

Sea Ice Modeling in the CESM

CESM 2026 Tutorial

David Clemens-Sewall (David.Clemens-Sewall@colorado.edu)

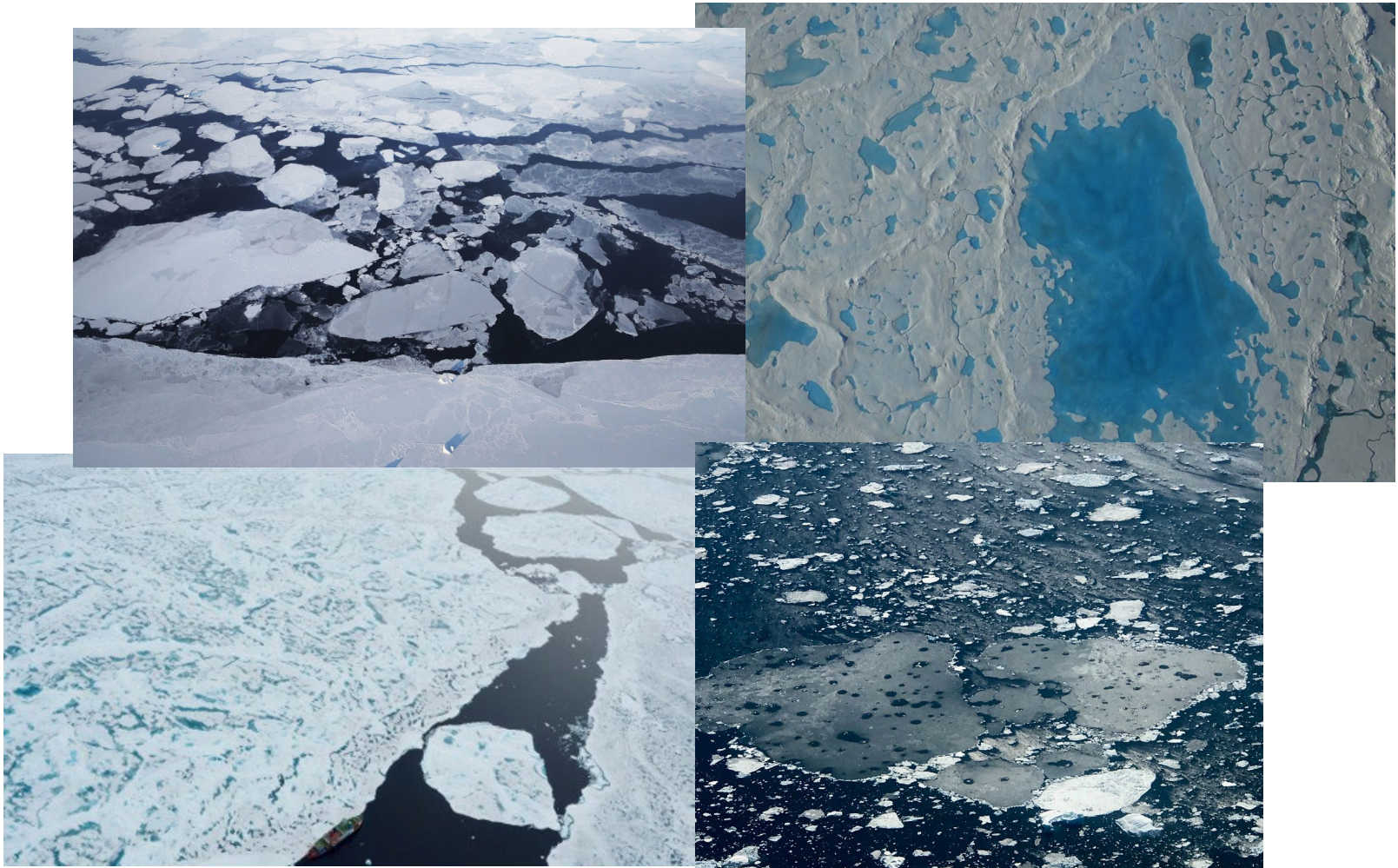
Adapted from slides by Alice DuVivier (NCAR) with contributions from:

David Bailey (NCAR), Marika Holland (NCAR)

