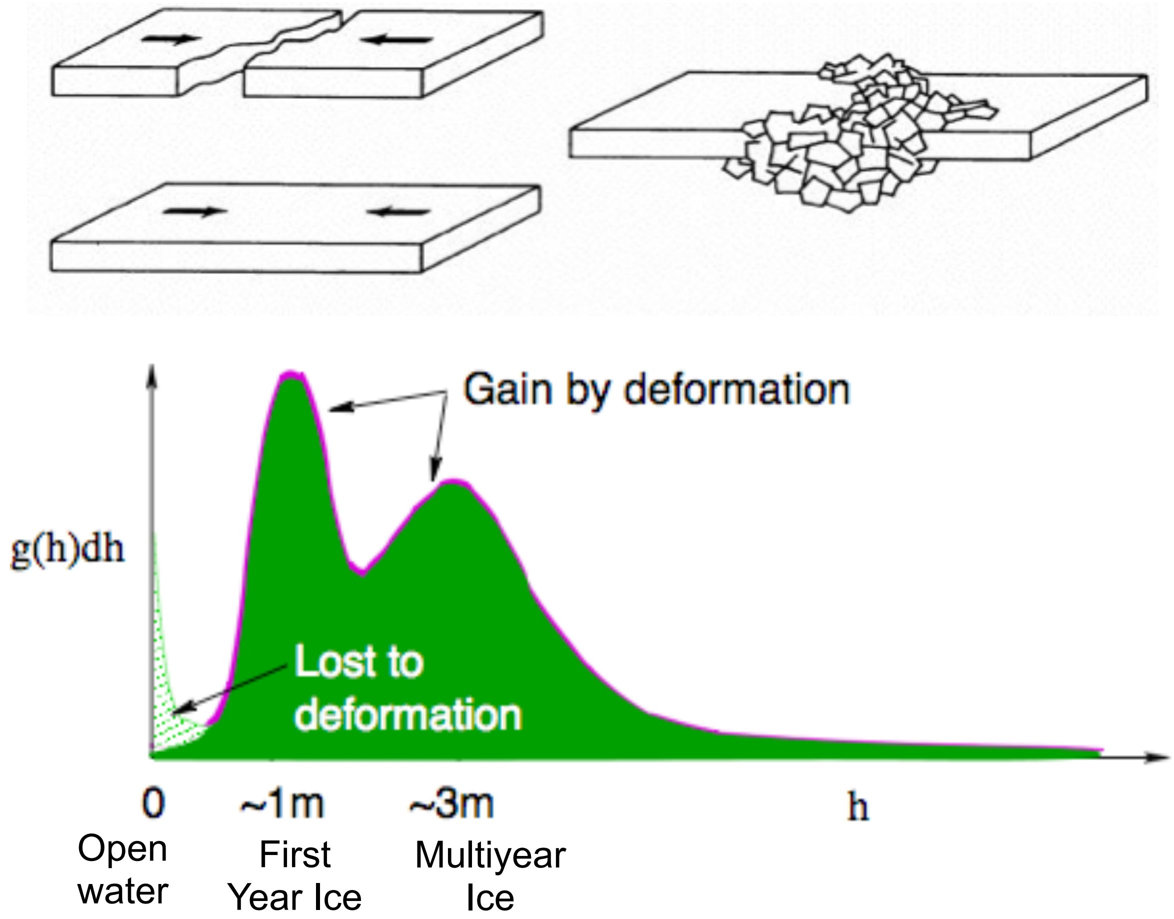
g(h)dh is the fractional area covered by ice of thickness h to h+dh



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

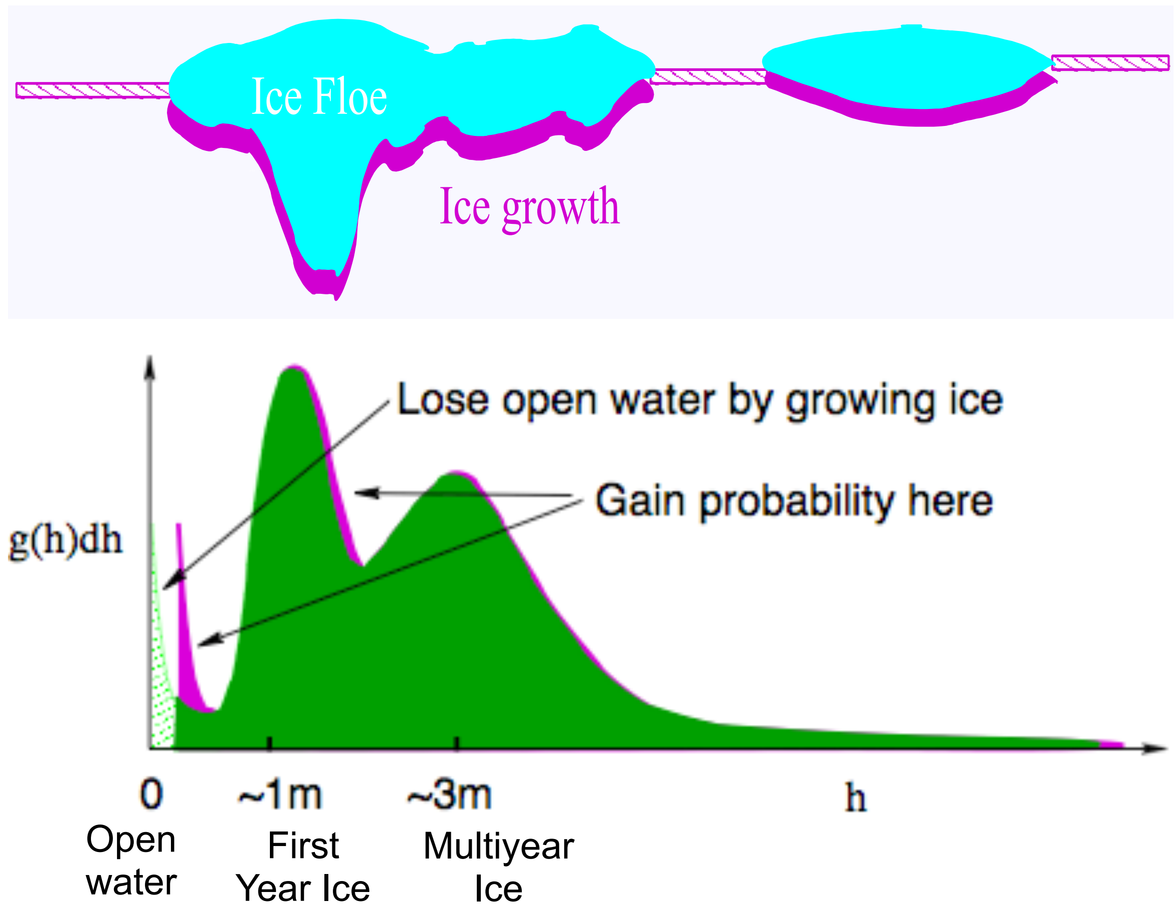
Ice Thickness Distribution: impact of convergence

