Sea Ice Modeling in the CESM

CESM 2025 Tutorial

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With contributions from:

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+ the Polar Climate Working Group

NCAR | CLIMATE & GLOBAL DYNAMICS

NSF

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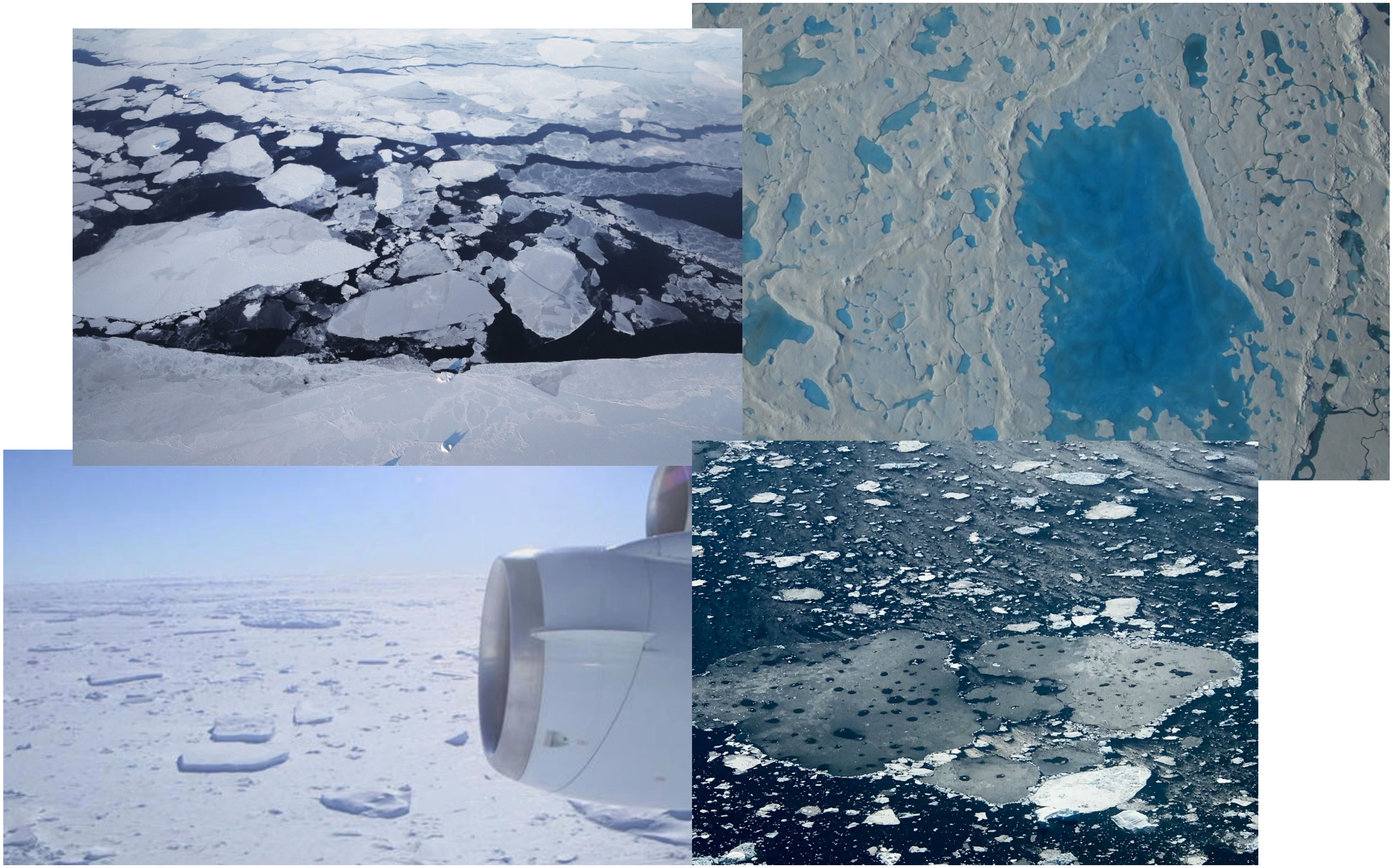
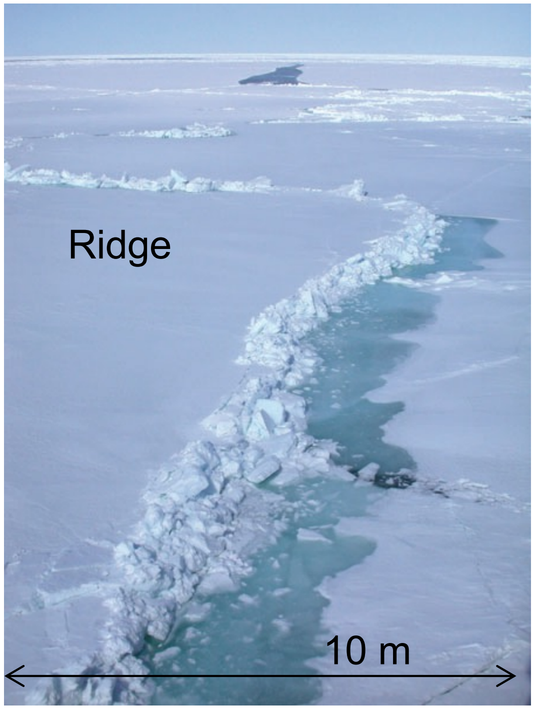
What is Sea Ice?

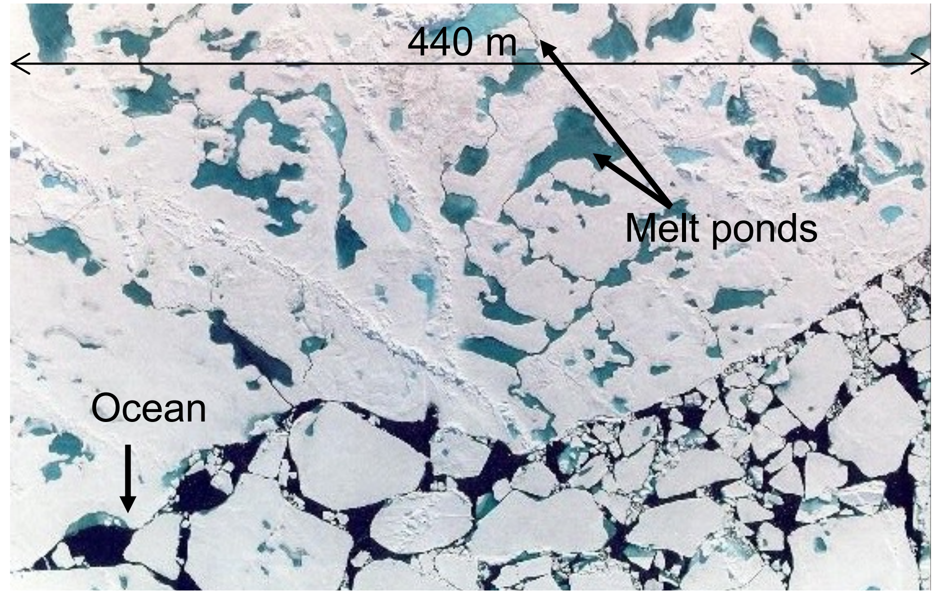
Sea Ice is <u>frozen sea water</u> that forms seasonally



Photos from NASA Operation IceBridge

Sea ice Cover



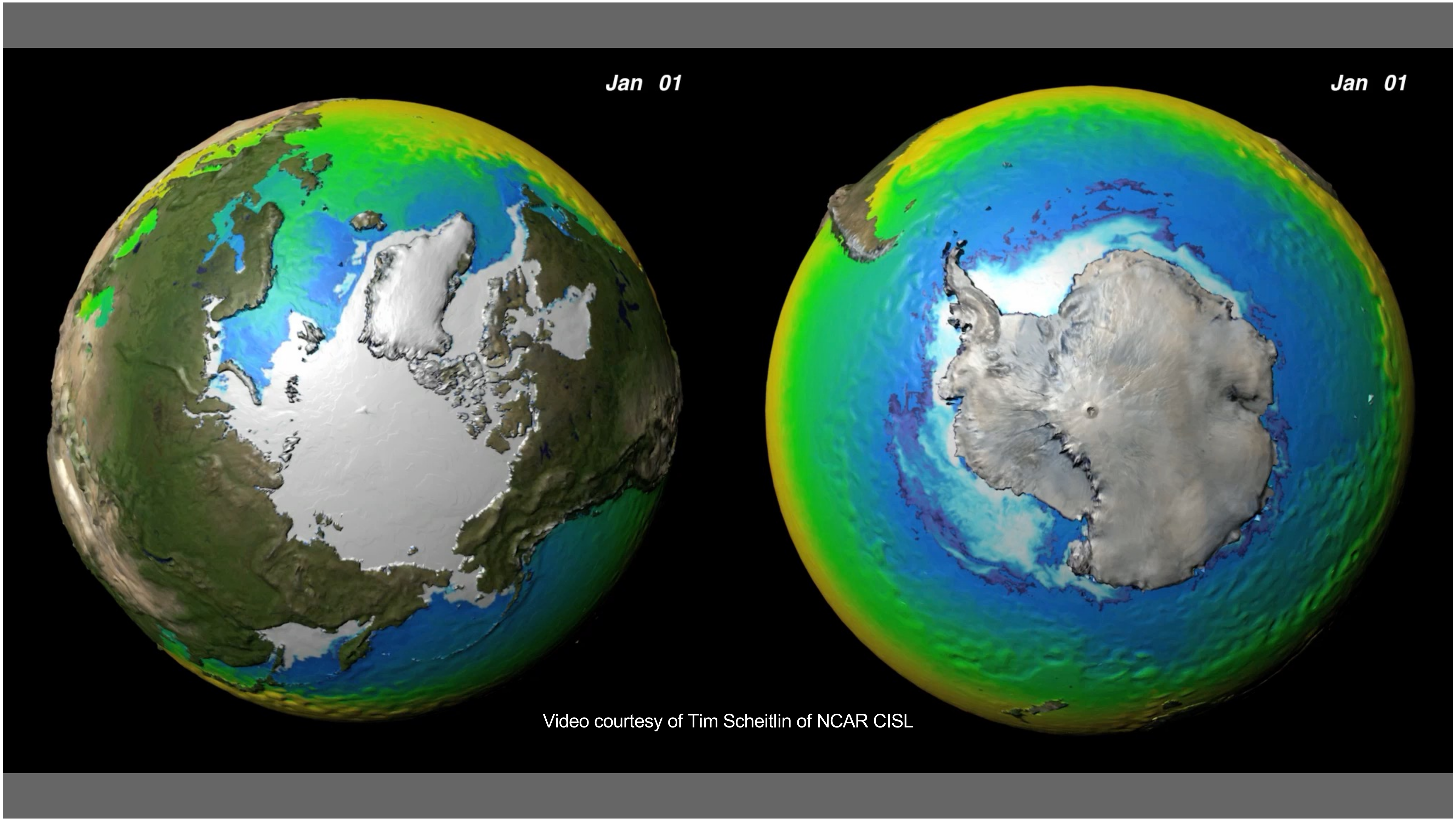


← Photos from Feltham, 2008 by Hajo Eicken

↑ Photo from Don Perovich

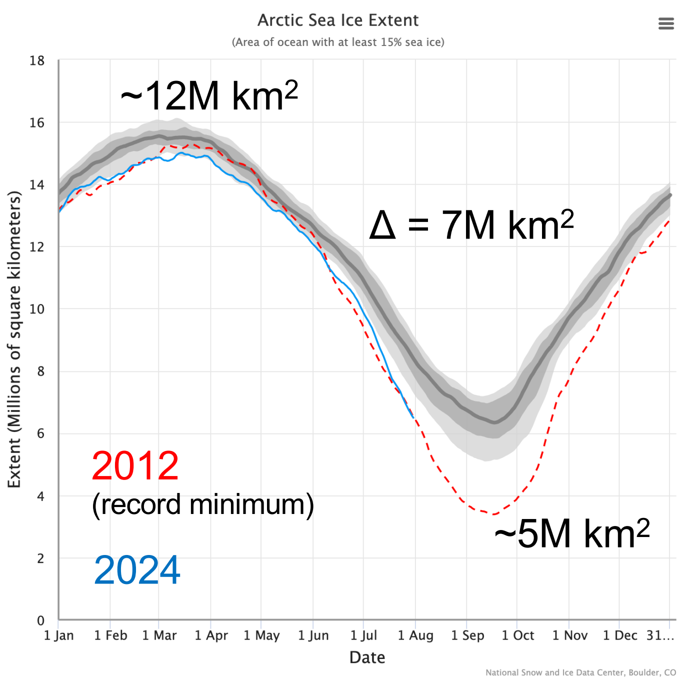
- Heterogeneous – lots of subgridscale variability
    - Leads, ridges, melt ponds, floes, albedo, snow cover, etc.
- Individual floes of varying size can form a continuous cover
- Thickness on the order of meters

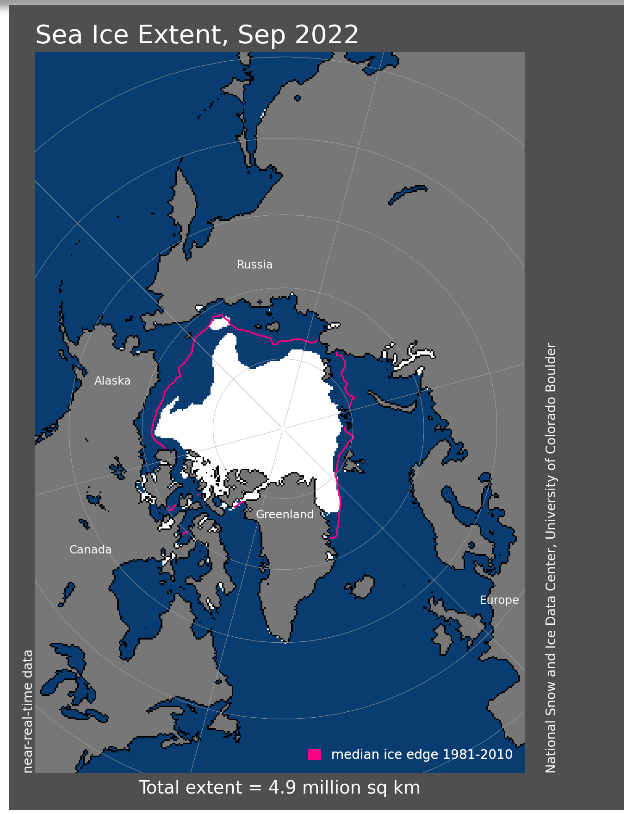
Sea Ice in CESM

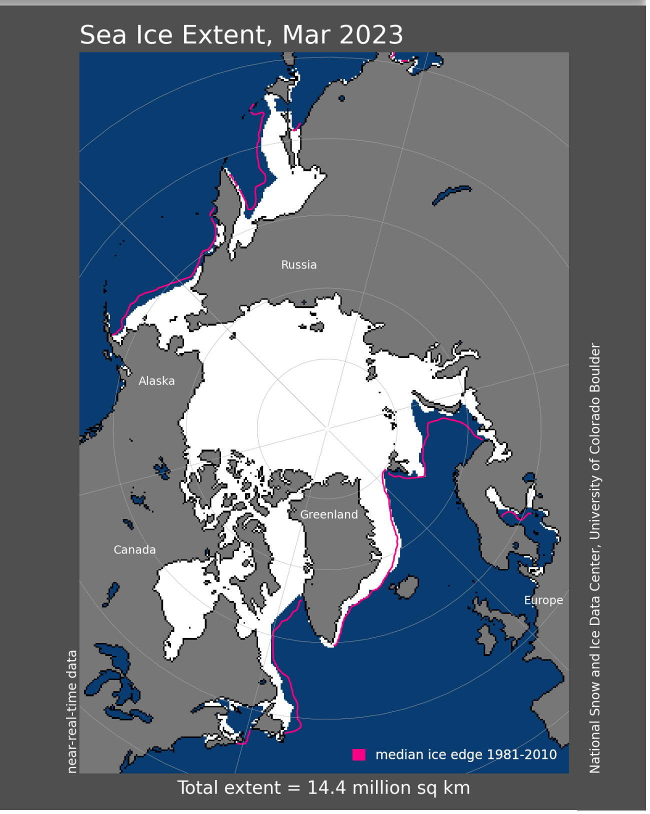


Arctic vs. Antarctic

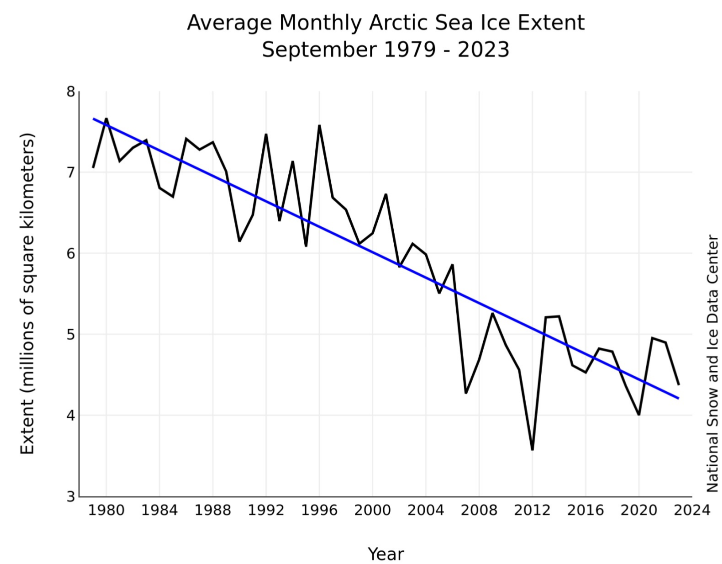
September (minimum) March (maximum)