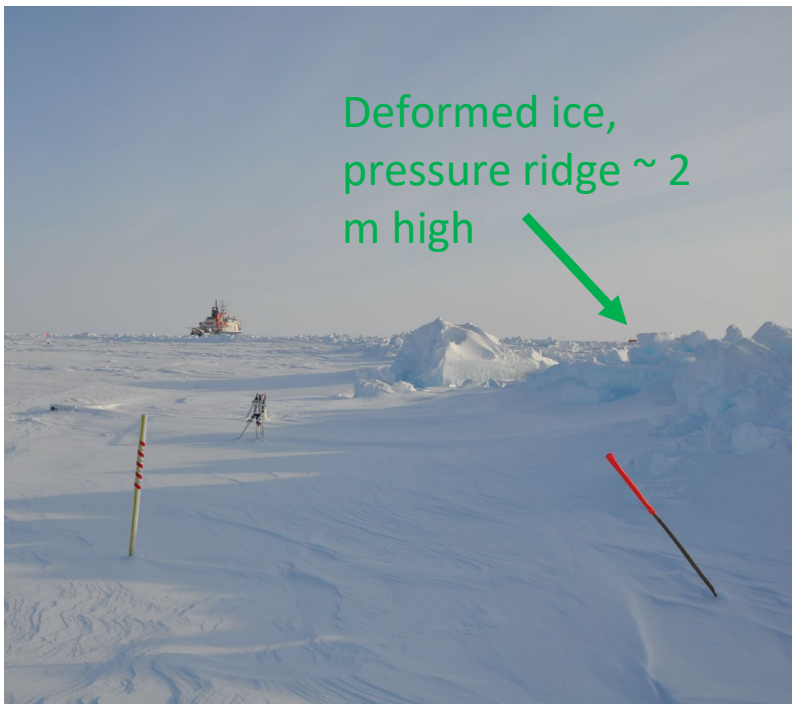
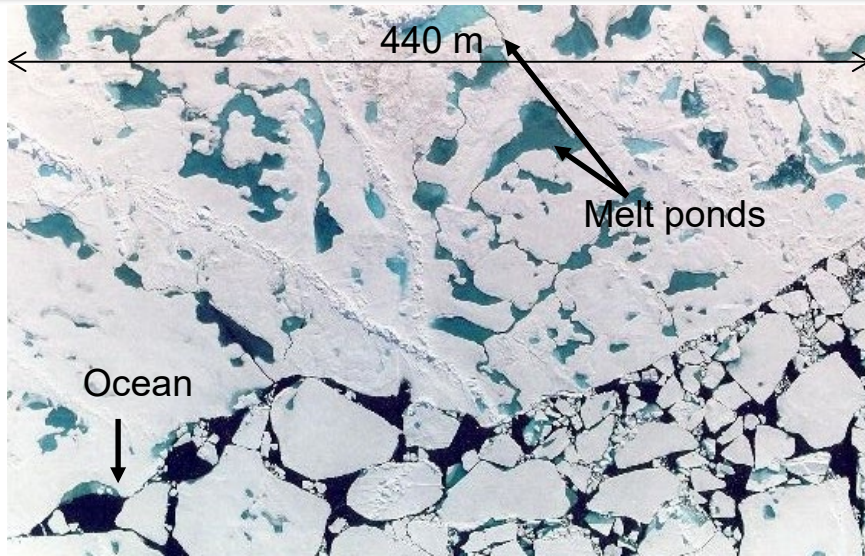
+ the Polar Climate Working Group

What is Sea Ice?