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

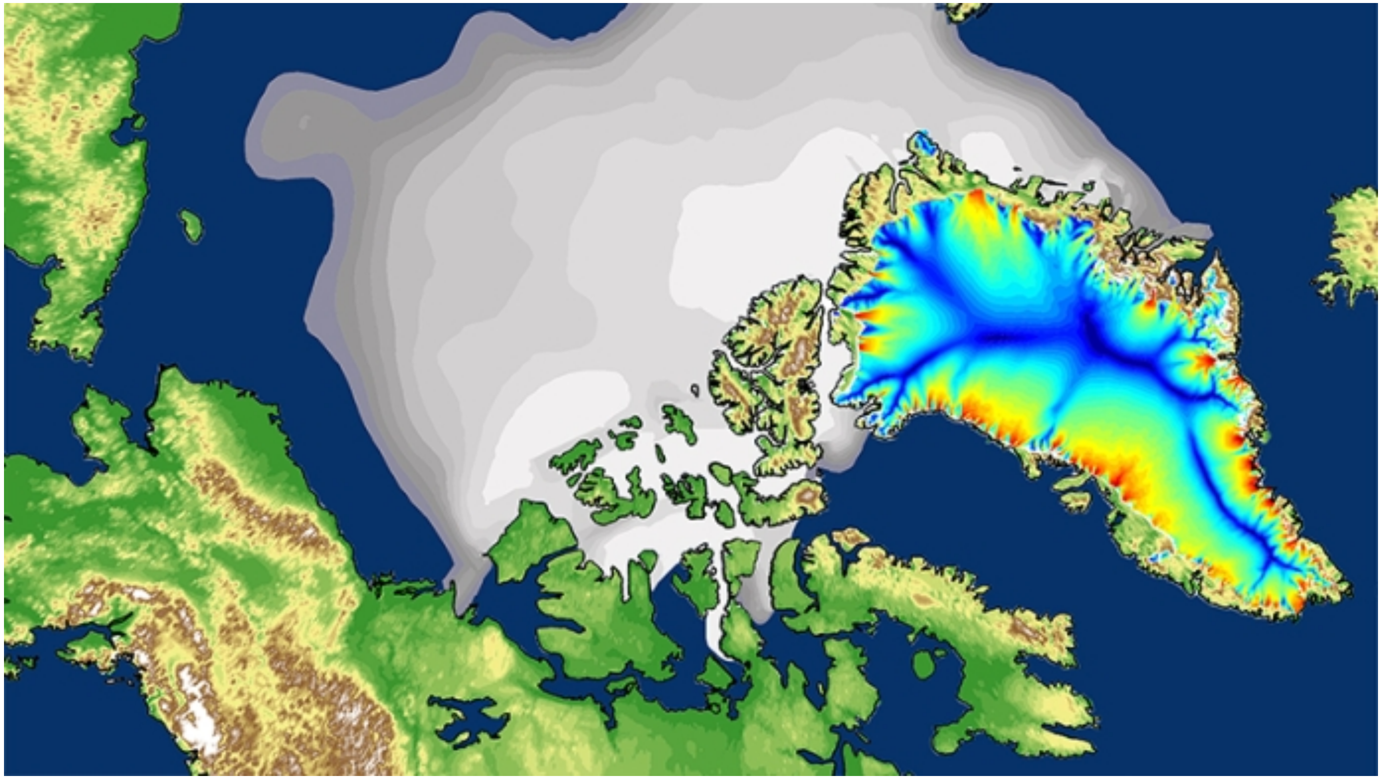


Ice Thickness Distribution: impact of ice growth

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



CESM2 Sea Ice Validation



Summary

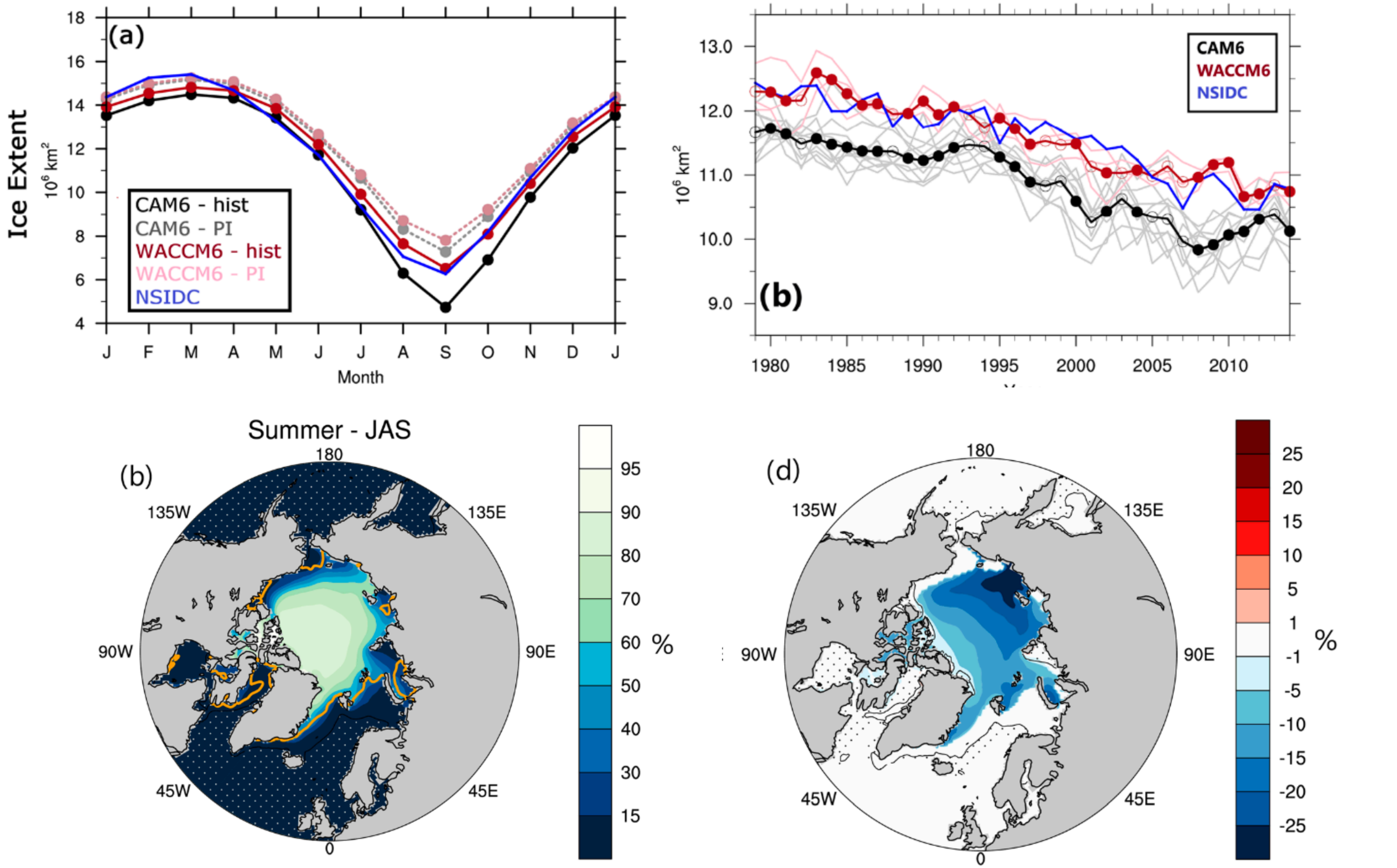
- CICE in CESM2
  - EVP dynamics
  - Sophisticated mushy layer thermodynamics (Turner and Hunke 2015)
  - 8 sea ice vertical levels; 3 snow vertical levels
  - Sub-gridscale ice thickness distribution – 5 categories
  - Level ice ponds (Hunke et al. 2013)
  - Salinity dependent freezing point

Sea ice volume budget

- Main CICE <u>thermodynamic</u> budget terms:
  - melt_t – sea ice top melt
  - melt_b – sea ice bottom (basal) melt
  - melt_l – lateral sea ice melt
  - frazil – frazil (open water) ice growth
  - congel – congelation (bottom) ice growth
  - snoice – snow-ice formation
  - dvidtt – total thermodynamic volume tendency

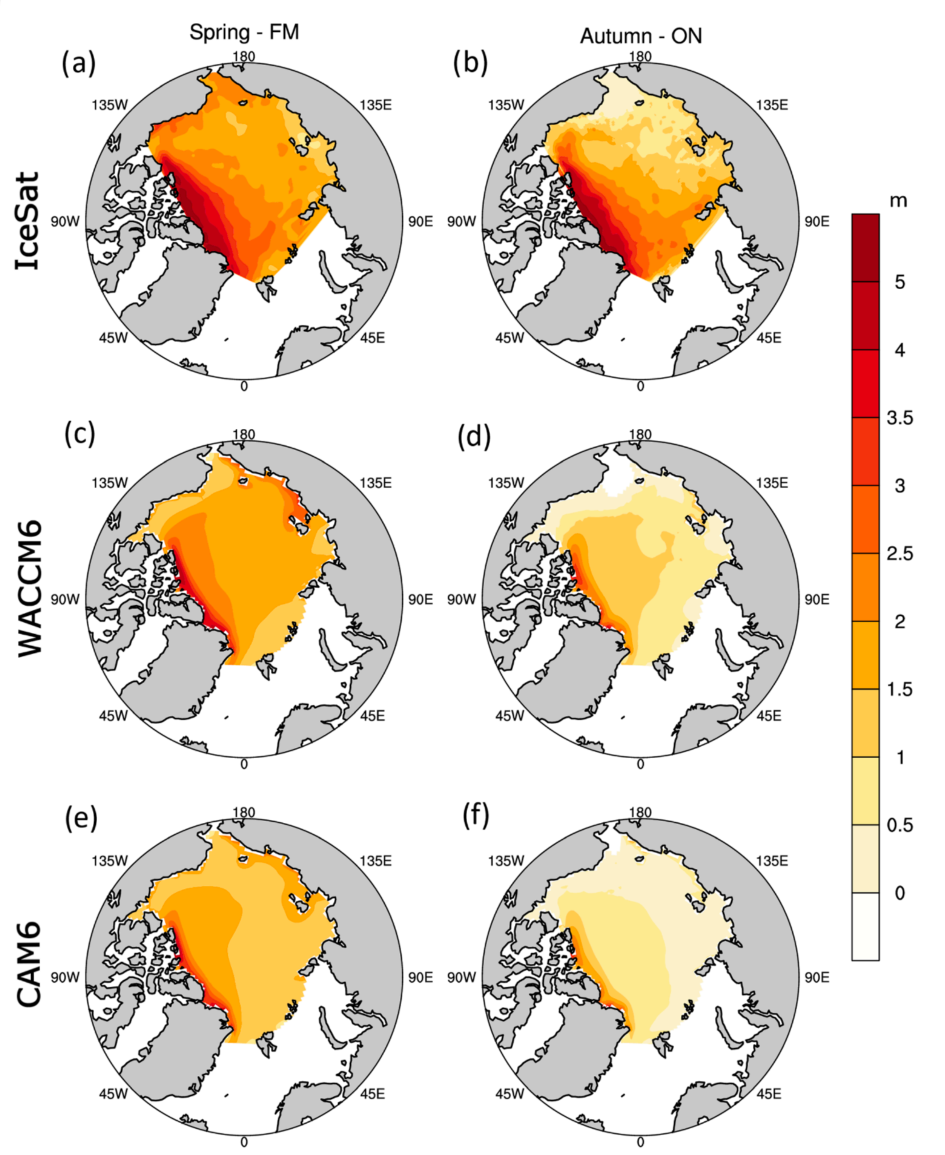
- Total volume budget is the sum of thermodynamic and dynamic tendencies
  - dvidtt – total thermodynamic volume tendency
  - dvidtd - total dynamic volume tendency (due to advection, convergence, divergence, etc.)