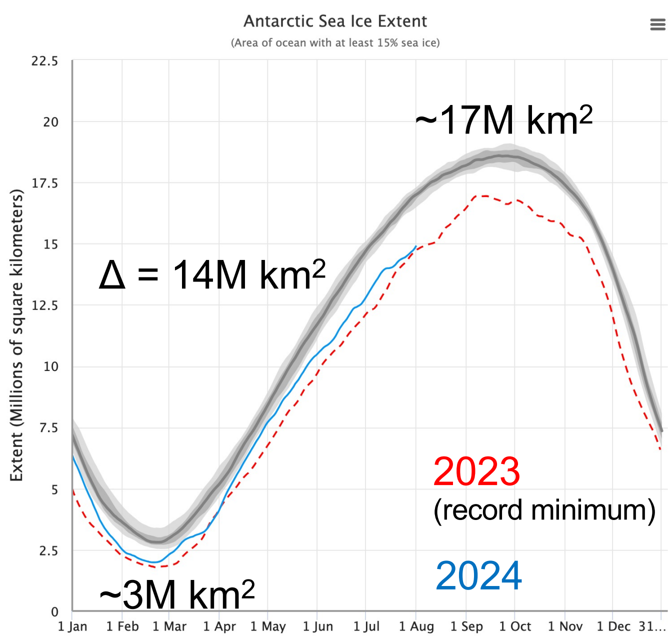


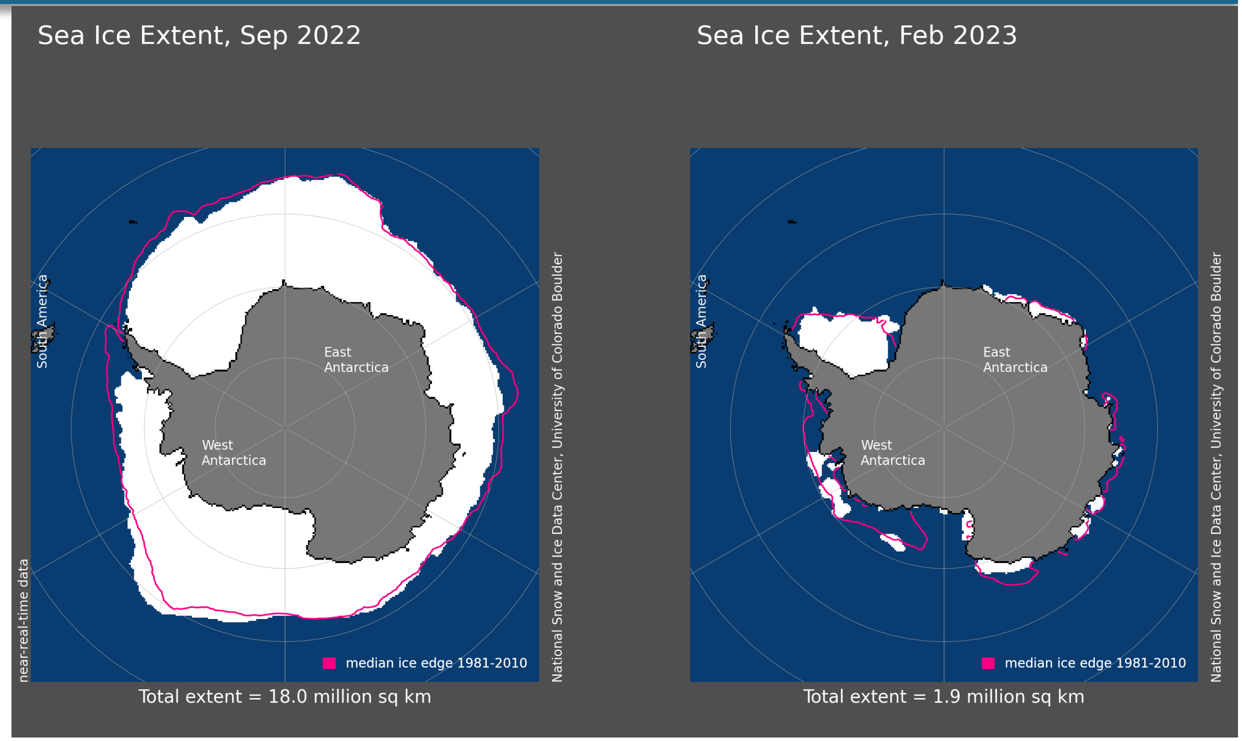
- Ocean bounded by land → ice converges at land, thick!
- Land boundaries & ocean heat determine winter extent



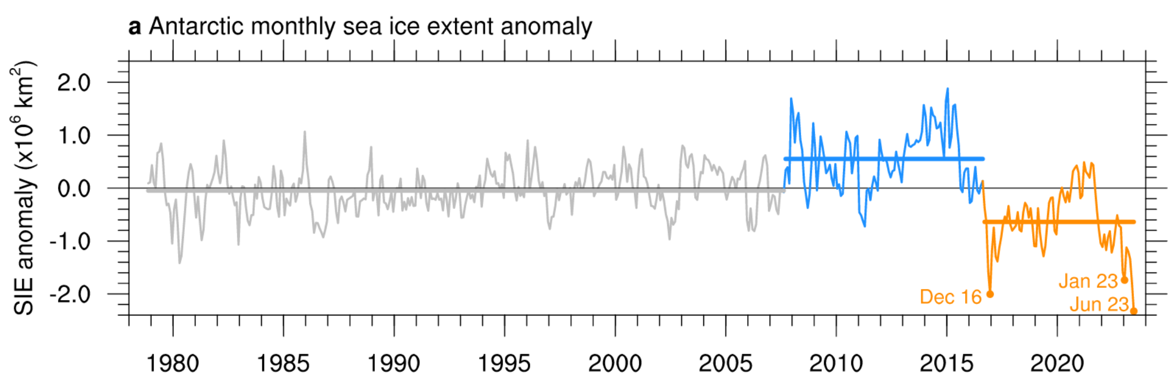
Arctic vs. Antarctic

September (Maximum) | March (minimum)



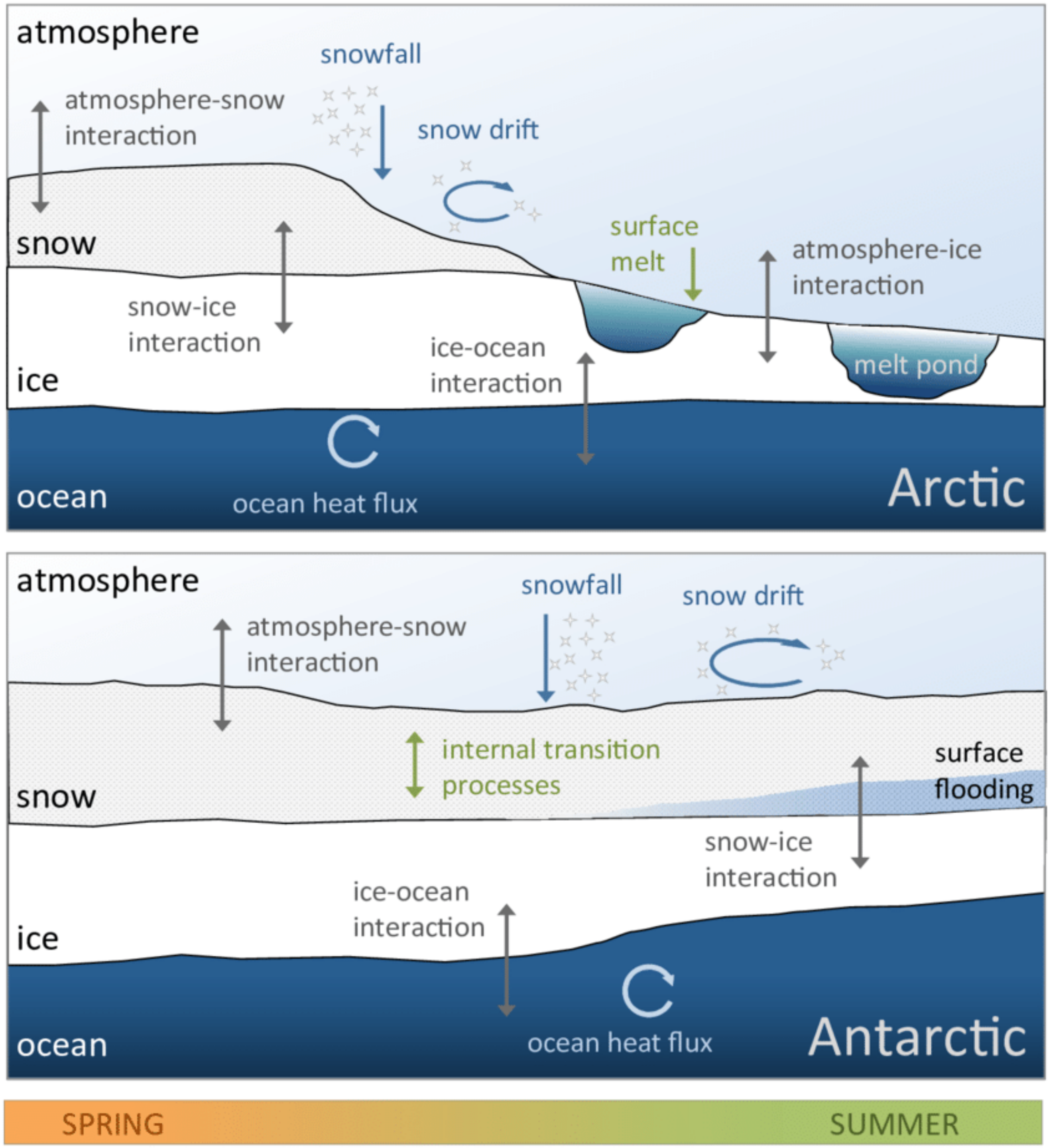


- Southern ocean is unbounded → ice in free drift
- Ocean heat determines winter extent



Purich and Doddridge 2023

Arctic vs. Antarctic – seasonal evolution



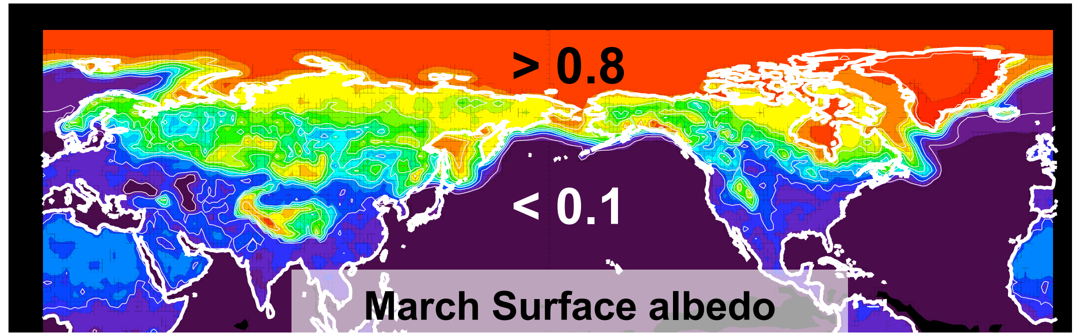
Arndt et al. 2017

Why sea ice matters in the Earth system

Surface energy budget

→ Albedo

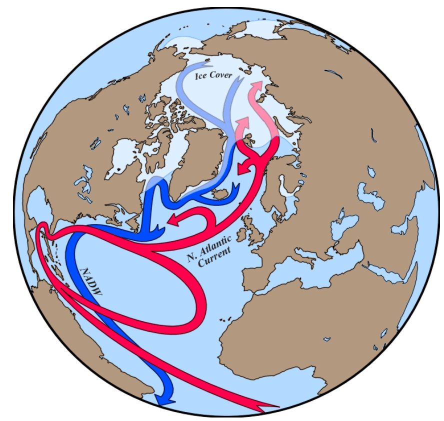
→ Surface turbulent fluxes



Hydrologic cycle/Ocean Circulation

→ Ice formation

→ Ice transport

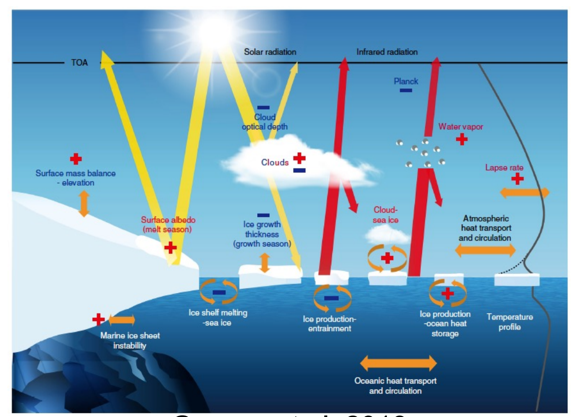


Climate Feedbacks (e.g.)

→ Albedo feedback

→ Ice growth/thickness feedback

→ Ice/Cloud feedback



Goosse et al. 2018

Sea ice models: needs

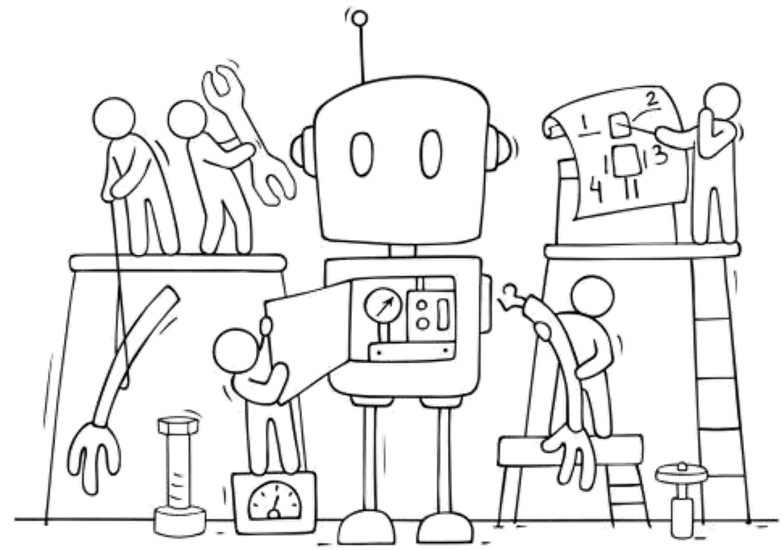
- Reasonable mean state & variability – concentration, thickness, mass budgets – in both hemispheres
- Realistically simulates ice-ocean-atmosphere exchanges of heat and moisture
- Realistically simulates response to climate perturbations
- Computationally efficient (need to run for 1000s of years, ensembles, etc.)

CICE (pronounced "sice"): The CICE Consortium Model

- CESM2 uses CICE V5.1.2 (Hunke et al.)
  - Full documentation available online: http://www.cesm.ucar.edu/models/cesm2.0/sea-ice/
- CESM3 uses CICE V6
- CICE development is through the international CICE Consortium
  - https://github.com/CICE-Consortium/

CICE (and other sea ice models): 3 essential components

1. Dynamics
2. Thermodynamics
3. Ice thickness distribution



Dynamics

- Dynamics
  - Solves force balance to determine sea ice motion and deformation
  - Rheology describes stress and deformation or flow of ice

Dynamics

(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

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

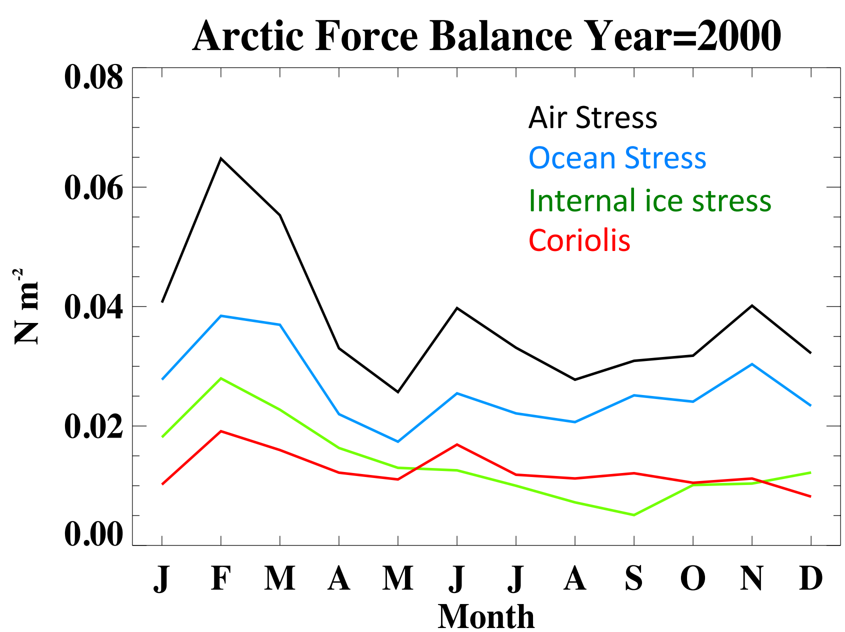
$$\vec{\tau}_w = c_w \rho_w \left|\vec{U}_w - \vec{u}\right| \left[\left(\vec{U}_w - \vec{u}\right)\cos\theta + \hat{k} \times \left(\vec{U}_w - \vec{u}\right)\sin\theta\right]$$