Sea Ice is frozen sea water



Sea ice Cover



- 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

Photos: D. Perovich, C. Rohleder, D. Clemens-Sewall

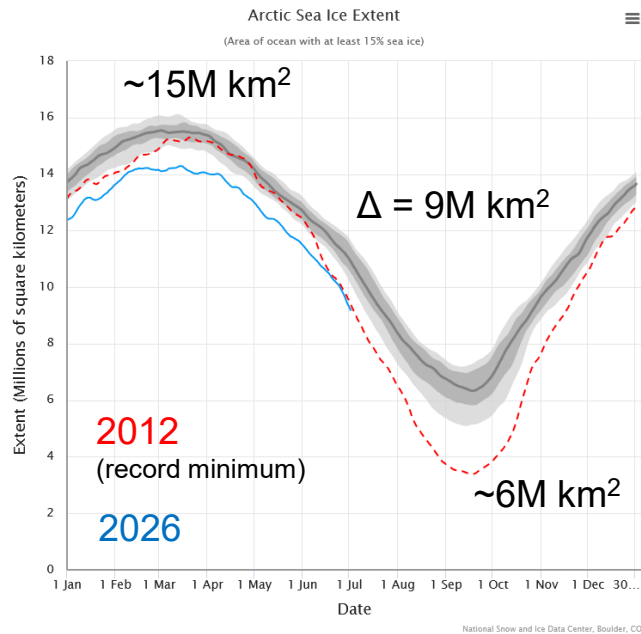
Sea Ice in CESM



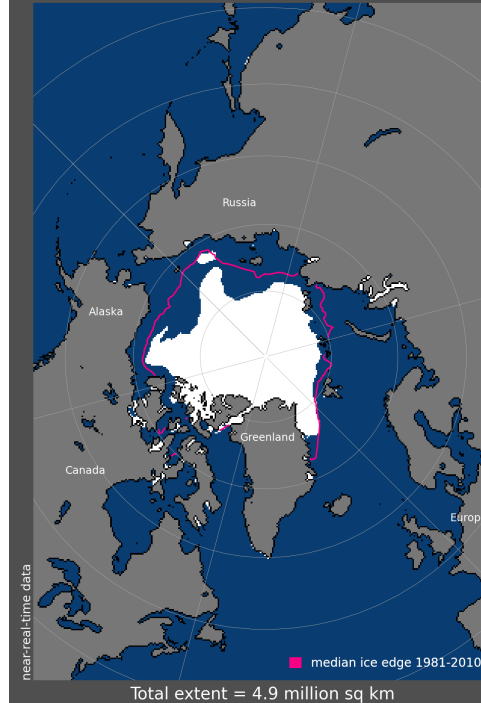
Arctic vs. Antarctic

September (minimum)

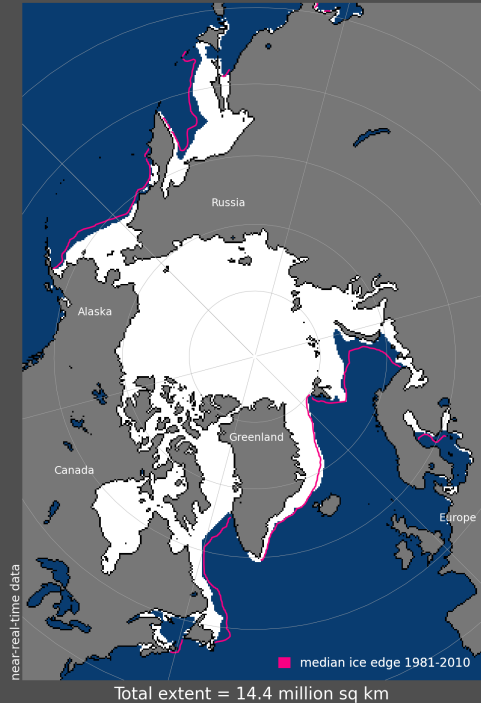
March (maximum)



Sea Ice Extent, Sep 2022



Sea Ice Extent, Mar 2023

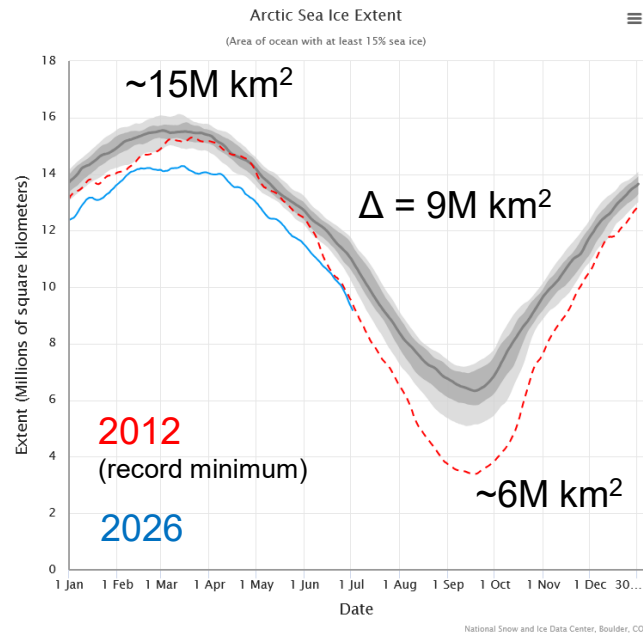


- Ocean bounded by land
→ ice converges at land, thick!
- Land boundaries & ocean heat (e.g., Gulf Stream) determine winter extent