CESM2 Historical (1979-2014) Arctic Sea Ice Extent



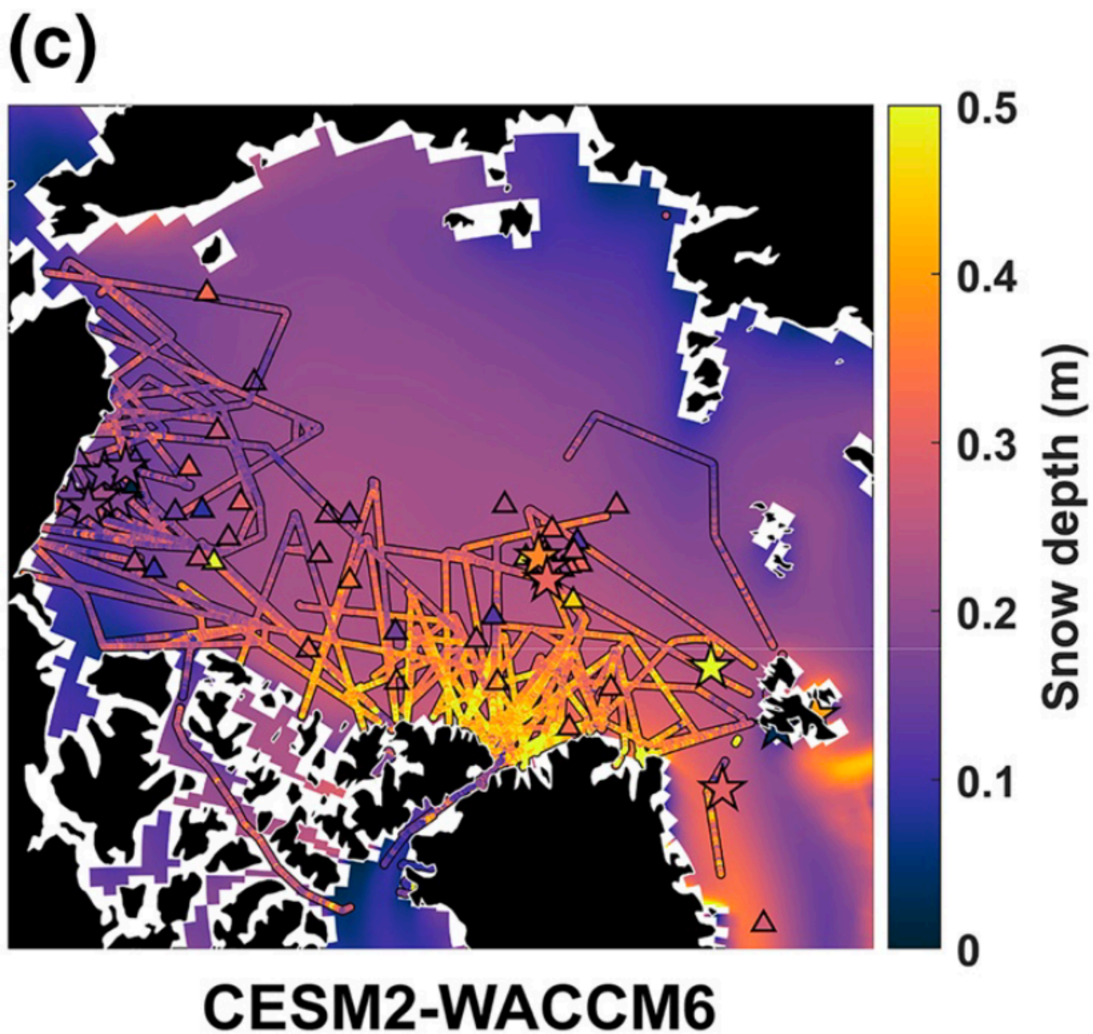
DuVivier et al. 2020

CESM2 Historical (2001-2005) Arctic Sea Ice Thickness



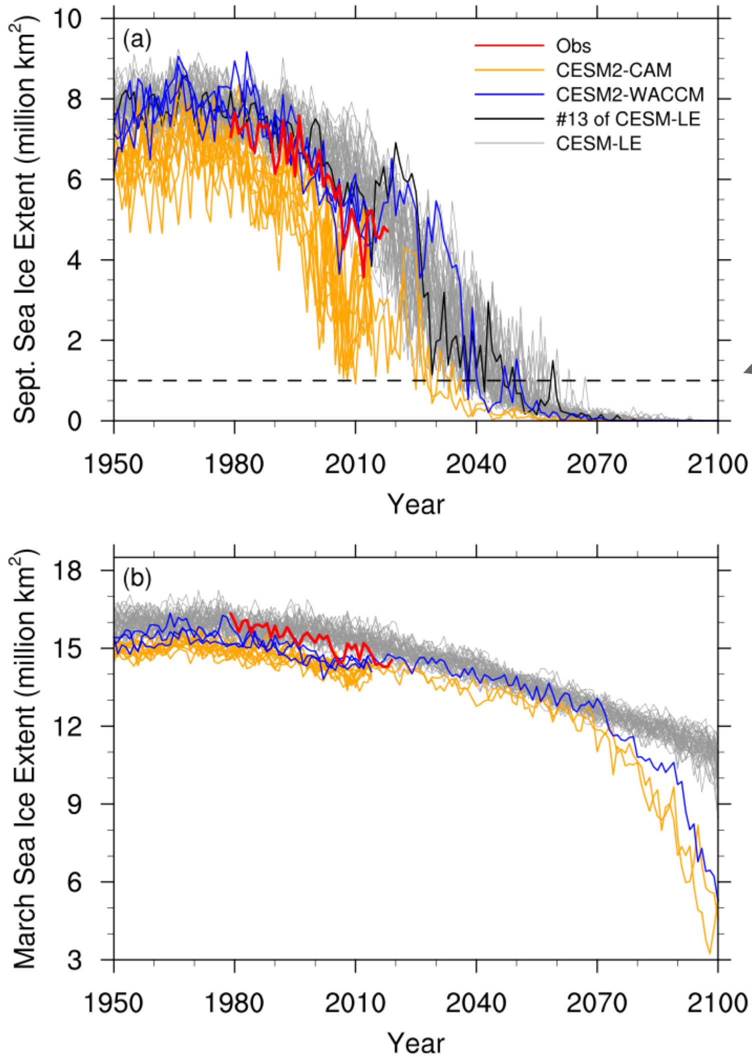
DuVivier et al. 2020

CESM2 Historical Arctic Sea Ice Snow



Webster et al. 2020

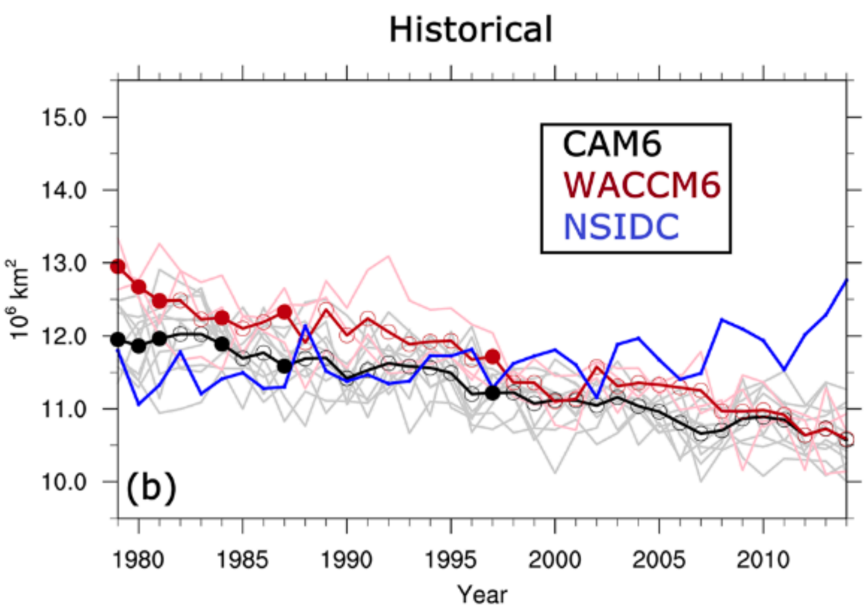
CESM2 Arctic Sea Ice Extent Projections



“Ice Free” Arctic

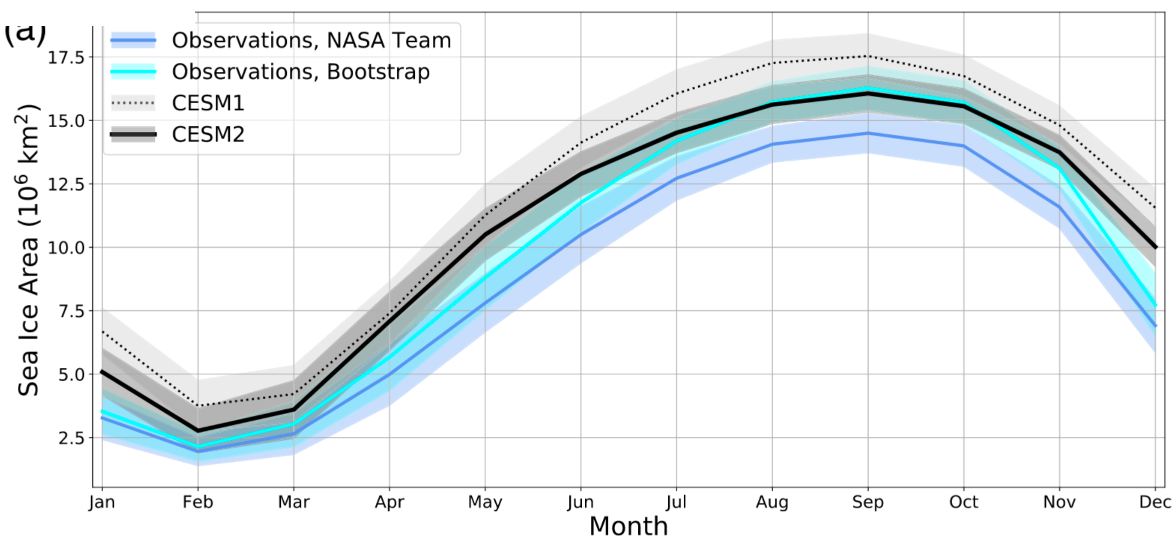
DeRepentigny et al. 2022

CESM2 Antarctic Sea Ice

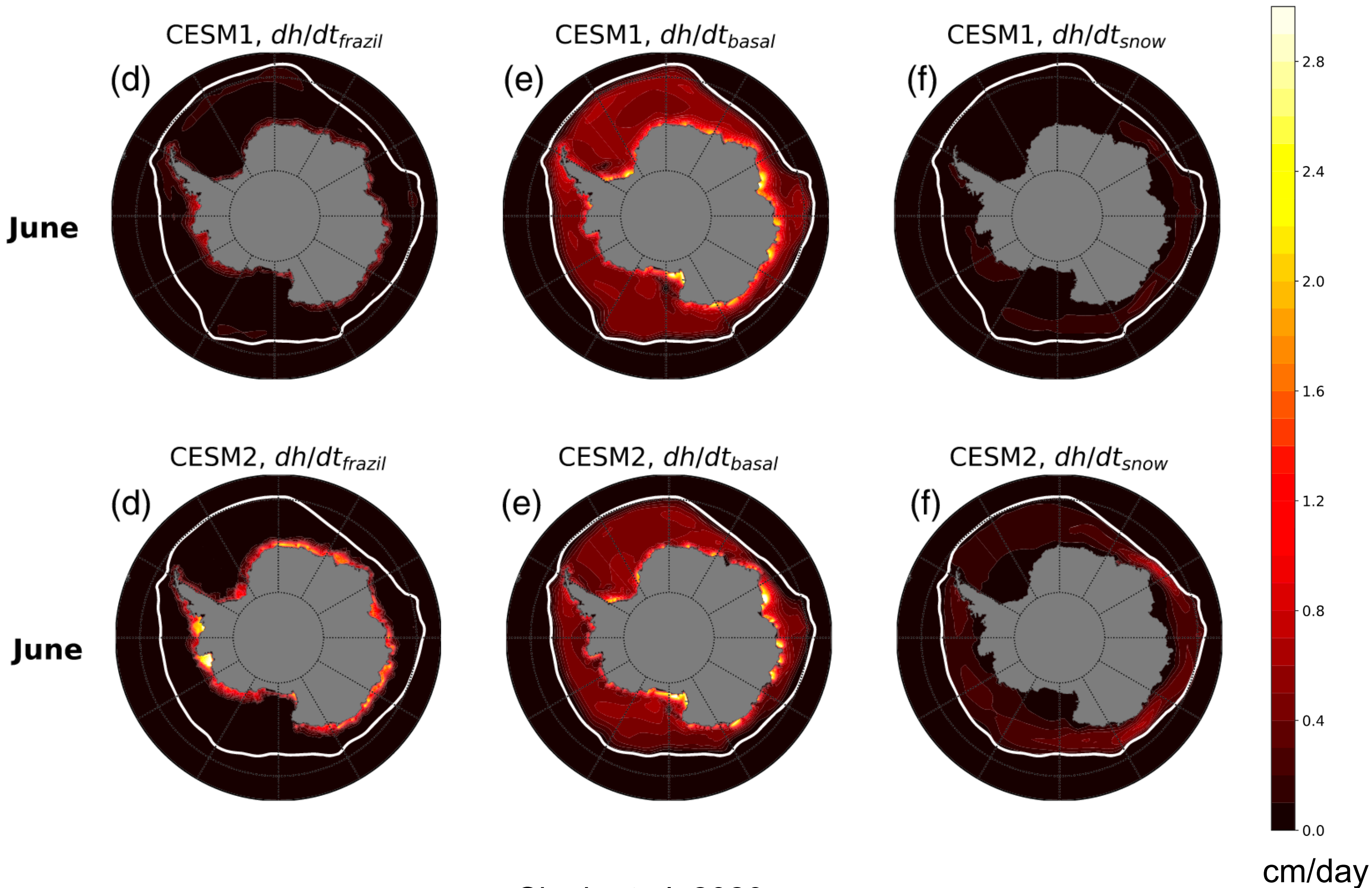


DuVivier et al. 2020

Singh et al. 2020



CESM2 Antarctic Sea Ice – growth processes are changing