Dynamics

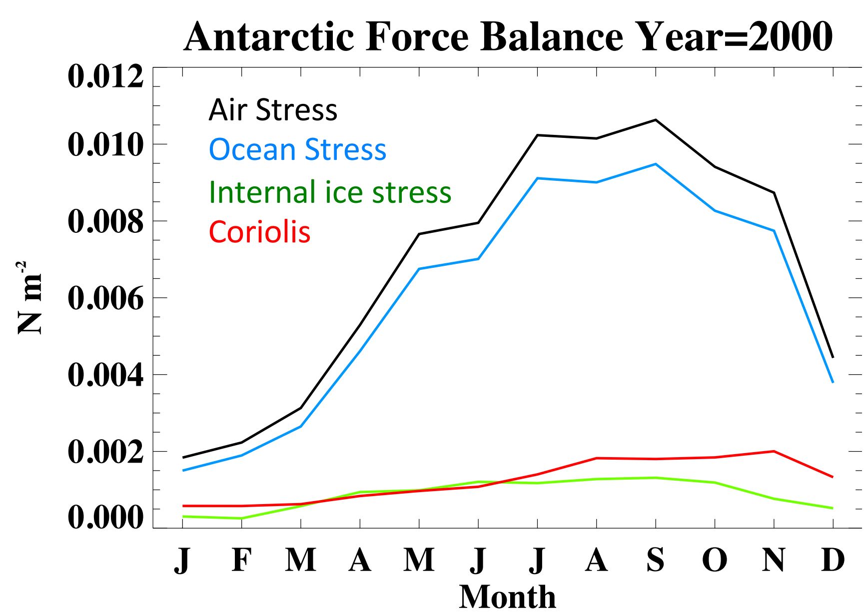
(e.g. Hibler, 1979)

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

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



Internal ice stress impactful in winter



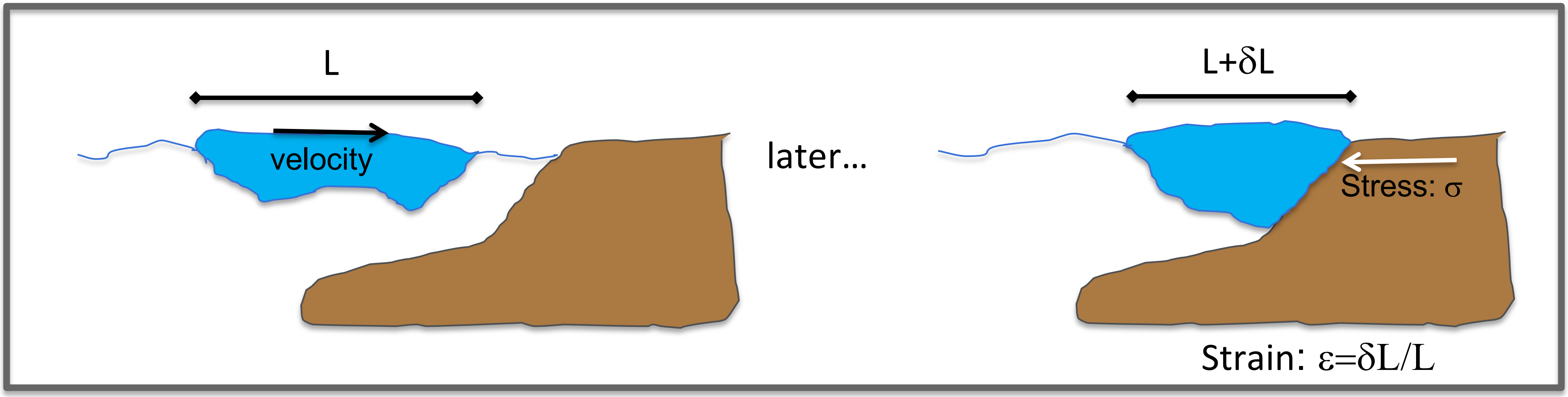
Free drift: Air stress ≈ Ocean stress

Dynamics

(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



– Relate ice stress (σ) to ice strain rate (ε)

– CESM uses Elastic-Viscous-Plastic (EVP) scheme:

Ice is a continuum and can deform elastically (like a spring), flow like a viscous fluid, and undergo plastic deformation (permanent deformation) under certain conditions.

Thermodynamics

- Thermodynamics
  - Solves for vertical and lateral melt & growth rates

Photo by Alice DuVivier

Photo by Robbie Mallett

Thermodynamics

Top surface flux balance

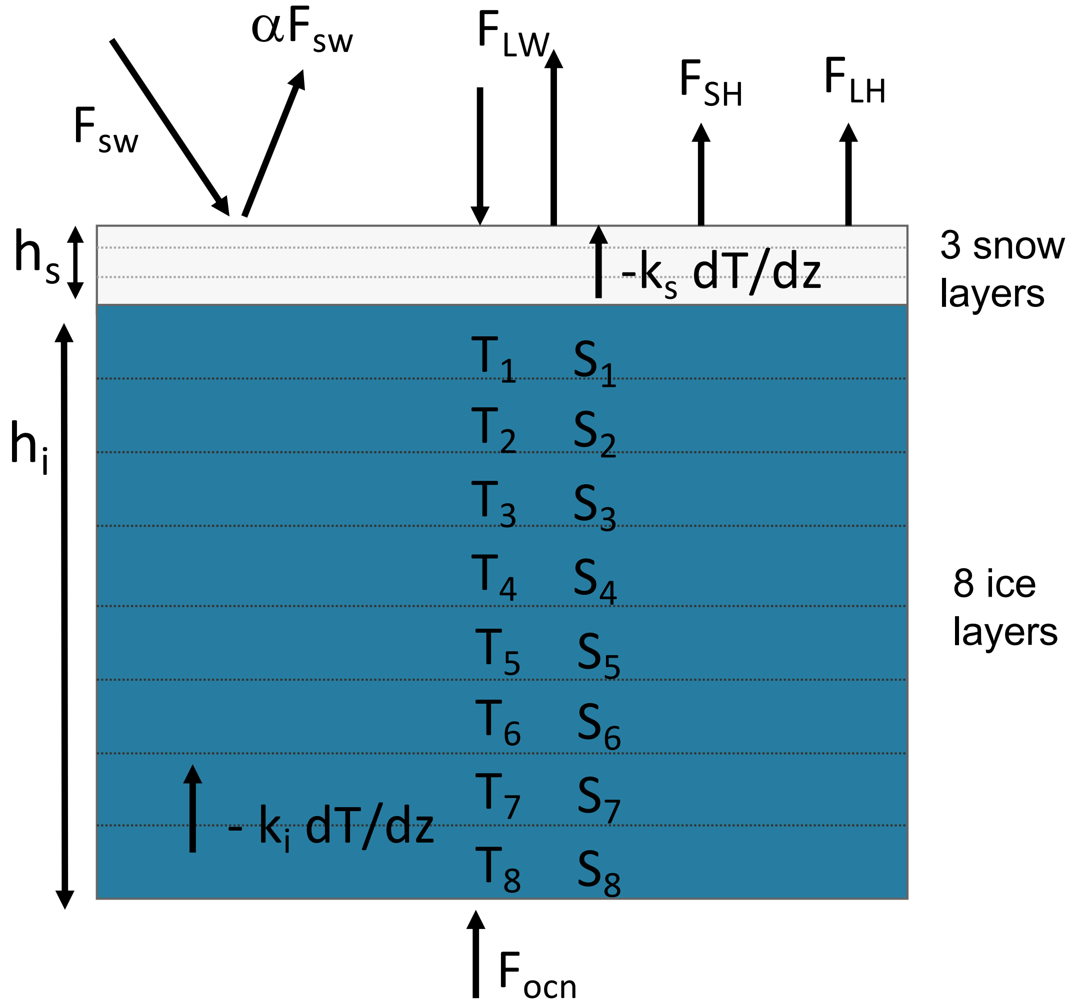
$$(1-\alpha)F_{SW} + F_{LW} - \sigma T^4 + F_{SH} + F_{LH} + k\frac{\partial T}{\partial z} = -q\frac{dh}{dt}$$

Vertical heat transfer (conduction)

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

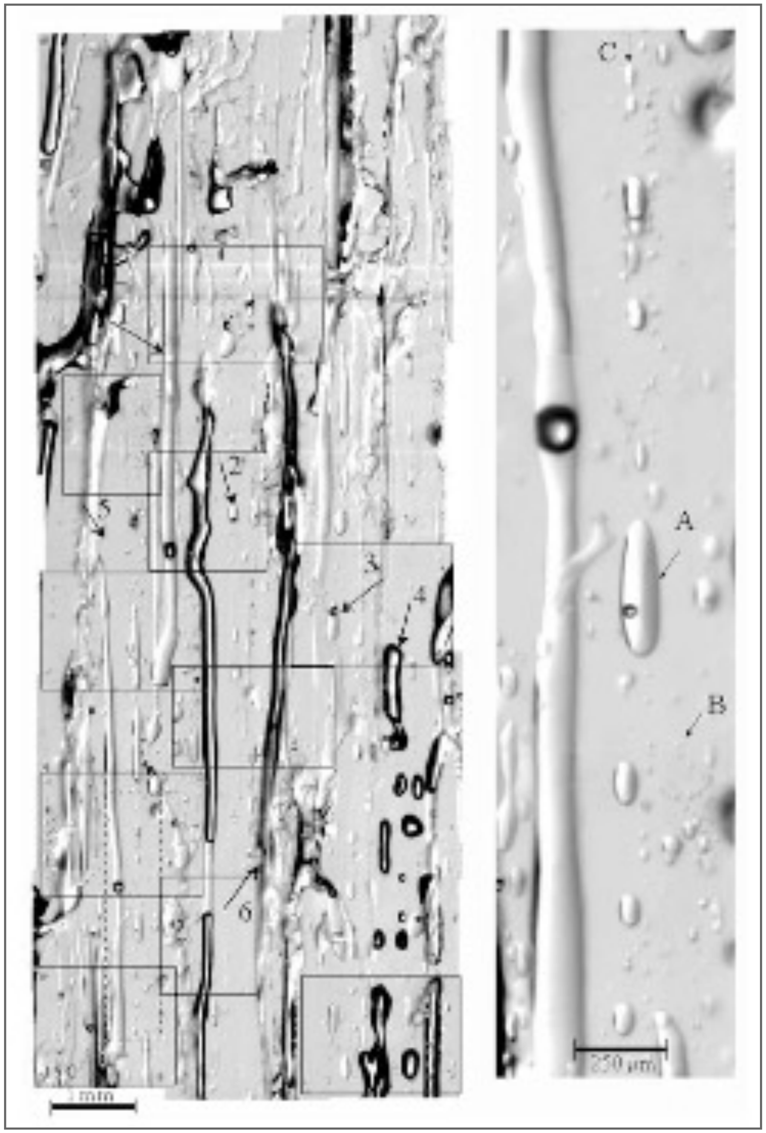
Bottom surface flux balance

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



k = conductivity
ρ = density (constant): ρ_i = 917 kg/m^3; ρ_s = 330 kg/m^3

Ice structure and heat fluxes



(from Light, Maykut, Grenfell, 2003)

CESM2 and CESM3: Mushy Layer thermodynamics scheme

- Prognostically determine temperature **and** salinity profiles using mushy layer thermodynamics
- Assume pockets/channels are brine filled and they are in thermal equilibrium with ice
- Assume salinity dependent freezing temperature
- Heat capacity and conductivity are functions of ice temperature and salinity

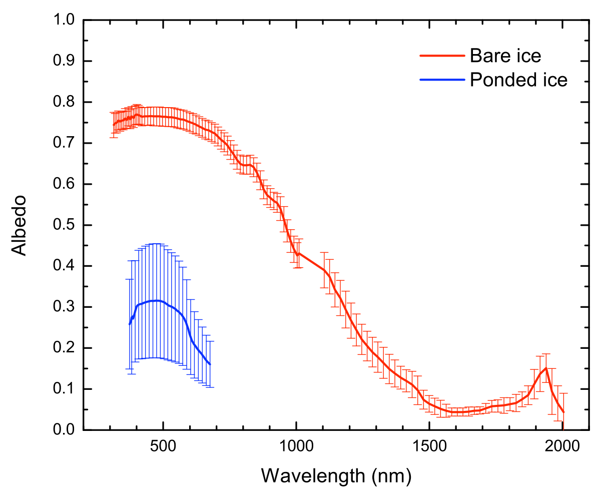
Delta Eddington Solar Radiation parameterization

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



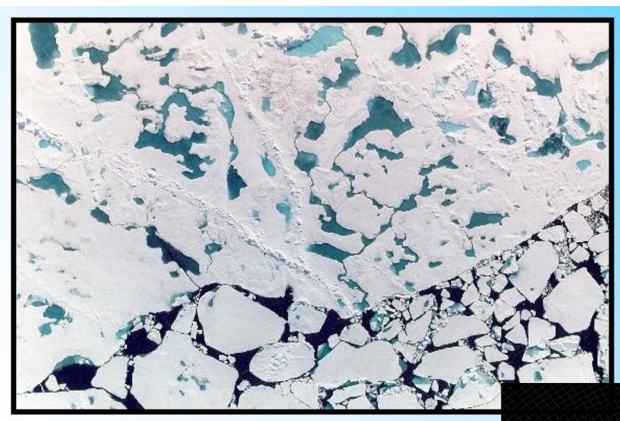
CLIMATE AND GLOBAL DYNAMICS DIVISION

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

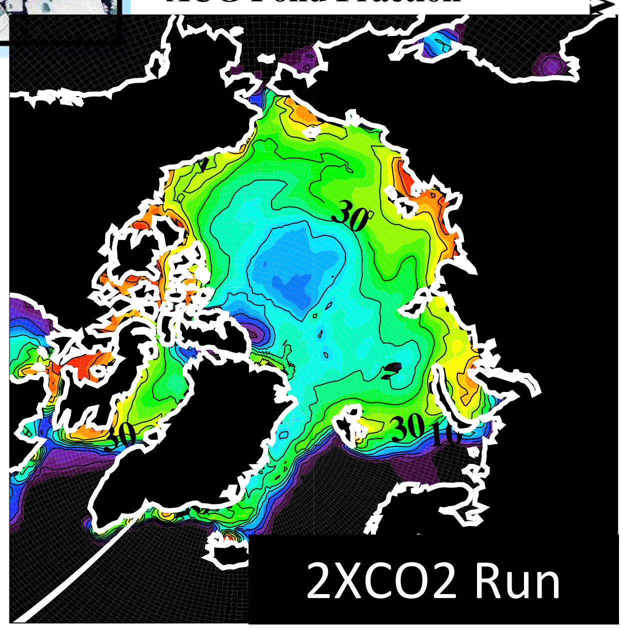
- Inherent optical properties define scattering and absorption properties for snow, sea ice, and absorbers.
- Calculate base albedo and then modify.
- Explicitly allows for included absorbers (e.g. algae, carbon, sediment) in sea ice
- Accounts for melt ponds, snow grain sizes, etc.
- Used in CESM1 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

Melt Pond Parameterization

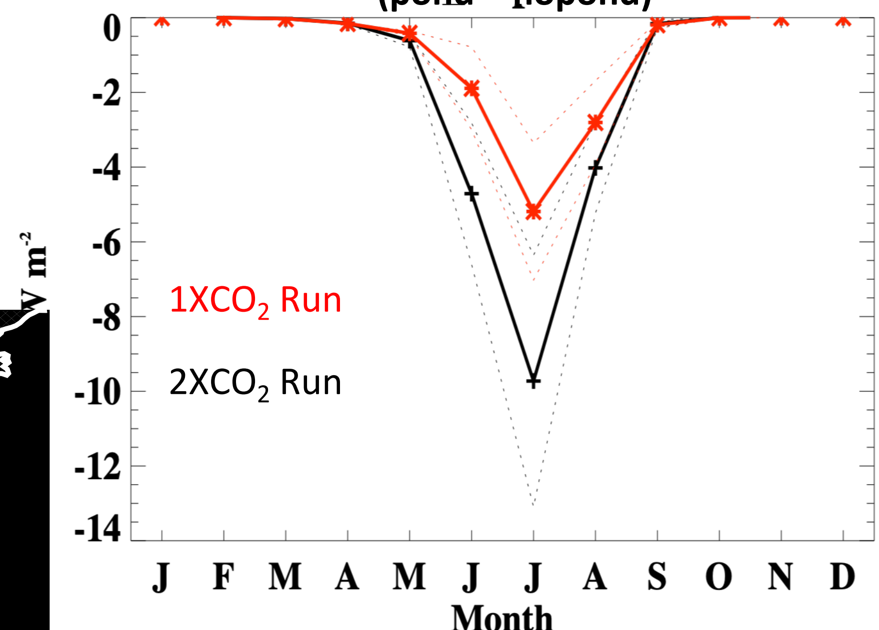
- Only influences radiation and has big influence on surface forcing
- Ponds evolve over time and are carried as tracers on the ice
- CESM2 pond evolution takes into account if sea ice is deformed