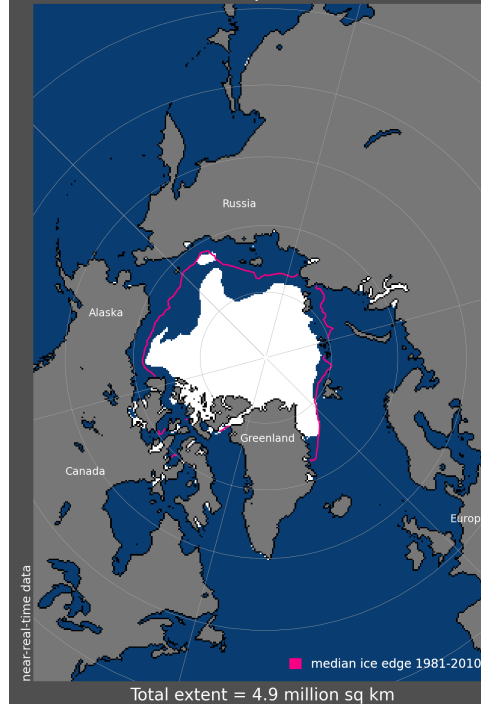
Arctic vs. Antarctic

September (minimum)

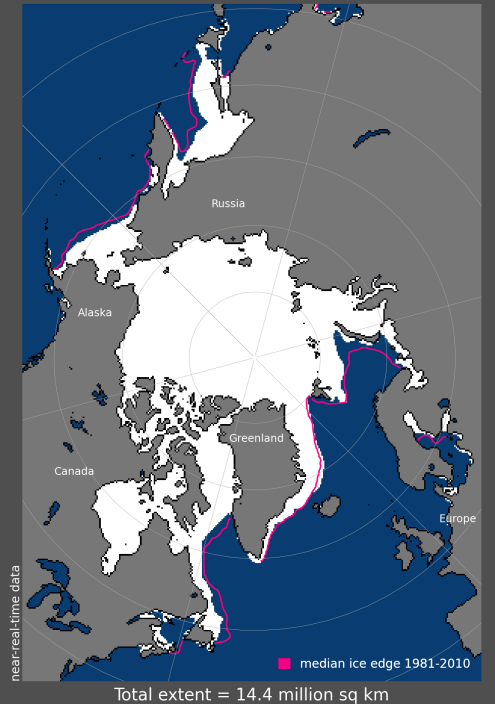
March (maximum)



Sea Ice Extent, Sep 2022



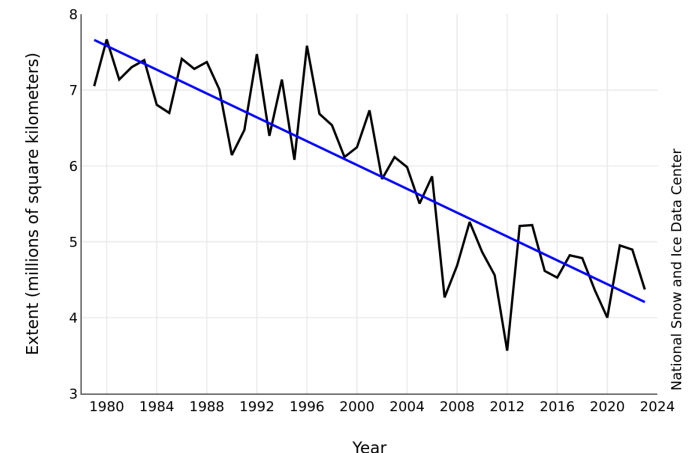
Sea Ice Extent, Mar 2023



- Ocean bounded by land
→ ice converges at land, thick!
- Land boundaries & ocean heat (e.g., Gulf Stream) determine winter extent