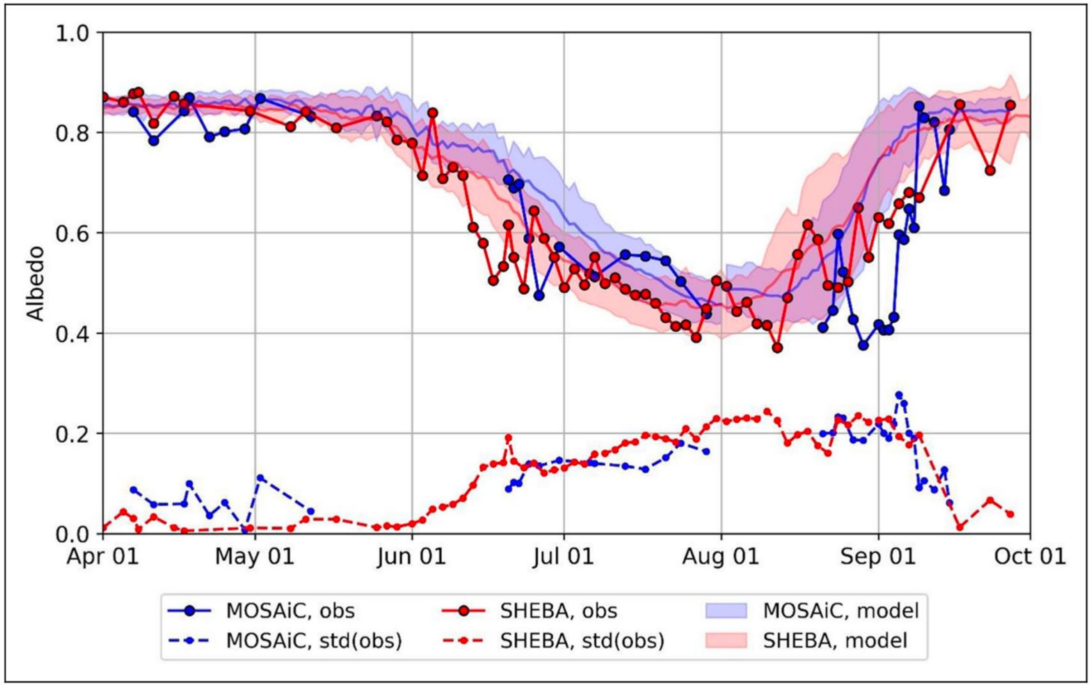


Singh et al. 2020

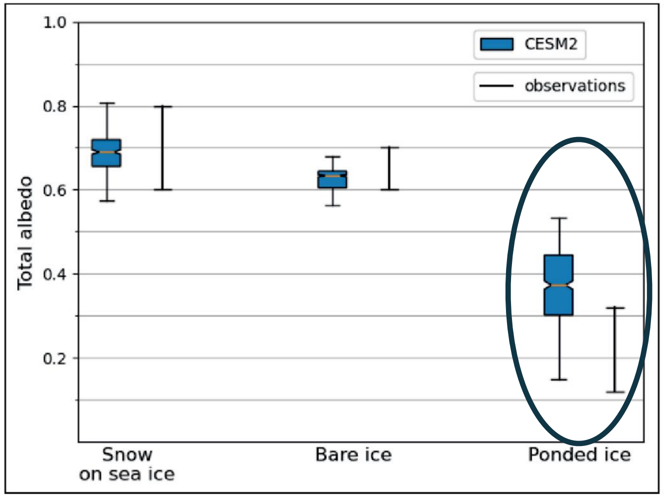
In development for CESM3 and beyond…

ThaNK U, NexT

CESM3 – Albedo and Melt ponds

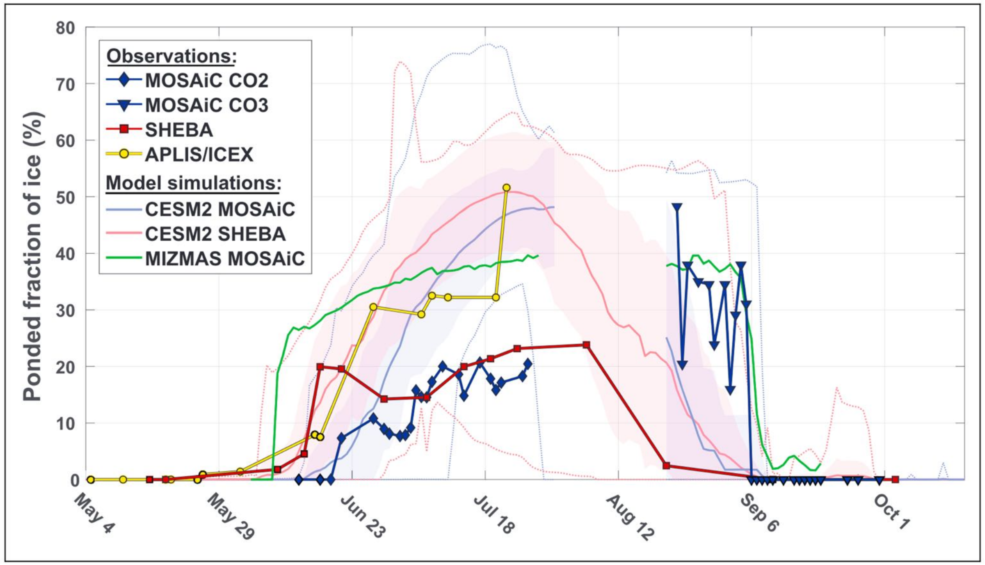


Light et al. 2022

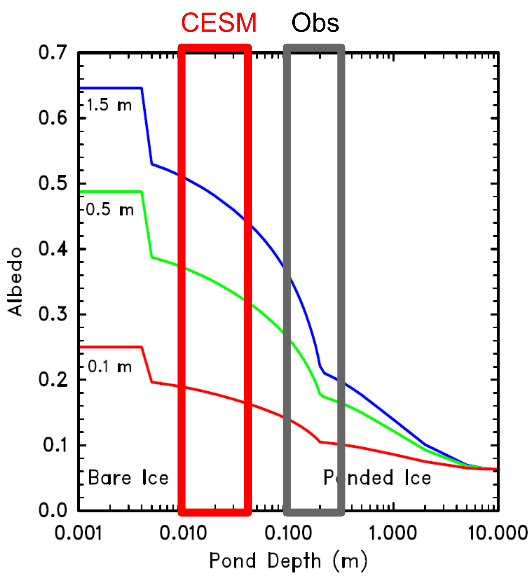


From: David Clemens-Sewell

CESM3 – Albedo and Melt ponds



Webster et al. 2022



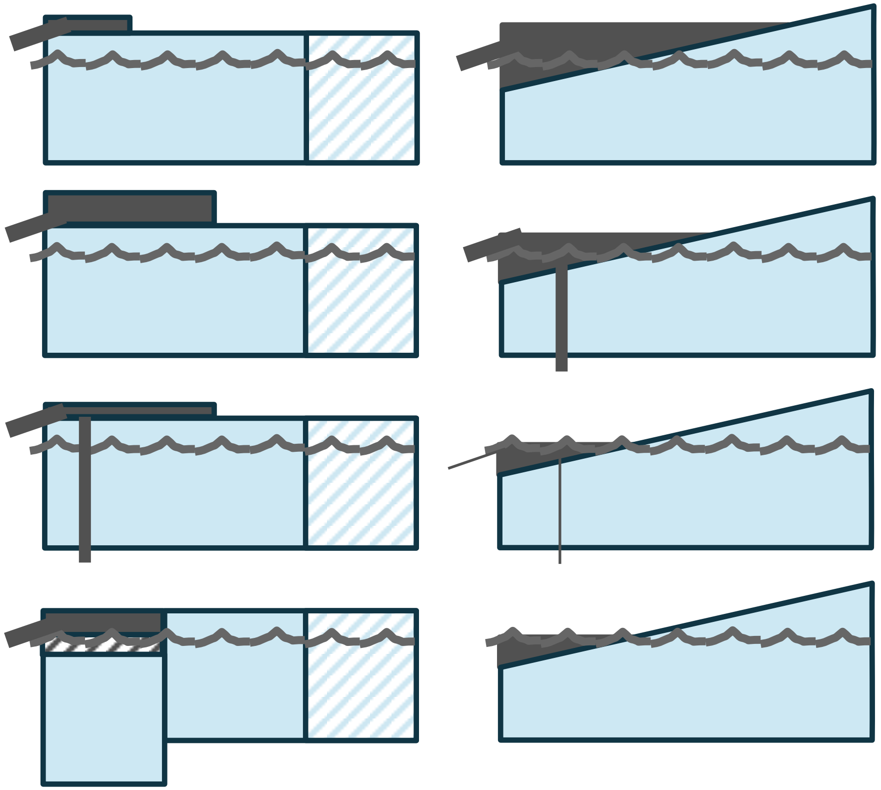
Briegleb and Light 2007

Ponds are too extensive, but not deep enough.

→ Compensating biases lead to reasonable albedo.

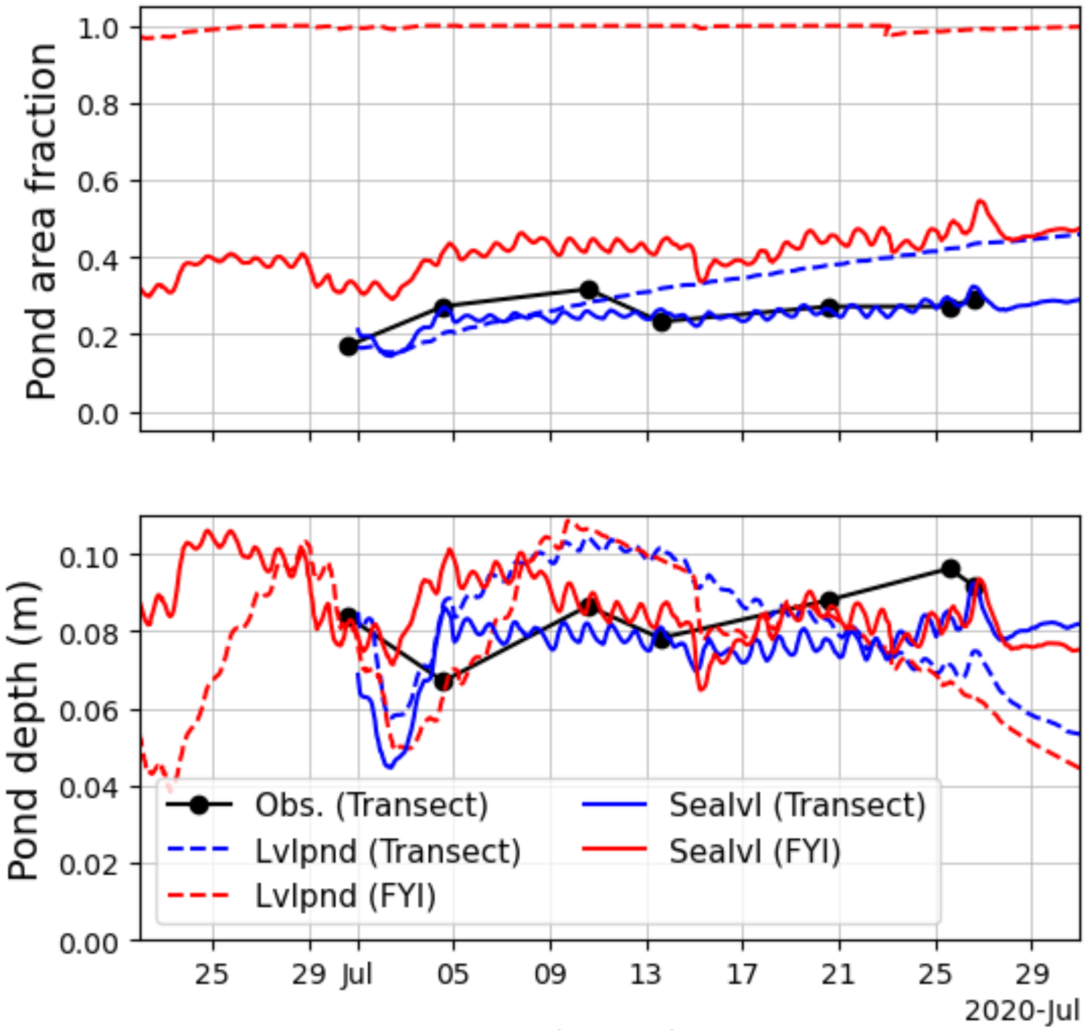
CESM3 – Albedo and Melt ponds

CESM2 (level pond)		CESM3 (sealevel pond)
Ponds are perched above the ice surface and exponentially decay.		Pond area, depth, and pressure head depend on linear hypsometry.
Pond area and depth grow by fixed ratio. Drainage only reduces depth.		Drainage reduces both depth and area based on hypsometry
The pressure head for percolation drainage assumes perched ponds.		Percolation and macroscopic drainage depend on pressure head.
If pond mass would depress ice locally below freeboard, instantaneous drainage.		Category has nonnegative buoyancy. Ponds can be locally below freeboard.