AUG Pond Fraction



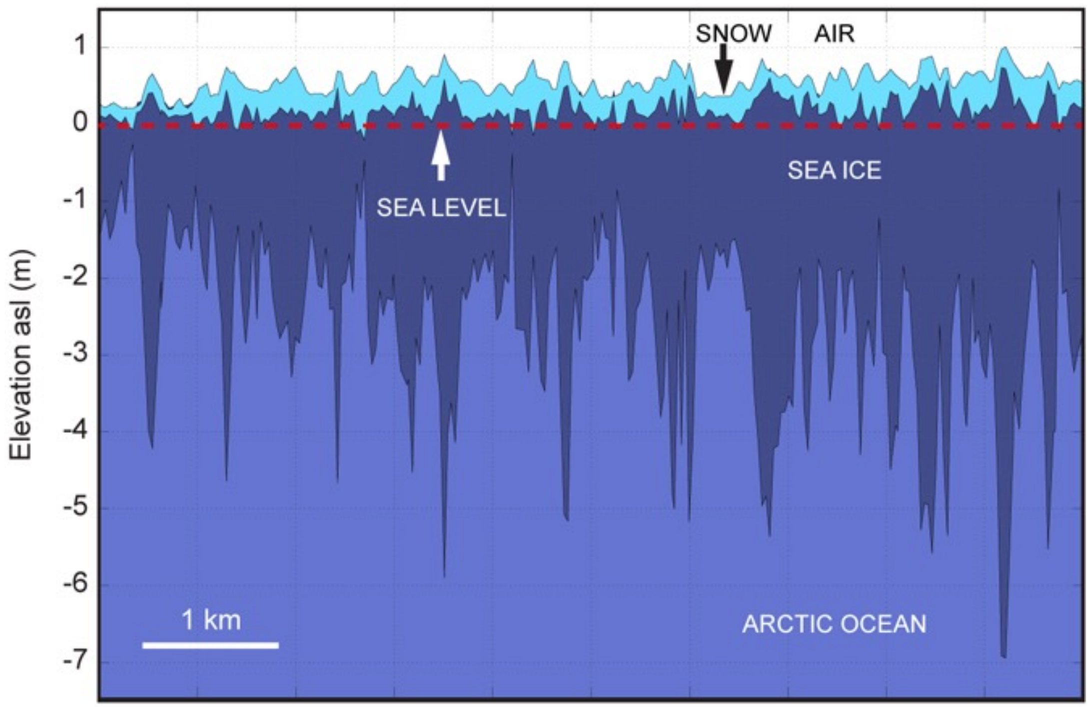
Arctic Basin Average SW flux (pond – nopond)



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

Ice Thickness Distribution

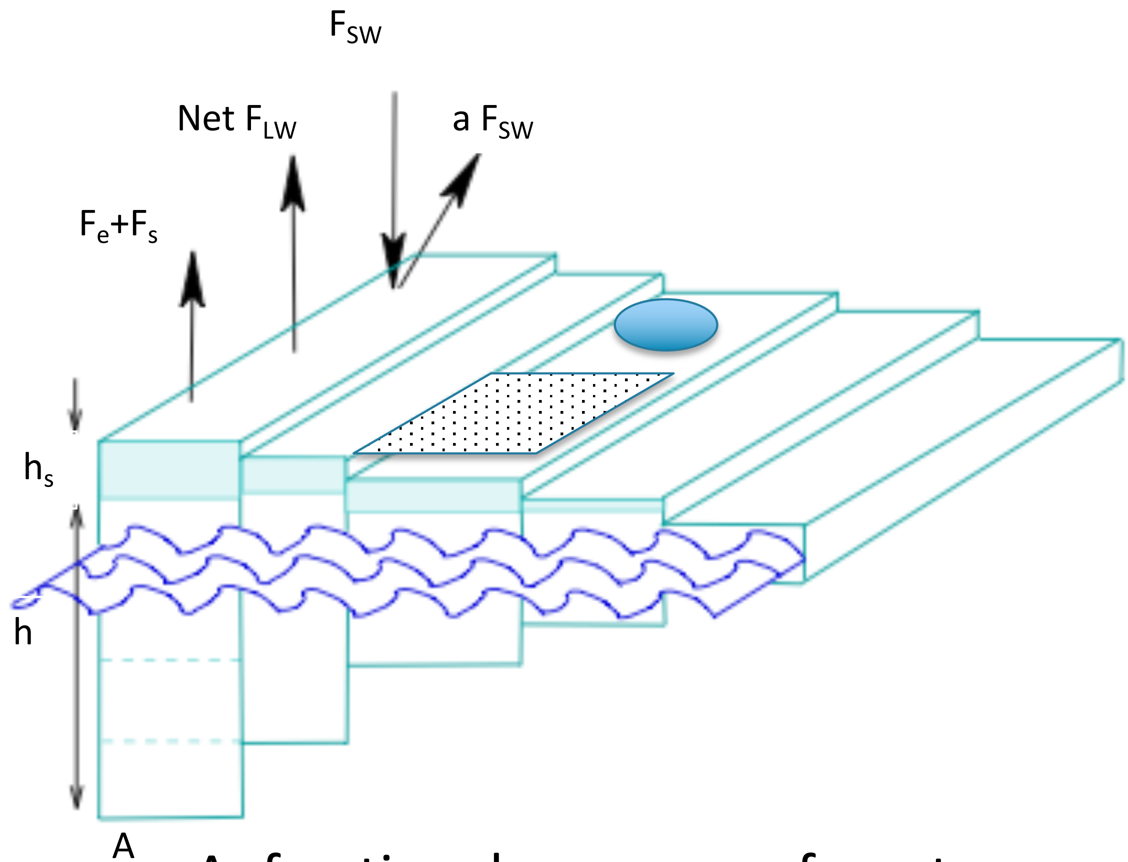
- Ice Thickness Distribution
  - Sub-gridscale parameterization
  - Accounts for high spatial heterogeneity in ice
  - Discreet probability density function



Ice Thickness Distribution

- Fluxes computed by category and merged based on fractional area.
- Keep track of tracers (e.g. snow depth) for each thickness category

- *Albedo example:*
  - 5 thickness categories
  - 3 surface types: bare ice, snow covered ice, ponded ice
  - 15 calculations per gridcell, merged based on area



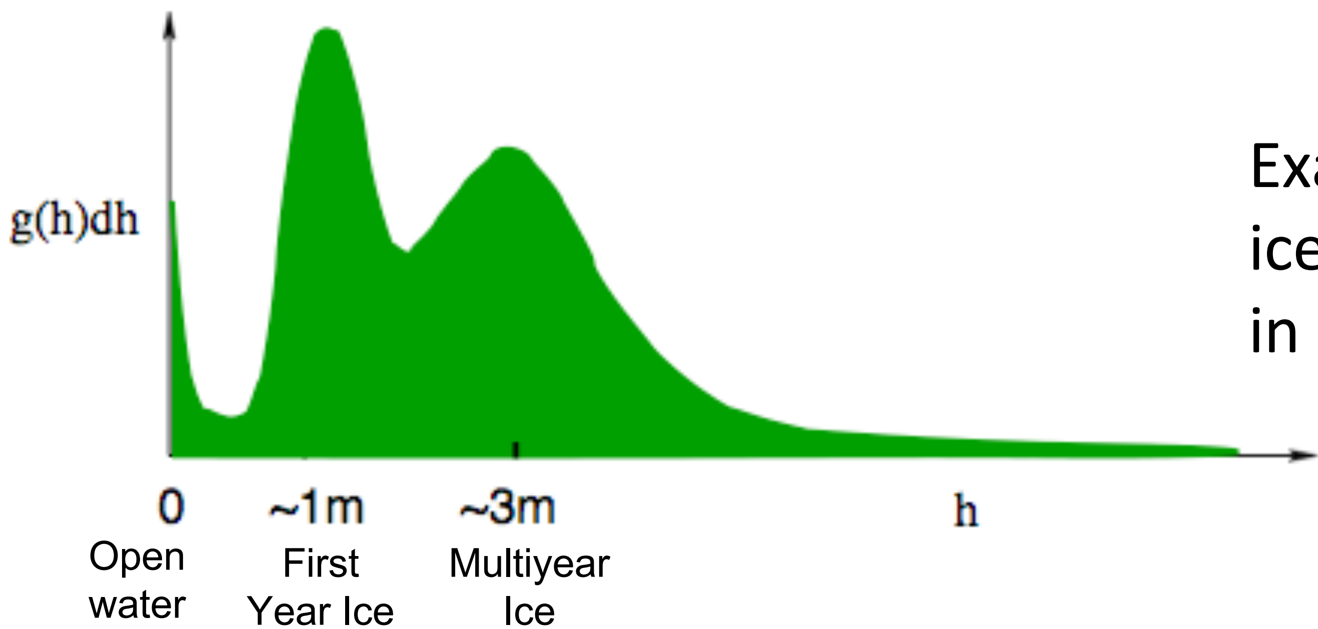
A=fractional coverage of a category

Ice Thickness Distribution

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

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

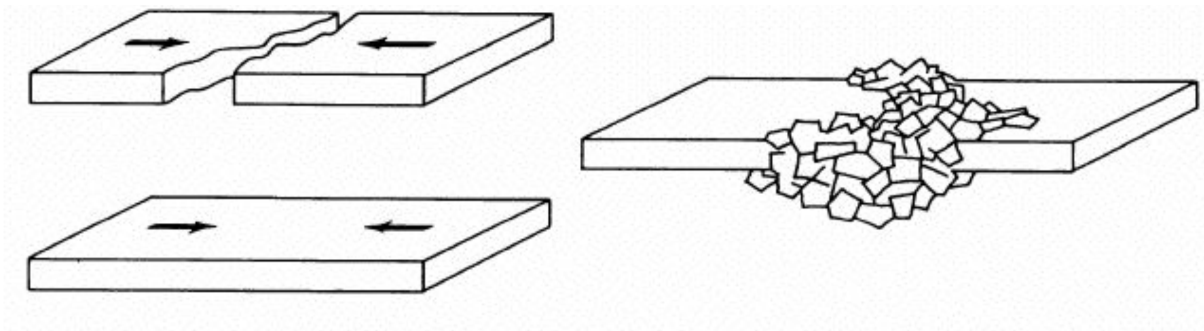
Ice Growth — Lateral Melt — Convergence — Mechanical Redistribution

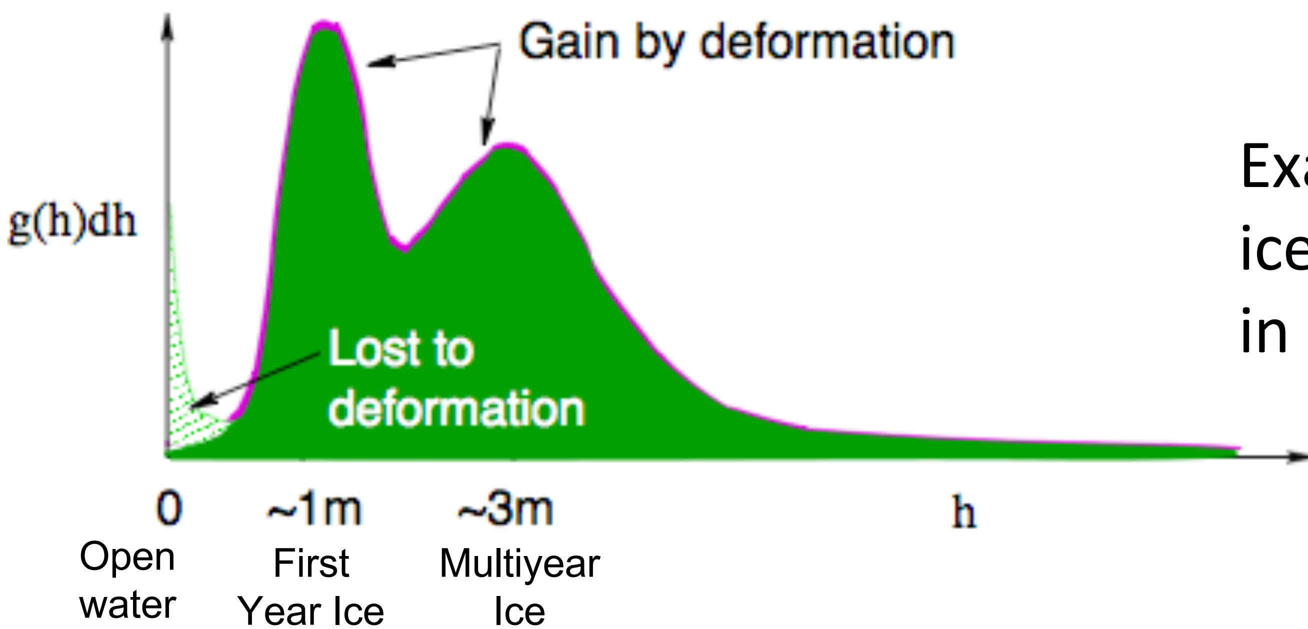


Example PDF of ice thickness (h) in a grid cell

Ice Thickness Distribution: impact of convergence

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

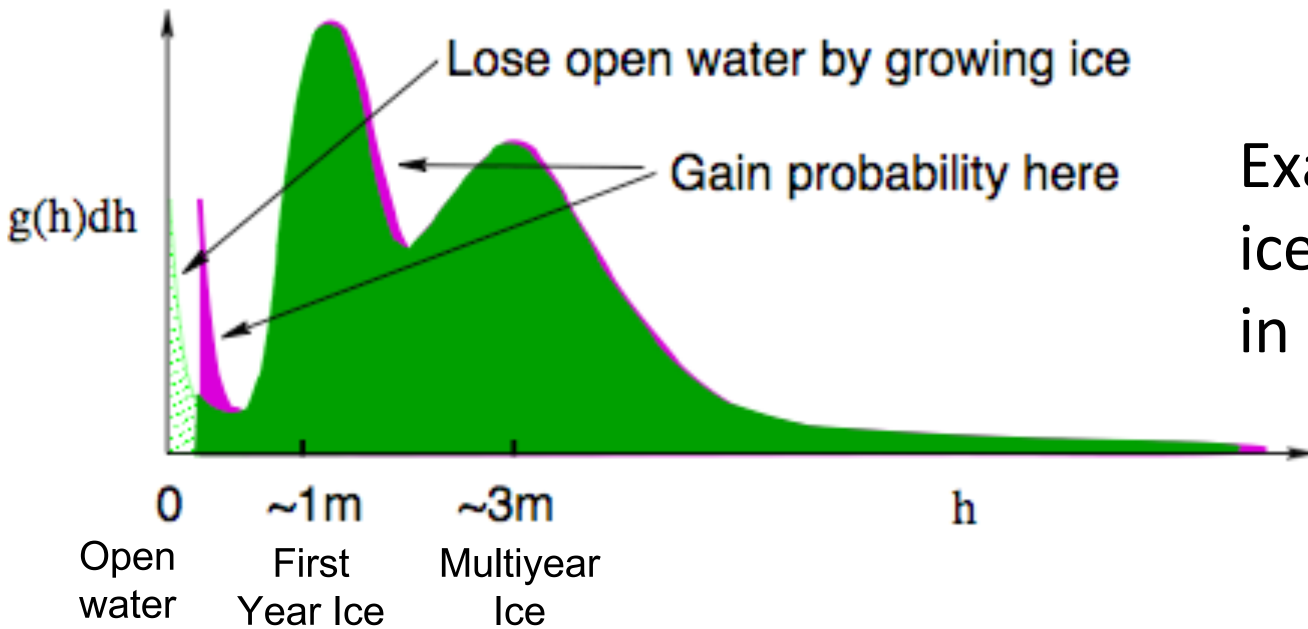




Example PDF of ice thickness (h) in a grid cell

Ice Thickness Distribution: impact of thermodynamic growth

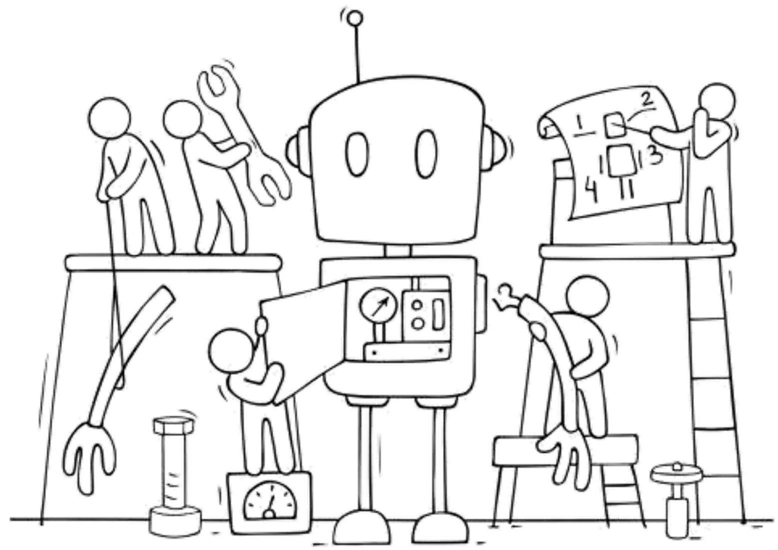
Lose open water, gain probability of both thin ice and thicker ice



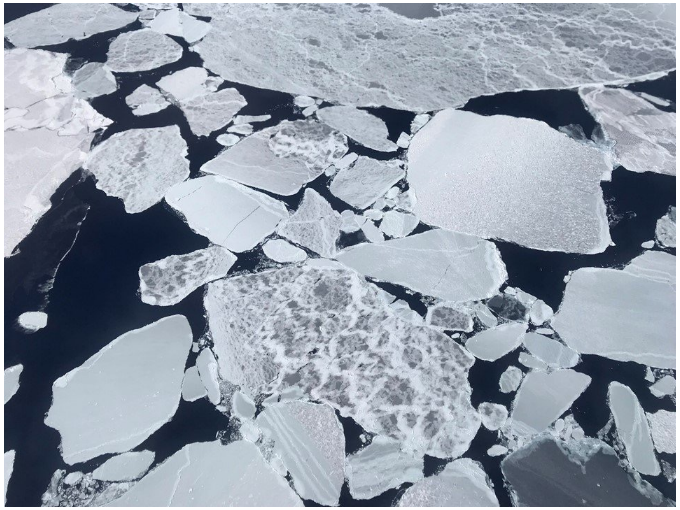
Example PDF of ice thickness (h) in a grid cell

Sea ice models: what will be in CESM3?

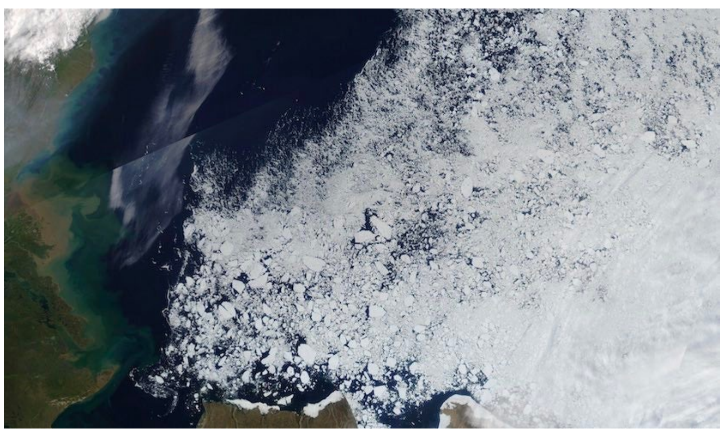
1. Dynamics
2. Thermodynamics
3. Ice thickness distribution
4. Floe size distribution
5. Updated parameterizations
   I. Melt ponds
   II. Snow



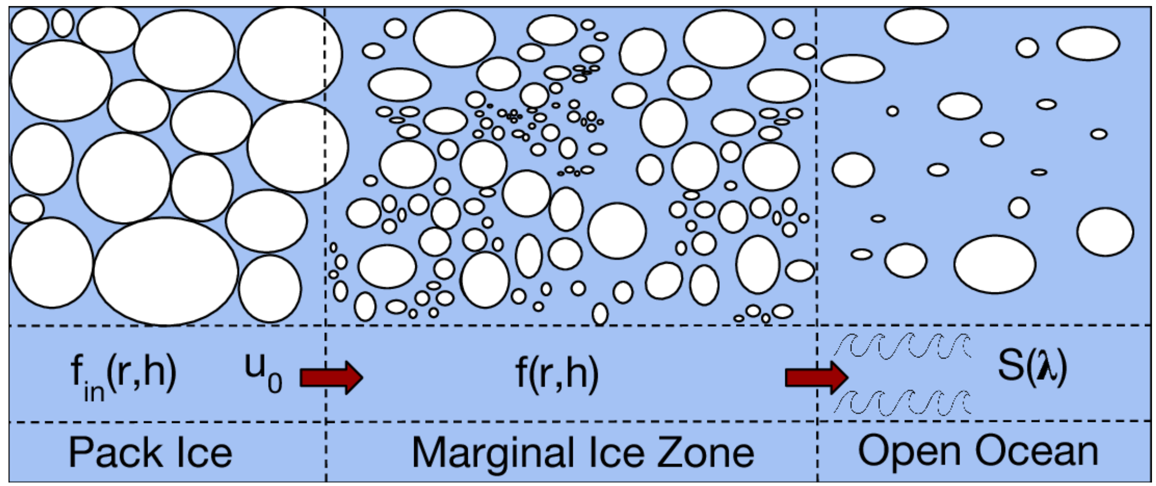
Floe Size Distribution



NASA Operation IceBridge (10/29/17)



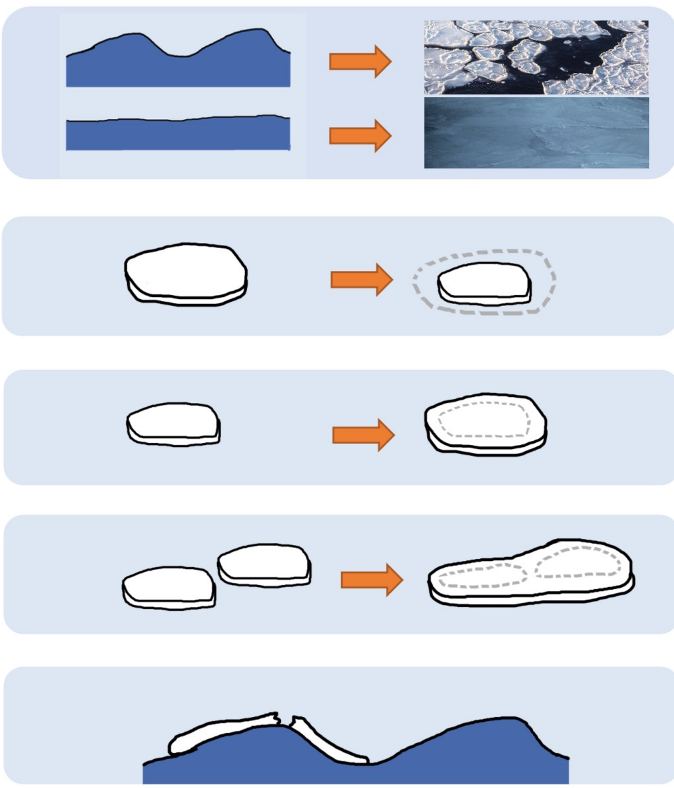
MODIS satellite (7/27/19)



Floe Size Distribution

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

$$\frac{\partial f(r,h)}{\partial t} = \underbrace{-\nabla \cdot (f(r,h)\mathbf{v})}_{\text{Advection}} + \overbrace{\mathcal{L}_T}^{\text{Thermodynamics}} + \underbrace{\mathcal{L}_M}_{\text{Mechanical Interactions}} + \overbrace{\mathcal{L}_W}^{\text{Fracture}}$$



Waves affect sea ice

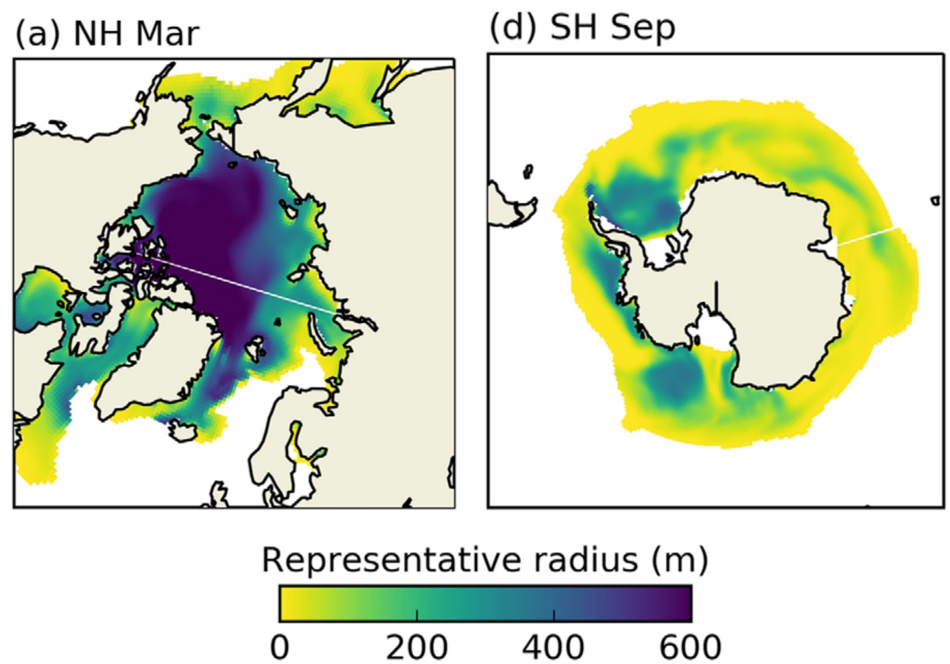
Floe thermodynamic melt & growth

Floe welding

Floe Fracture

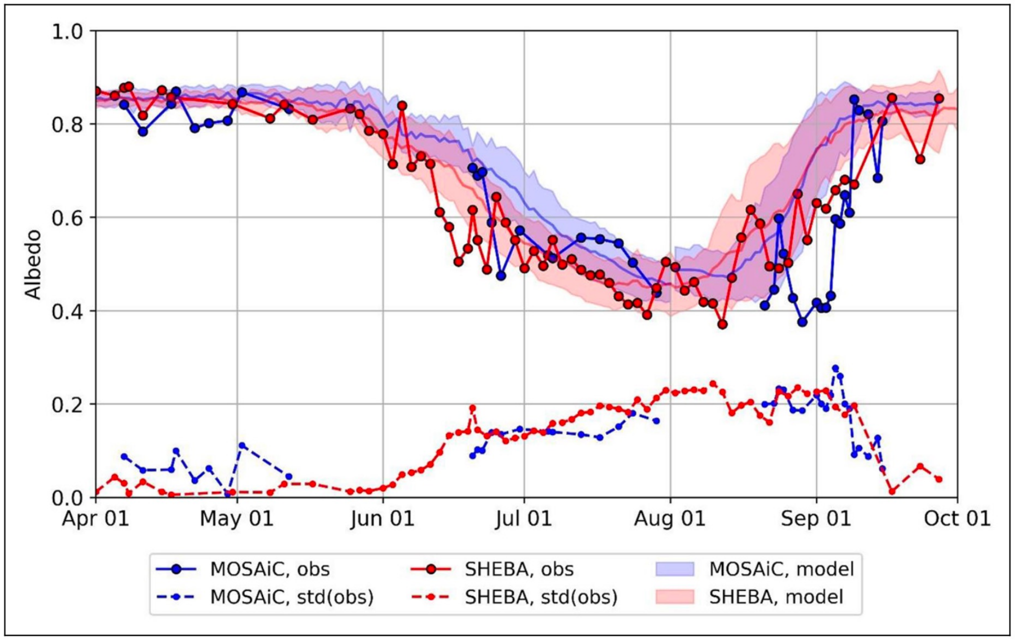
From: Roach et al. 2018

CESM3 testing



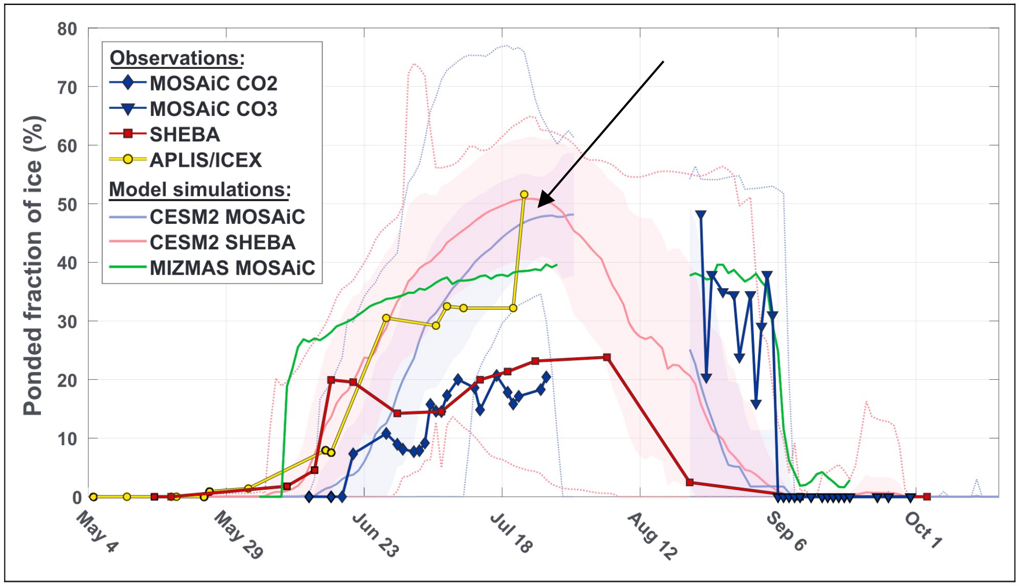
Melt Ponds

CESM2 albedo looks great!



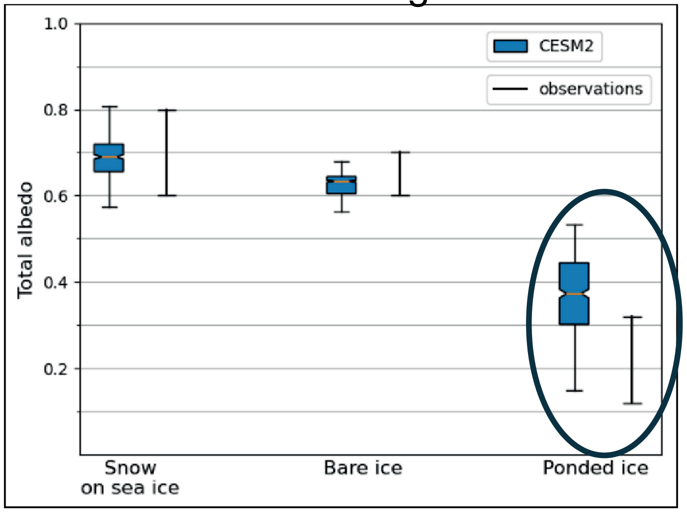
Light et al. 2022

Ponds are too extensive…



Webster et al. 2022

And too bright!

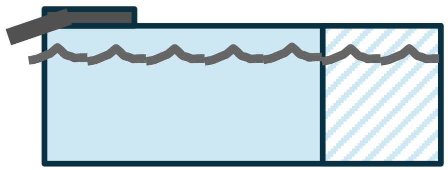


From: David Clemens-Sewell

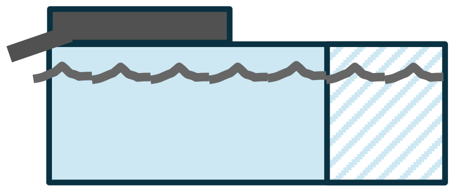
Melt Ponds

CICE: level ponds

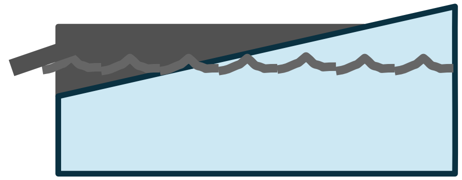
Ponds are perched above the ice surface and exponentially decay.



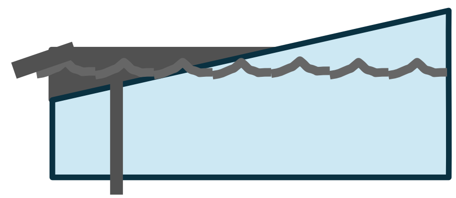
Pond area and depth grow by fixed ratio. Drainage only reduces depth.



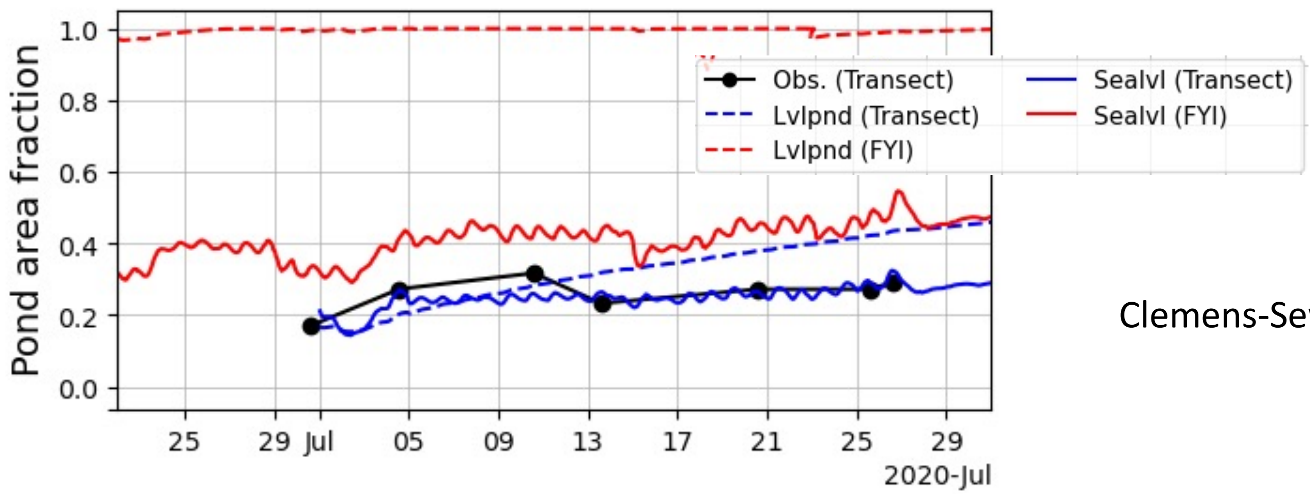
CICE: sealvl ponds (new)



Pond area, depth, and pressure head depend on linear hypsometry.



Drainage reduces both depth and area based on hypsometry.