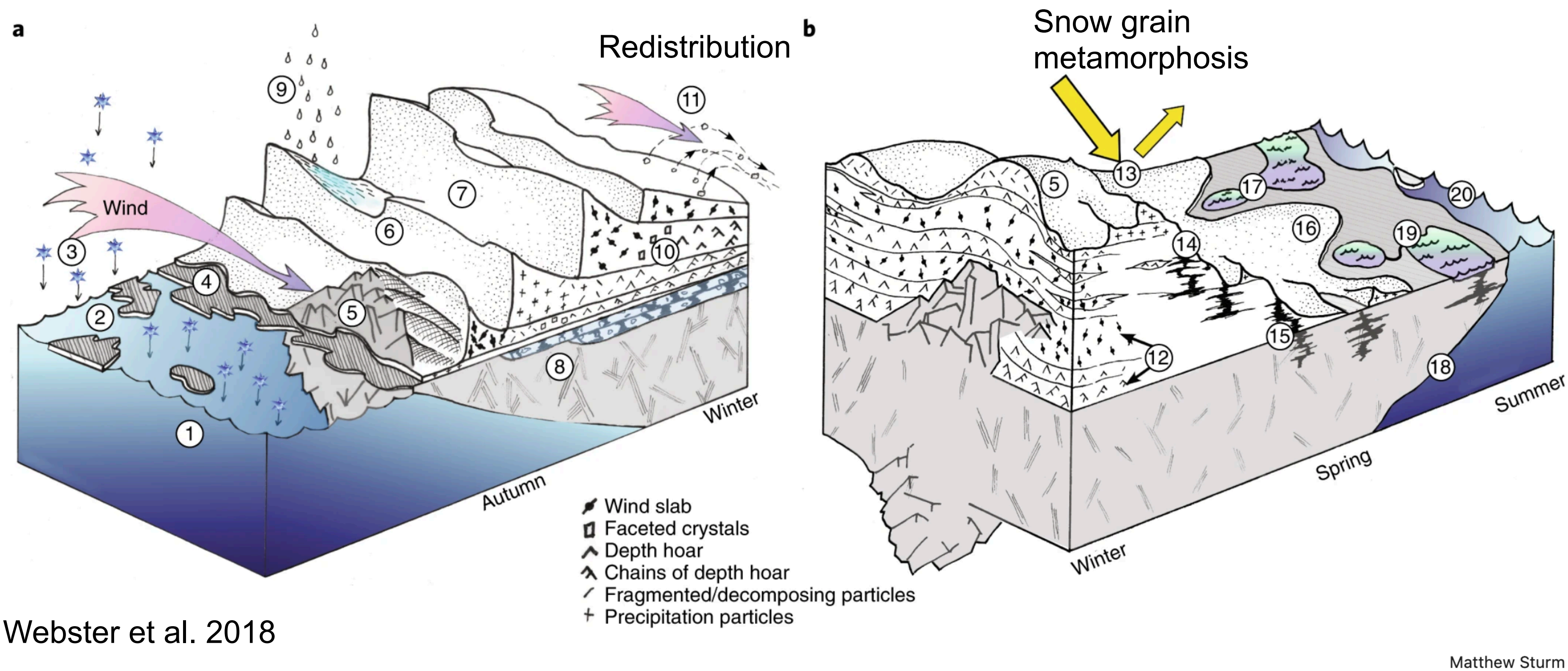
From: David Clemens-Sewell

CESM3 – Albedo and Melt ponds



From: David Clemens-Sewell

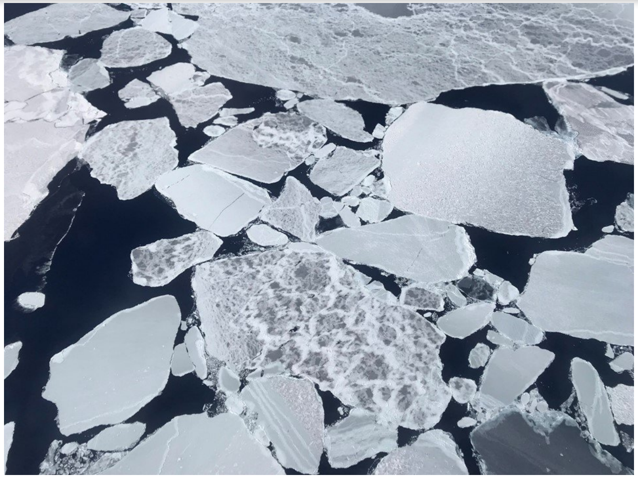
CESM3 – advanced snow physics



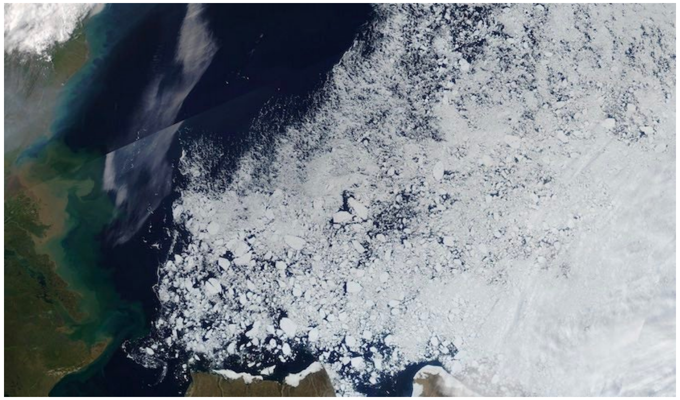
Webster et al. 2018

Documentation:
https://cice-consortium-icepack.readthedocs.io/en/icepack1.3.3/science_guide/sg_snow.html

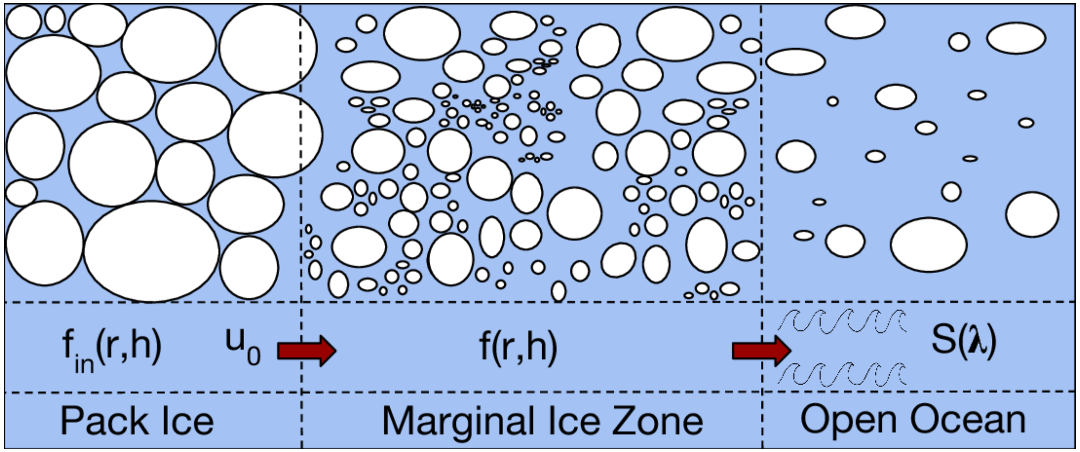
CESM3 – Floe size distribution



NASA Operation IceBridge (10/29/17)



MODIS satellite (7/27/19)



Waves affect sea ice
→ Fracture of floes
→ Floe welding

CESM3 – Floe size distribution

Joint floe size(r) & ice thickness(h) distribution

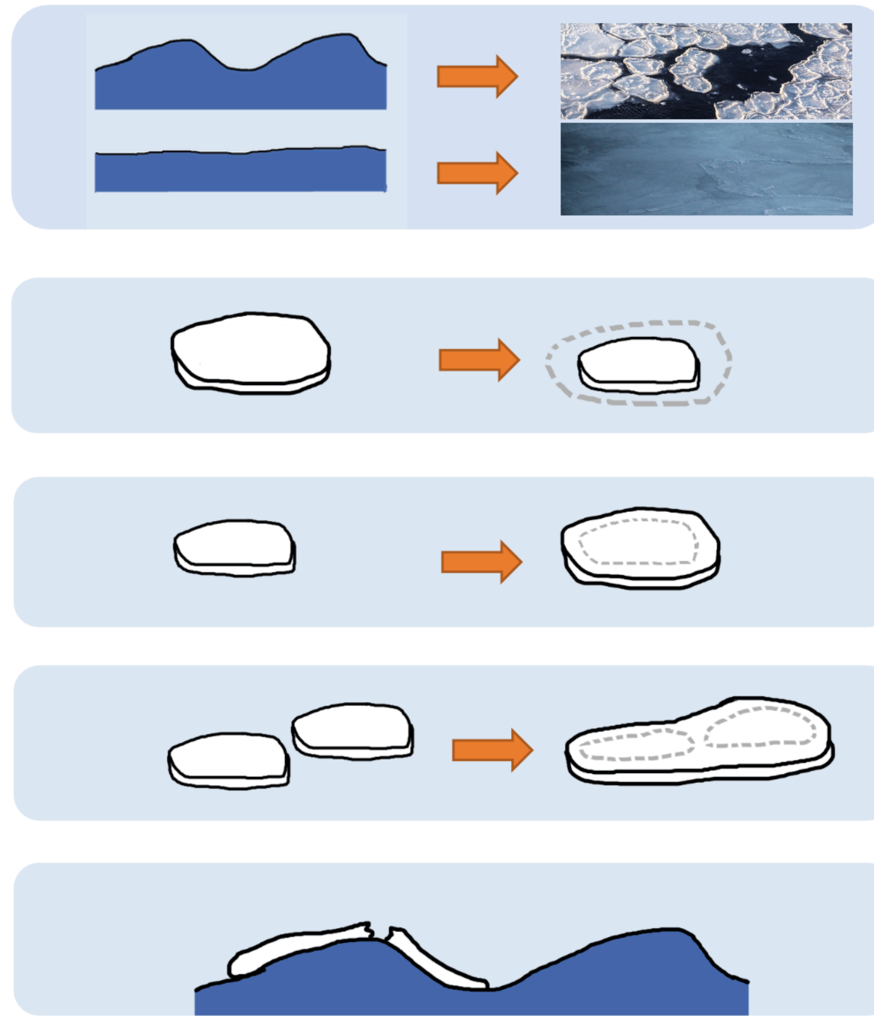
$$\frac{\partial f(r,h)}{\partial t} = -\nabla\cdot\left(f(r,h)\mathbf{v}\right) + \mathcal{L}_T + \mathcal{L}_M + \mathcal{L}_W$$

Advection

Mechanical interactions
- Divergence/Convergence
- Rafting
- Ridging

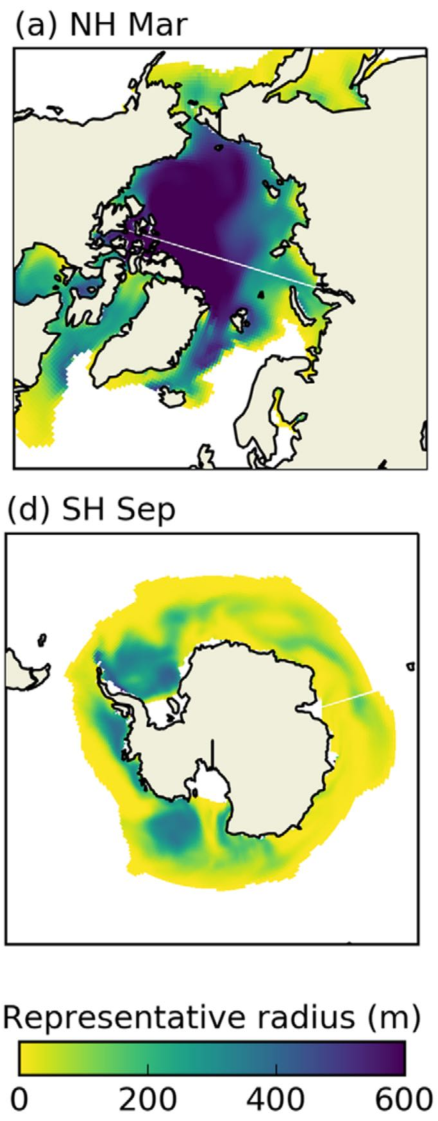
Thermodynamics
- Ice formation (pancakes)
- Lateral freezing/melting
- Basal freezing/melting