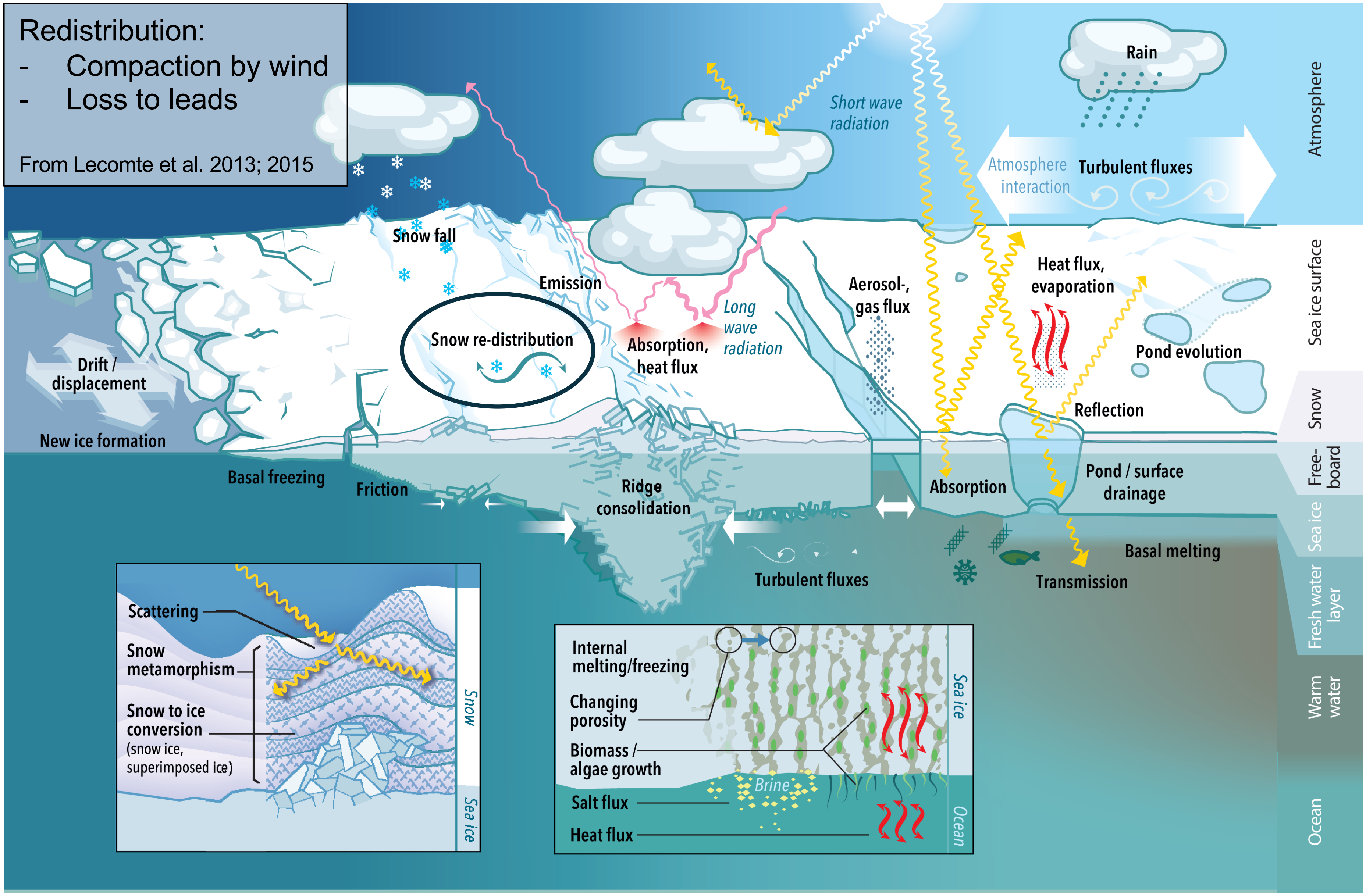


Clemens-Sewell, in prep.

Snow

Redistribution:
- Compaction by wind
- Loss to leads

From Lecomte et al. 2013; 2015



From: Nicolaus et al. 2022

Thank you! – Questions?

Please get in touch!

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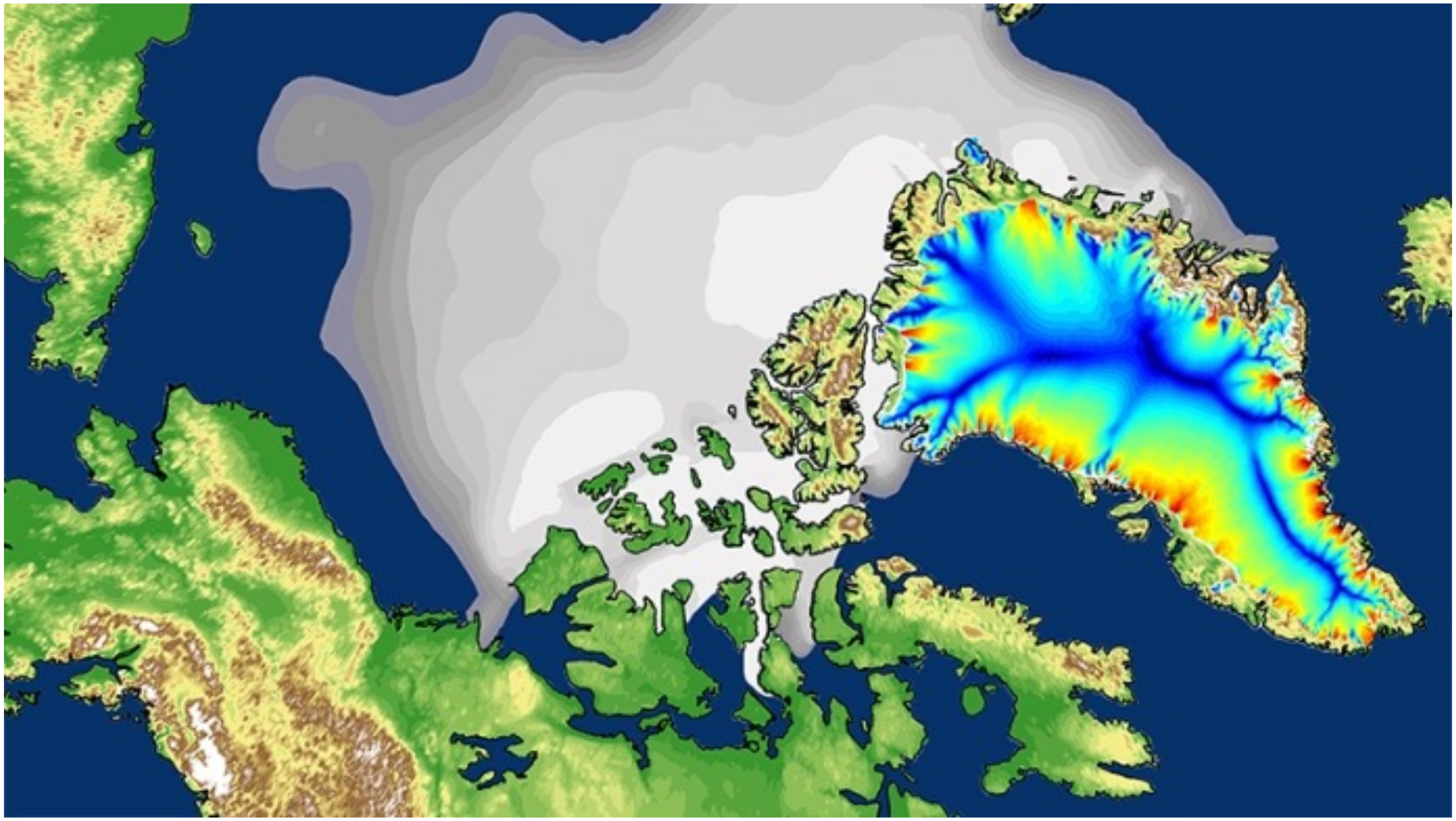
dbailey@ucar.edu

From: ChatGPT

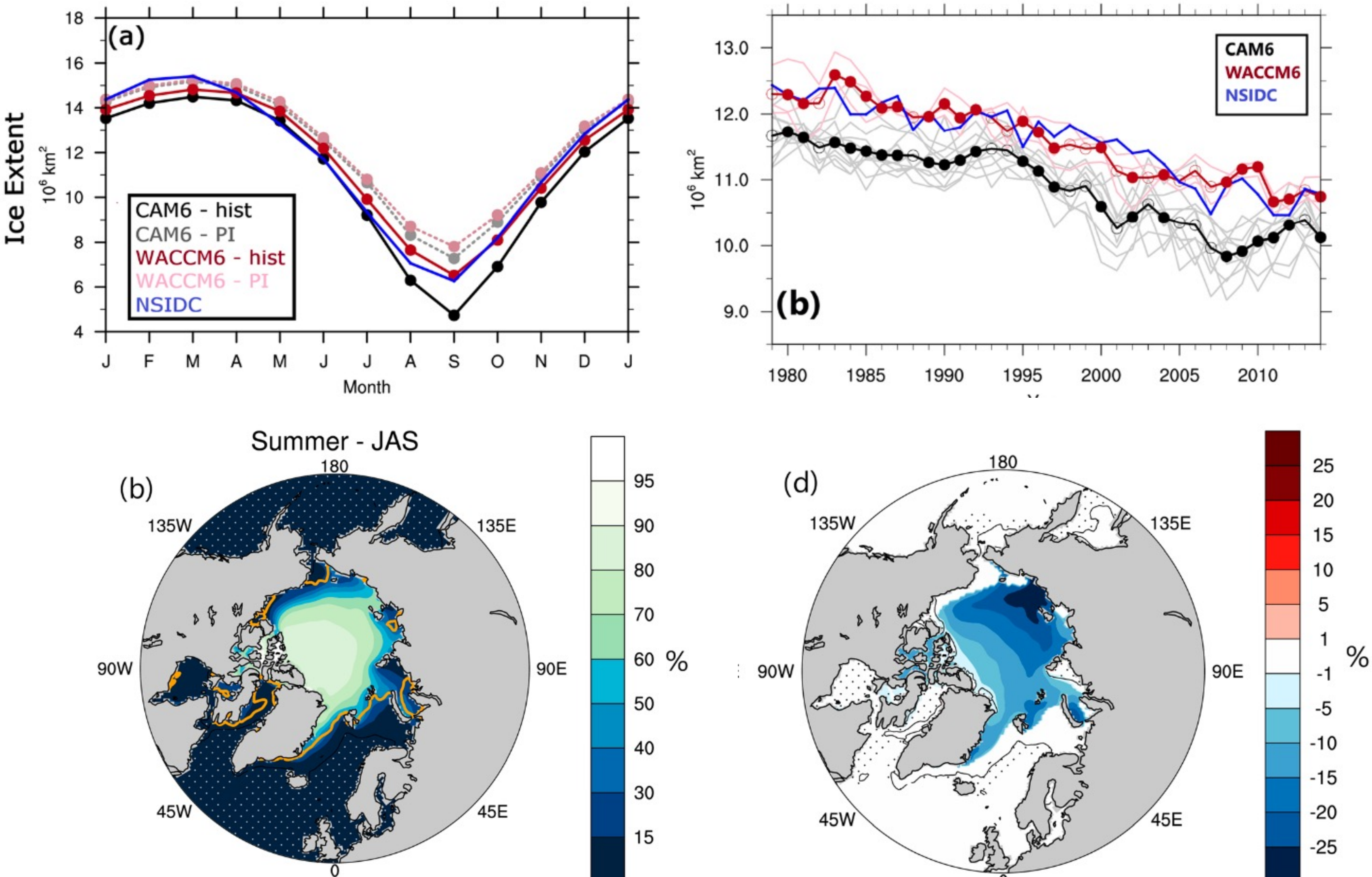
“Sea Ice party”

CESM2 Sea Ice Validation



The following slides provide some major results and references for polar climate and sea ice in the Arctic and Antarctic for CESM2.

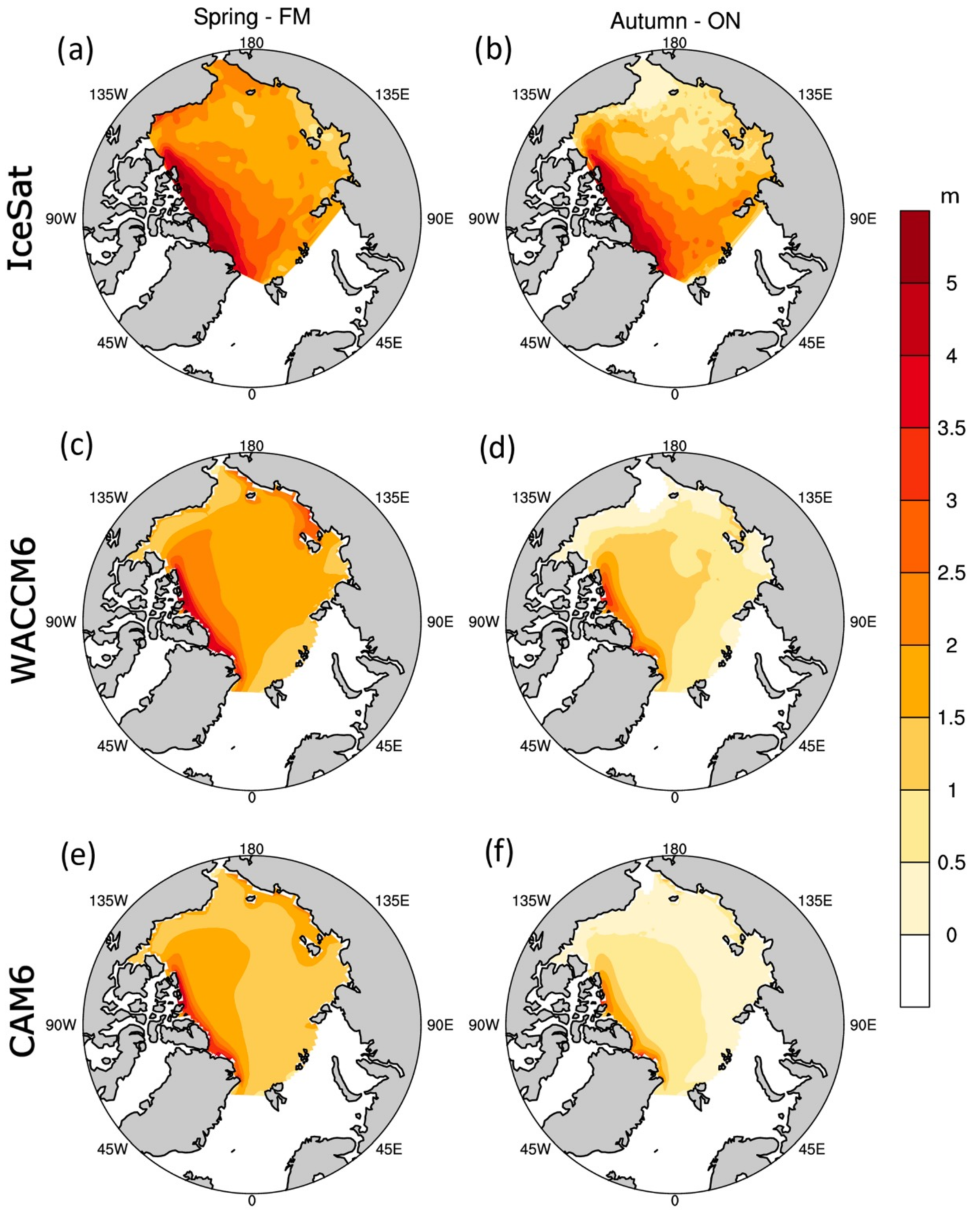
CESM2 Historical (1979-2014) Arctic Sea Ice Extent



DuVivier et al. 2020
https://doi.org/10.1029/2019JC015934

CESM2 with WACCM6 vs. CAM6 have different Arctic sea ice mean state due to treatment of aerosols. Antarctic impacts were minimal.

CESM2 Historical (2001-2005) Arctic Sea Ice Thickness

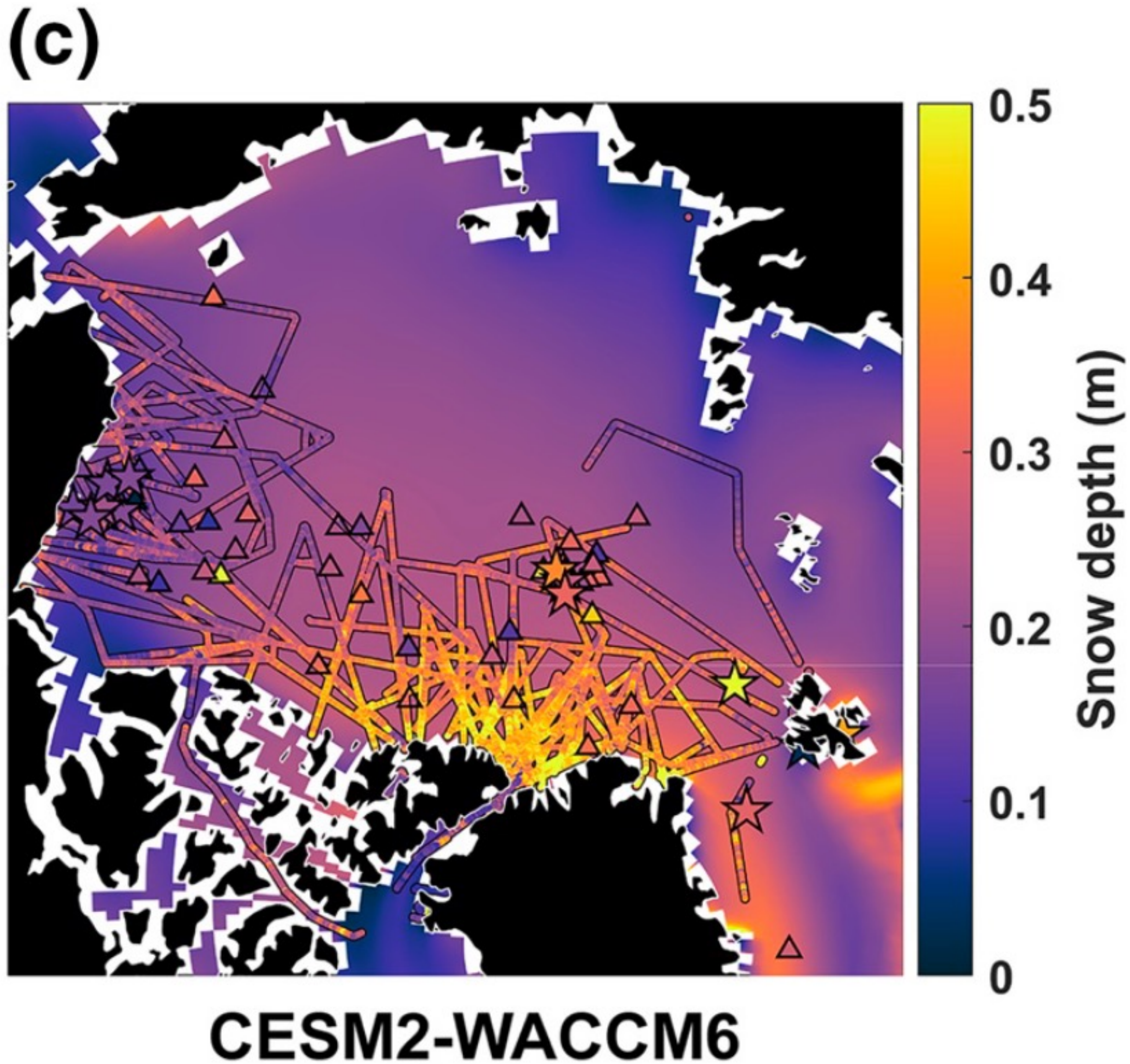


CESM2 with WACCM6 vs. CAM6 both have reasonable ice thickness distribution spatial patterns, but are too thin compared to observations from IceSat1

DuVivier et al. 2020

https://doi.org/10.1029/2019JC015934

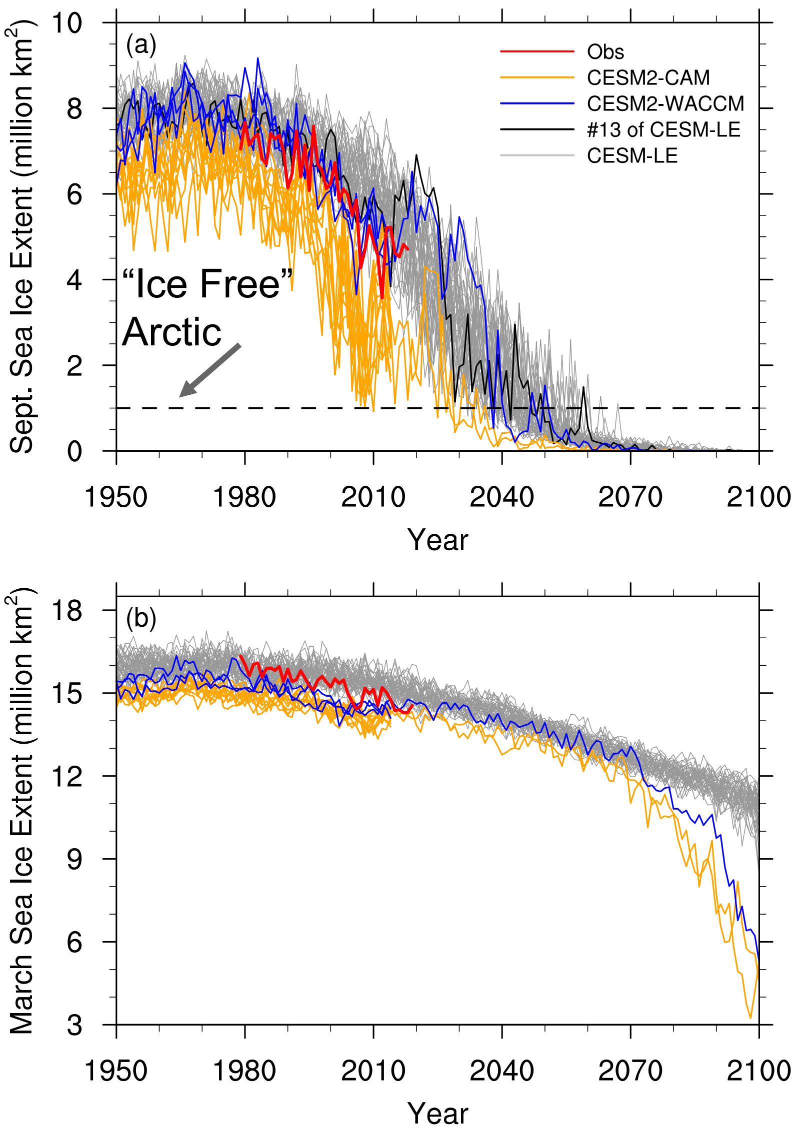
CESM2 Historical Arctic Sea Ice Snow

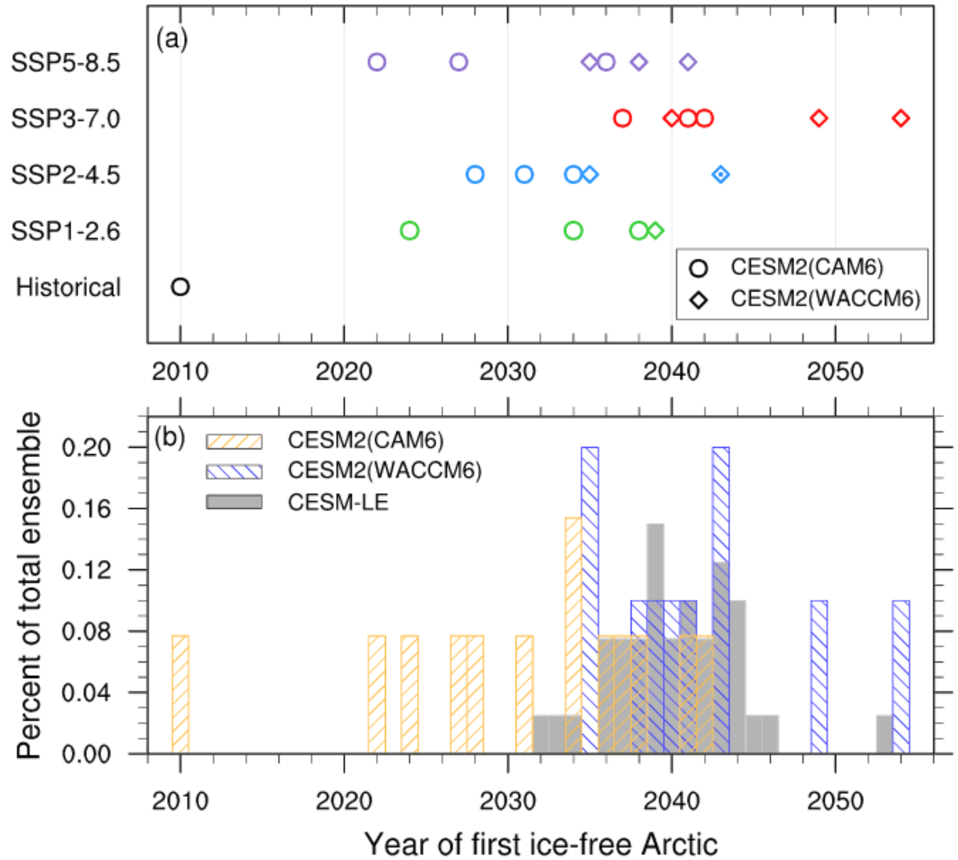


CESM2 with WACCM6 vs. CAM6 both have reasonable snow on sea ice thickness distributions, but snow depth is too little compared to NASA Operation IceBridge observations.

Webster et al. 2020
https://doi.org/10.1029/2020JC016308

CESM2 Arctic Sea Ice Extent Projections

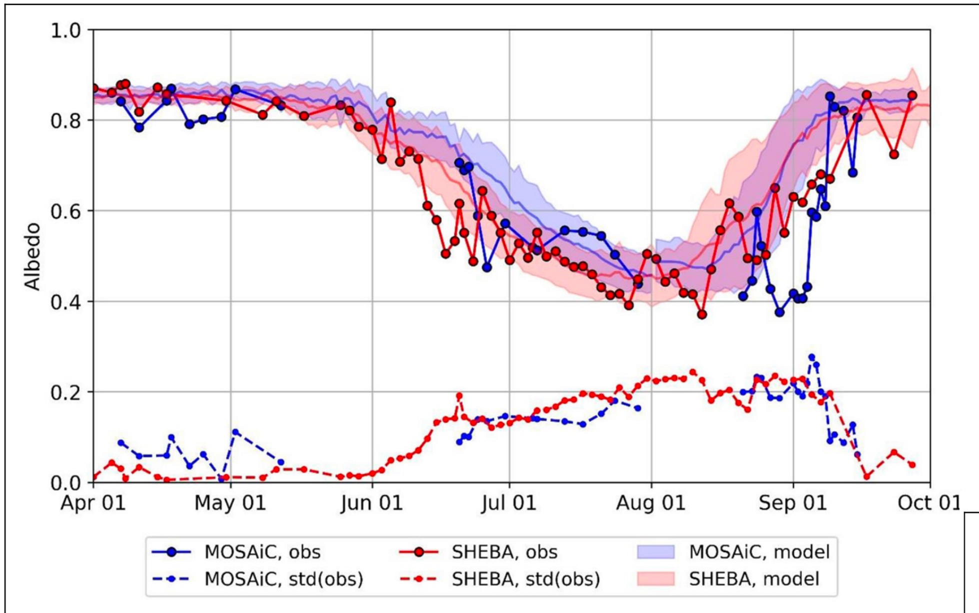




CESM2 with WACCM6 vs. CAM6 have similar ice-free dates and these are independent of scenario.

DeRepentigny et al. 2022
https://doi.org/10.1126/sciadv.abo2405

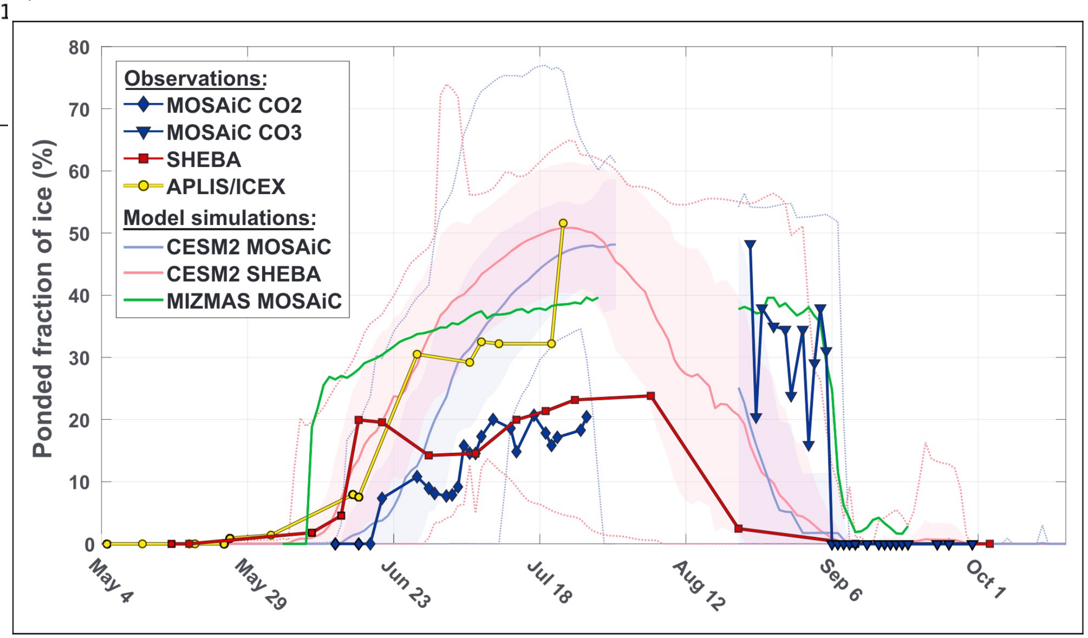
CESM2 Arctic Sea Ice – Melt ponds



Light et al. 2022
https://doi.org/10.1525/elementa.2021.000103

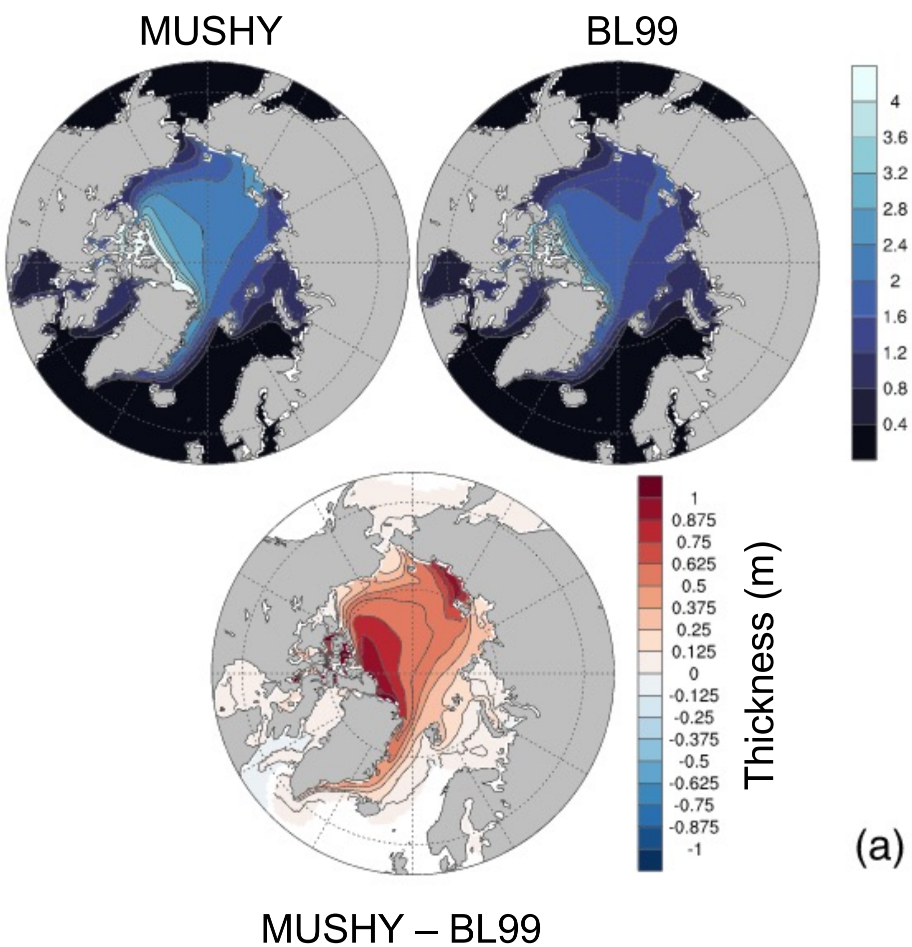
CESM2 Ponds are too extensive, but not deep enough.

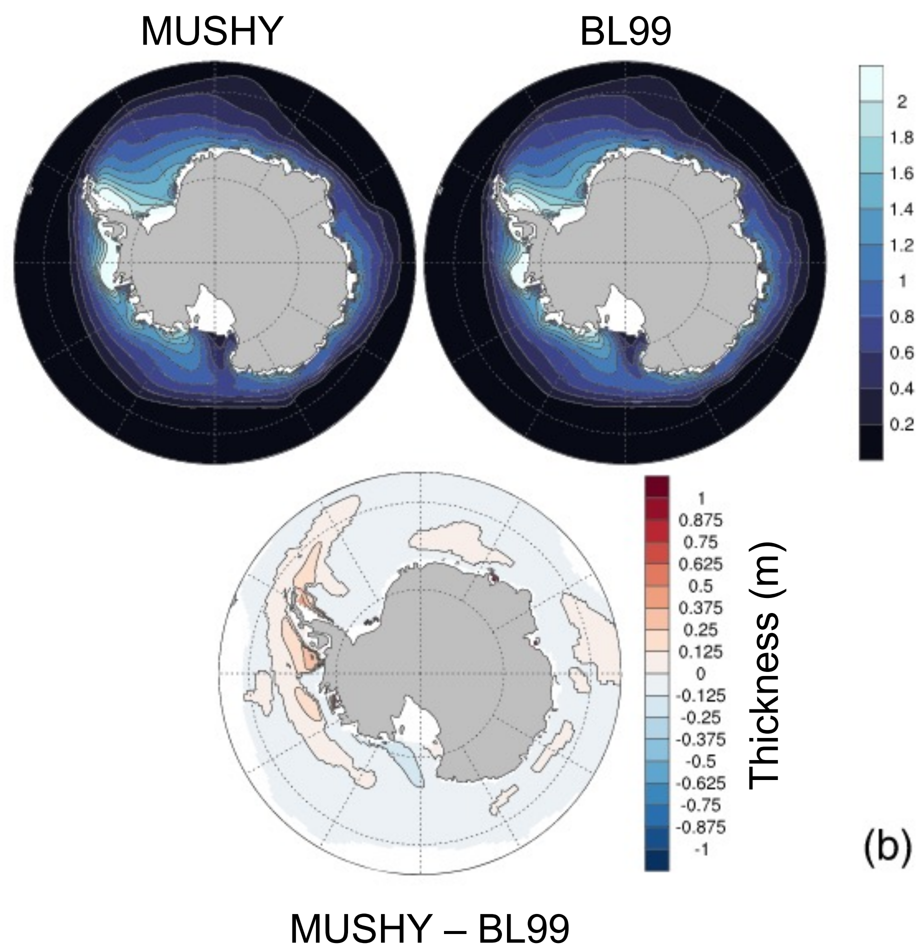
→ Compensating biases lead to reasonable albedo.