Wave fracture
- Strain fracture due to surface waves

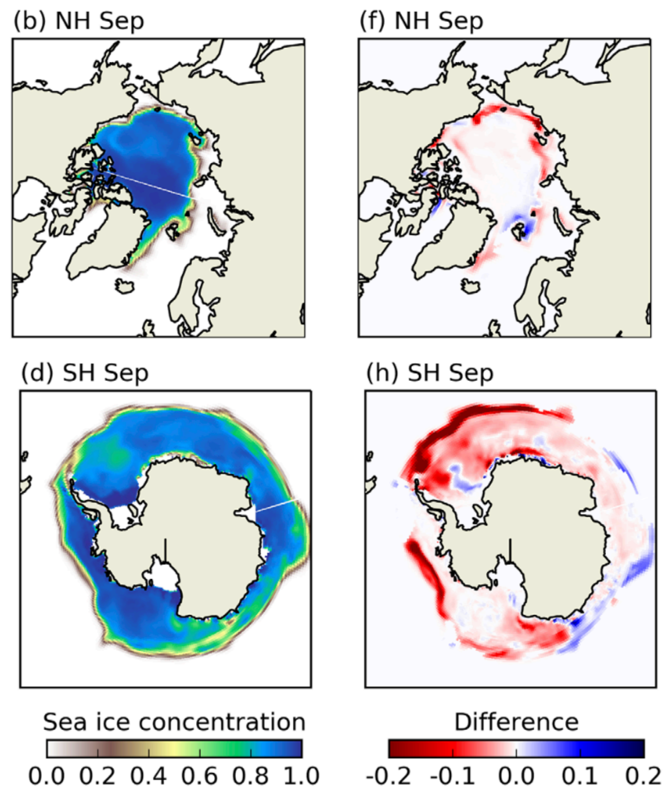


From: Roach et al. 2018

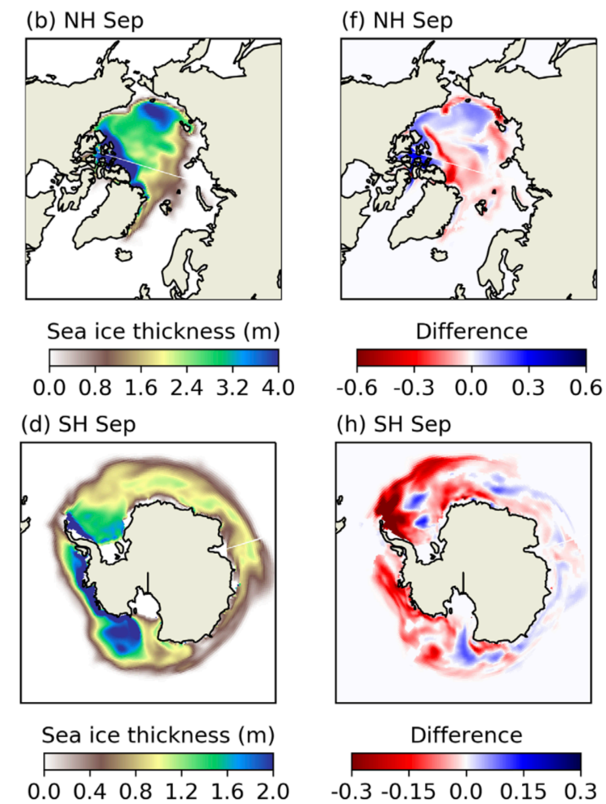
CESM3 – Floe size distribution



Impact on sea ice concentration



Impact on sea ice thickness



Differences = FSD – NO_FSD

From: Roach et al. 2018

CESM3.? – Sea ice biogeochemistry

- Coupling of pelagic and sea ice BGC
- Addition of polar specific phytoplankton (polar diatoms and phaeocystis)
- Addition of polar specific zooplankton (polar copepods or krill)
- Investigation of inclusion of Harmful Algal Bloom (HAB) species
- Investigation into how these processes impact ecosystem and physical system.

Recommended for funding by NOAA

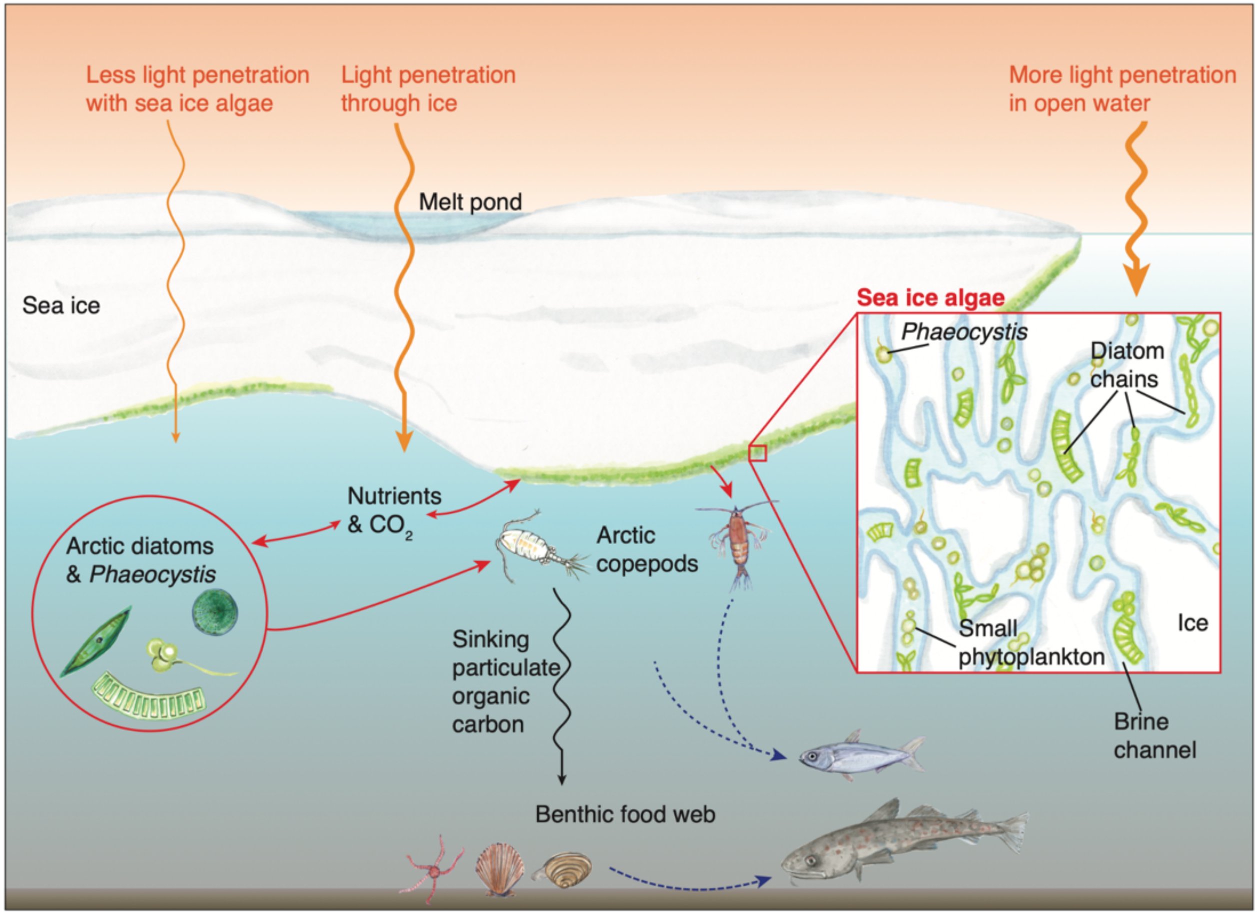
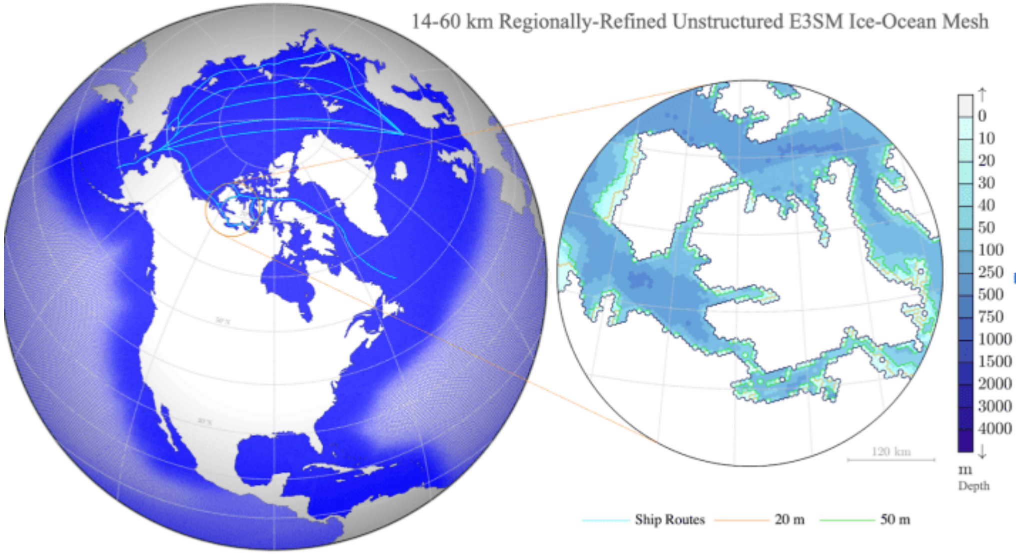


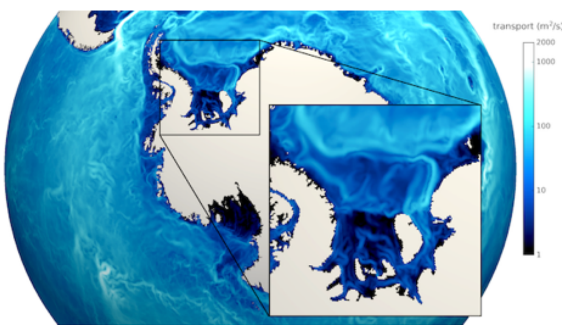
Image by Kristen Krumhardt (NSF NCAR)

Other Models

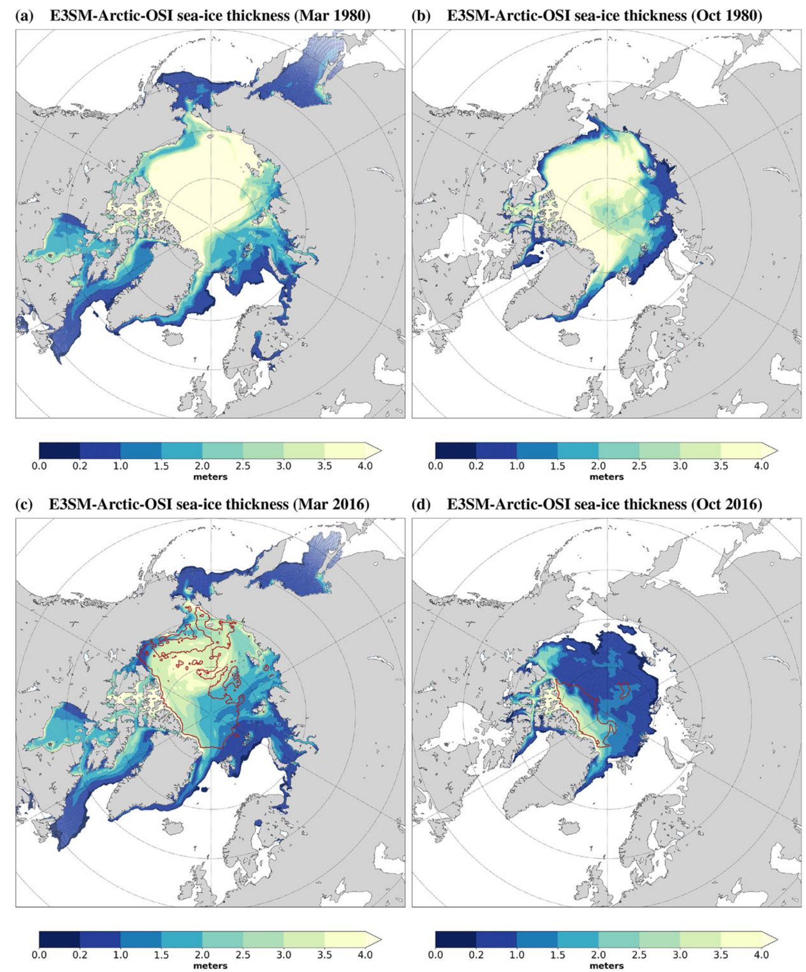
E3SM – Unstructured Mesh



https://arcticinterface.org/sea-ice-and-ocean-dynamics/



https://e3sm.org/research/cryosphere-ocean/v1-cryosphere-ocean/

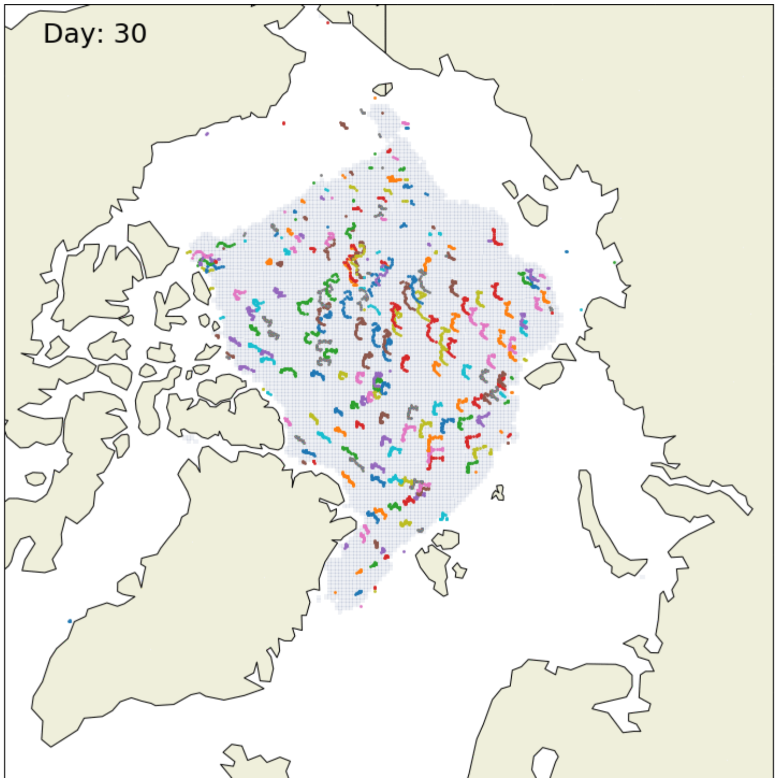


CryoSat-2 2m contour

Veneziani et al. 2022

Lagrangian sea ice modeling

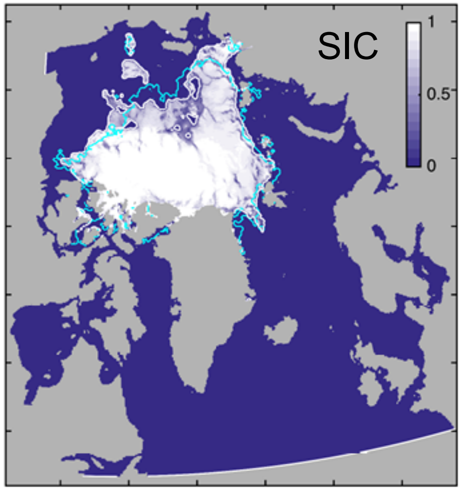
Spawns new trajectories as an ice parcel is created

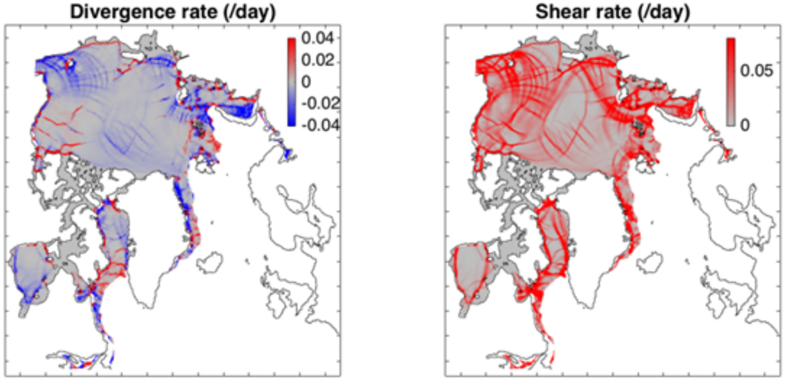


https://www.robbiemallett.com/lagrangian-modelling-of-sea-ice

neXtSIM

Built to address shift in dynamical regime and changing sea ice drift





Rampal et al. 2016


Thank You
Questions?
duvivier@ucar.edu
http://assets.nydailynews.com/polopoly_fs/1.17149.1313675705!/img/httpImage/image.jpg_gen/derivatives/gallery_635/gal-natures-best-08-jpg.jpg

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

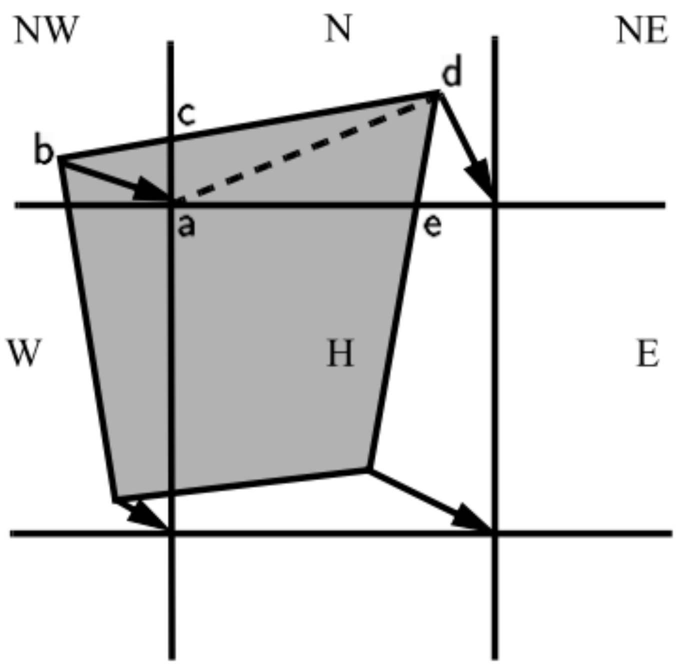
- Ice has no tensile strength but resists convergence and shear with strength dependent on ice state.
- Treats ice as a continuum, based on Viscous-Plastic Rheology (Hibler, 1979)

→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.

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



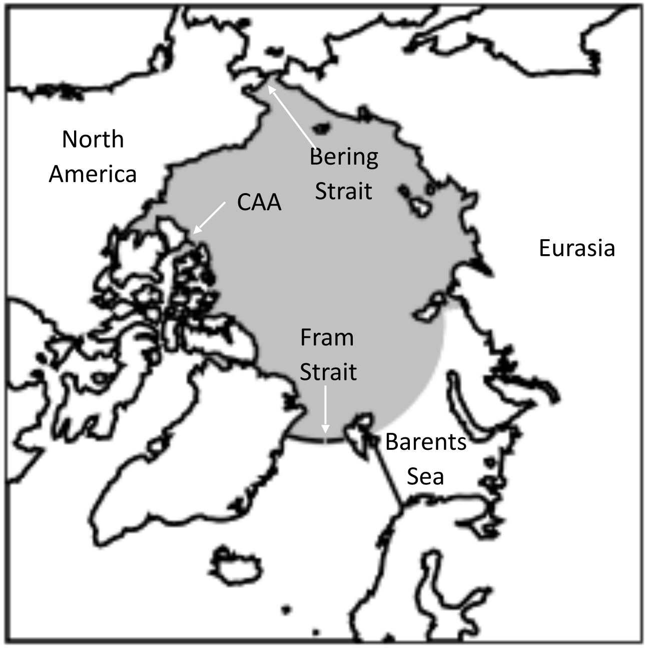
Conserved quantities are remapped from the shaded "departure region", which is computed from backward trajectories of the ice motion field.

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



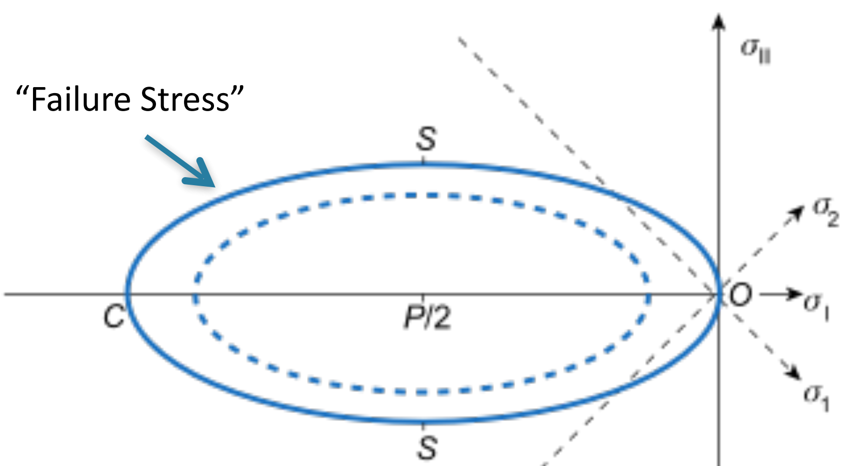
Climate model archive of monthly averaged ice thickness and velocity

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

Holland et al., 2010

Sea Ice 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)



Eliptical Yield Curve

Elastic-Viscous-Plastic Model

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