Webster et al. 2022
https://doi.org/10.1525/elementa.2021.000072

CESM2 – Mushy thermodynamics

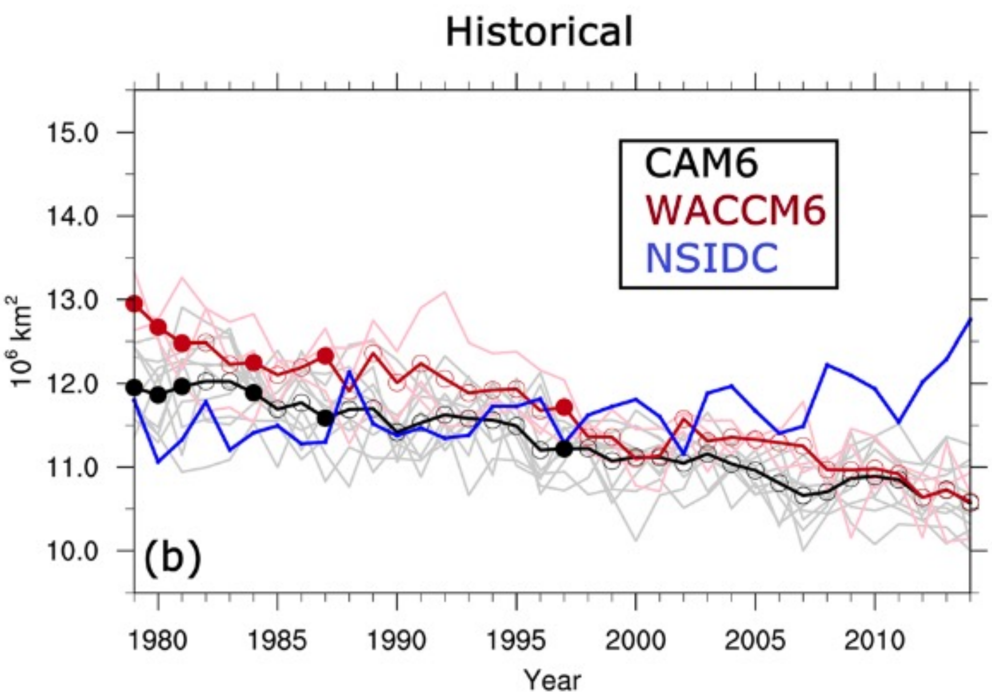




CESM2 tested with MUSHY (new) and BL99 thermodynamics shows that MUSHY leads to thicker and more extensive sea ice. Impacts are larger in the Arctic.

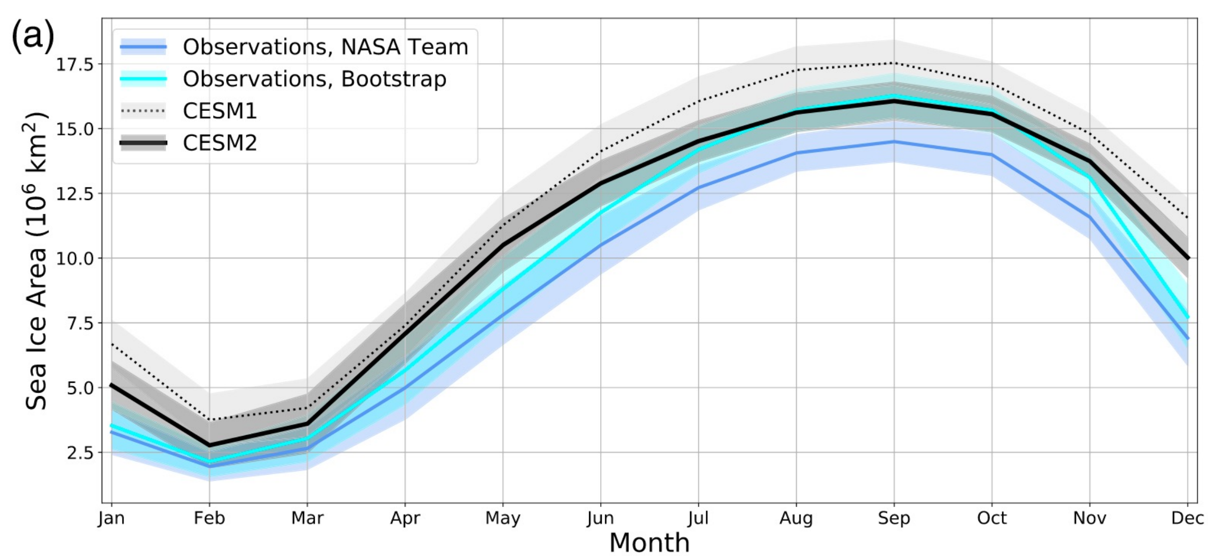
Bailey et al. 20220
https://doi.org/10.1029/2020MS002154

CESM2 Antarctic Sea Ice



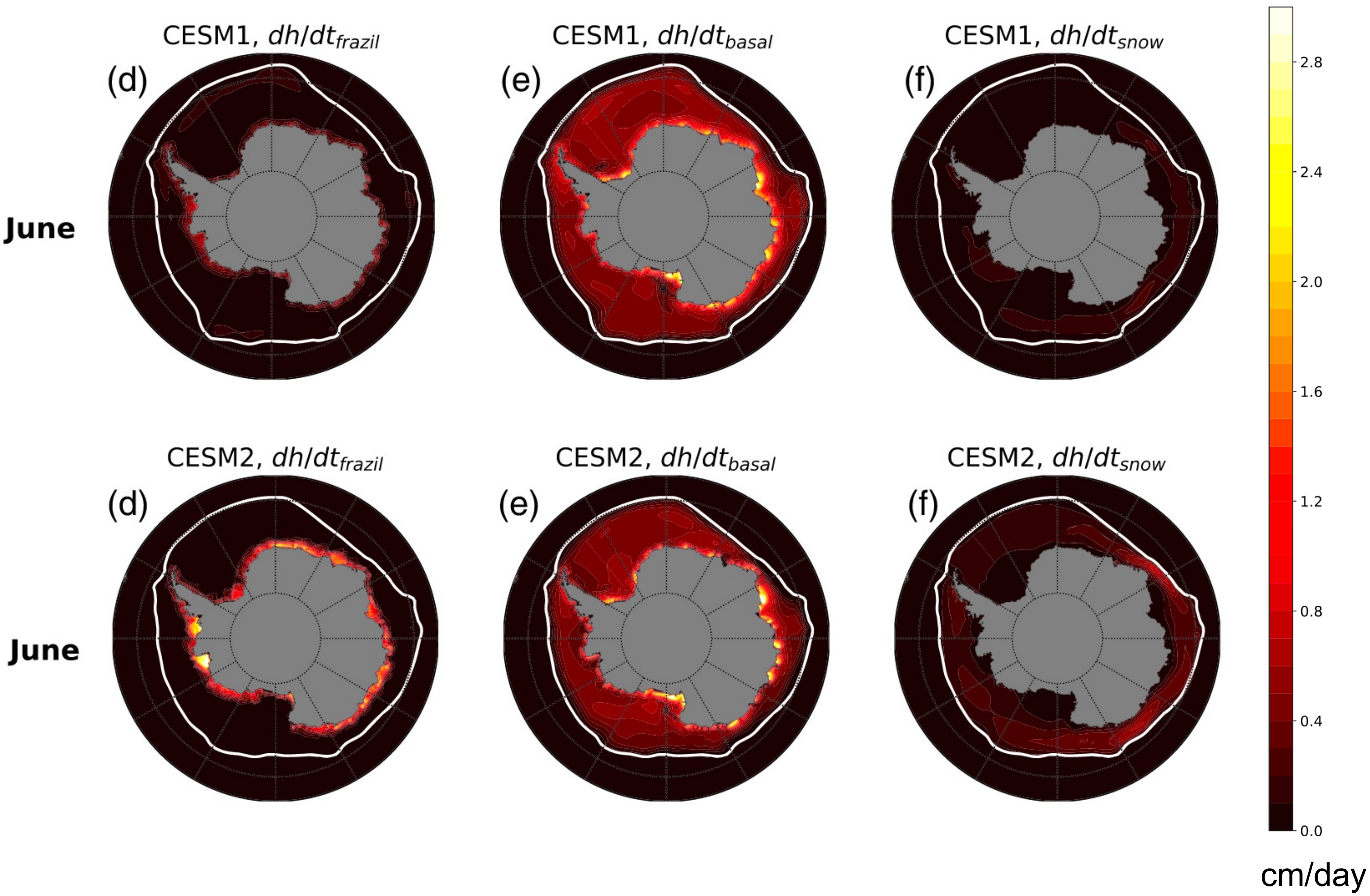
CESM2 mean Antarctic state is

DuVivier et al. 2020
https://doi.org/10.1029/2019JC015934



Singh et al. 2020
https://doi.org/10.1029/2020MS002143

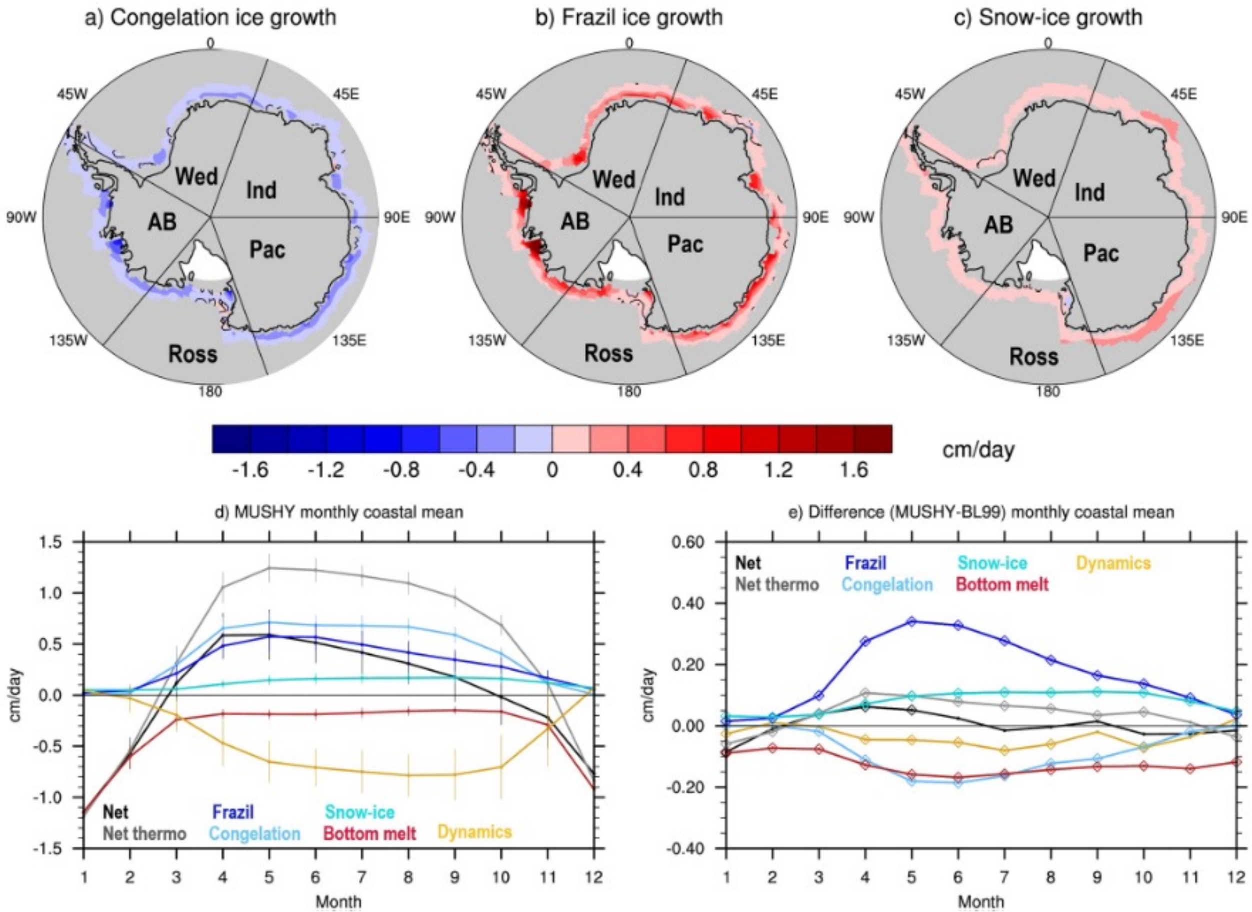
CESM2 Antarctic Sea Ice – growth processes are changing



CESM2 mass budget has shifted – growth along the coast is more frazil dominated and there is more snow ice formation.

Singh et al. 2020
https://doi.org/10.1029/2020MS002143

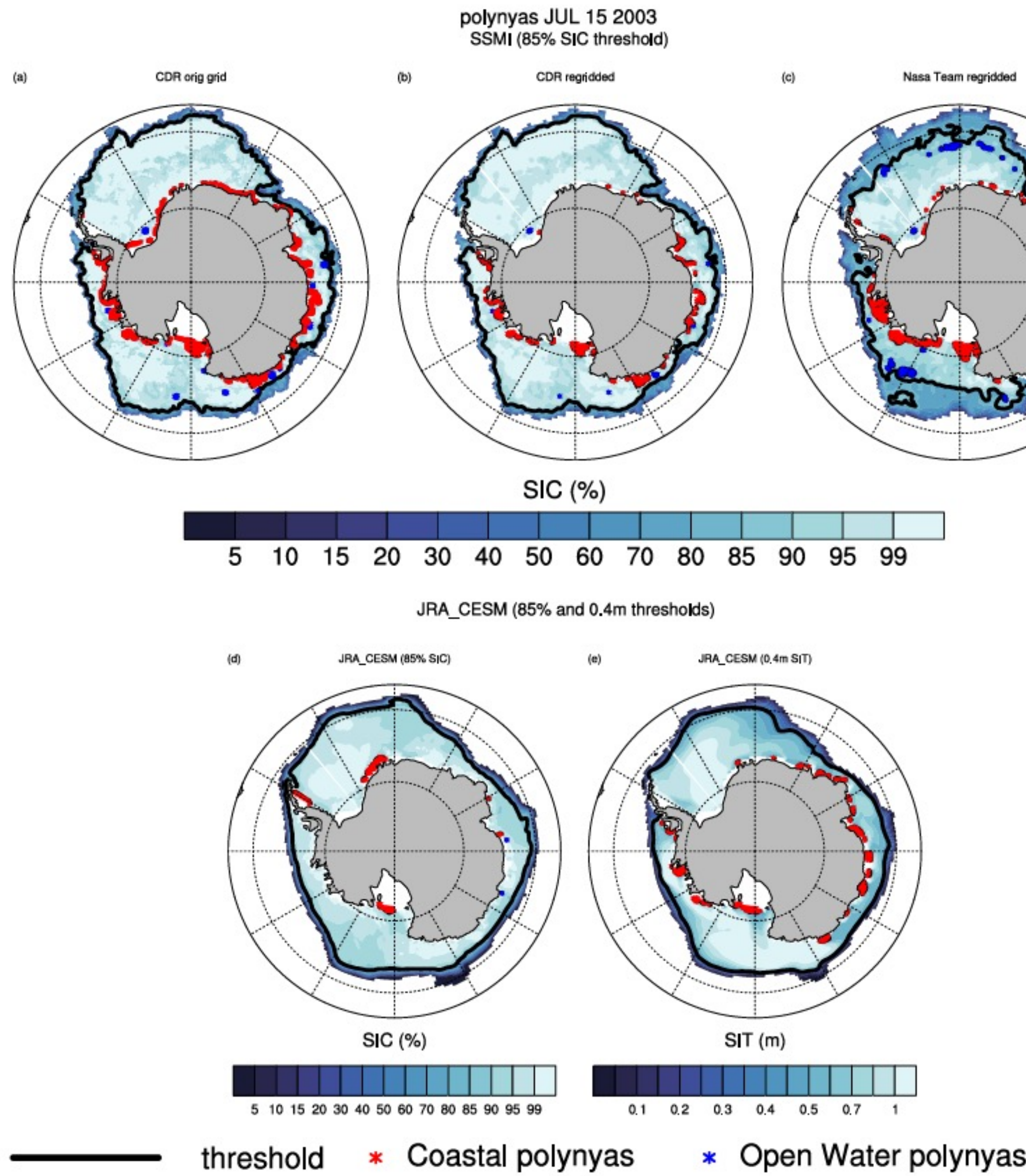
CESM2 Antarctic Sea Ice – growth processes are changing



CESM2 mass budget has shifted due to MUSHY (new) thermodynamics parameterization. These process shifts do not lead to significant mean state differences. There are impacts on the AABW formation rates though.

DuVivier et al. 2021
https://doi.org/10.1029/2021GL094287

CESM2 – Polynyas



CESM2 captures Antarctic polynyas in similar locations as observed, but the choice of threshold variable (concentration vs. thickness) is significant on the results and should be carefully assessed.

Landrum et al. 2025
https://doi.org/10.5194/egusphere-2024-3490