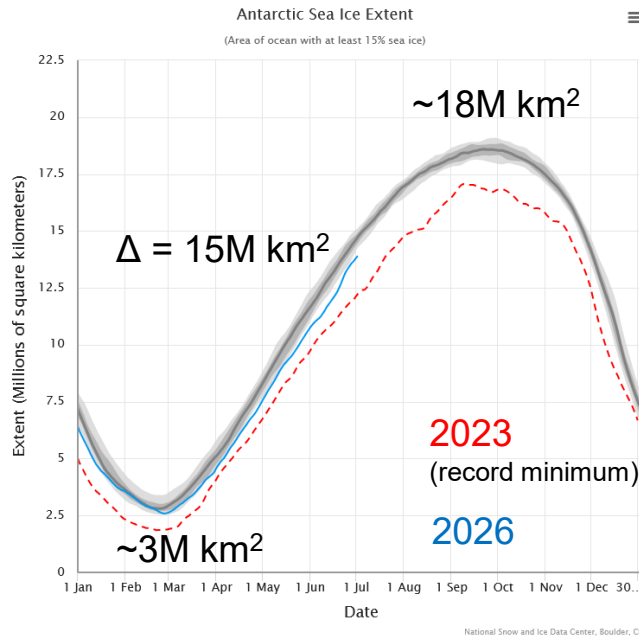
Average Monthly Arctic Sea Ice Extent
September 1979 - 2023



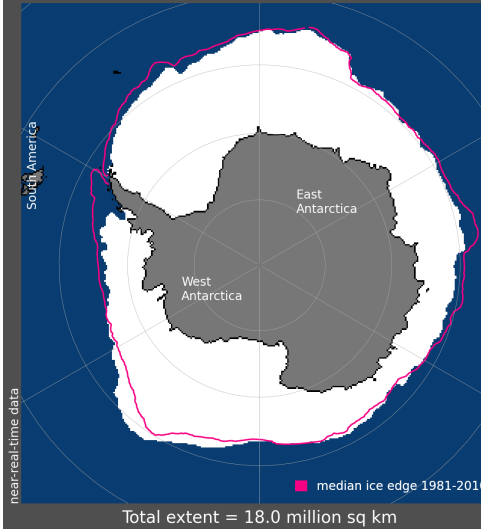
Arctic vs. Antarctic

September (Maximum)

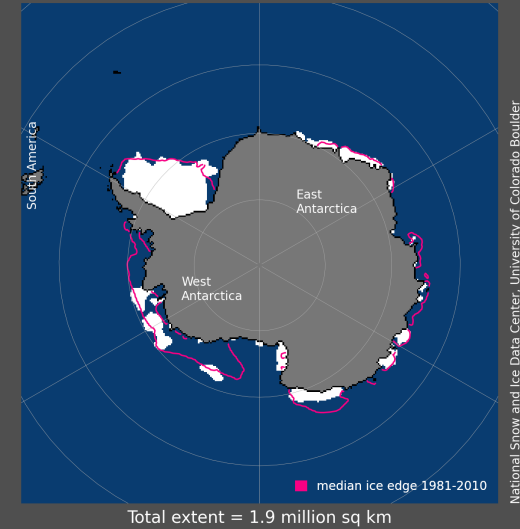
March (minimum)



Sea Ice Extent, Sep 2022

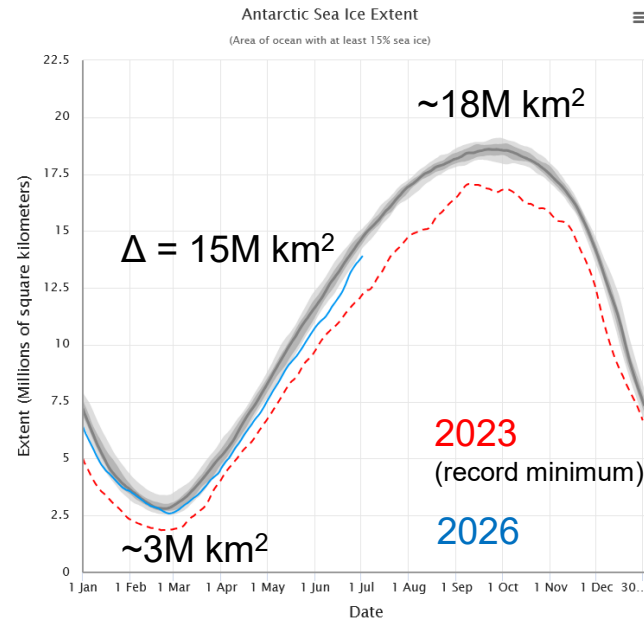


Sea Ice Extent, Feb 2023



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

Arctic vs. Antarctic



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

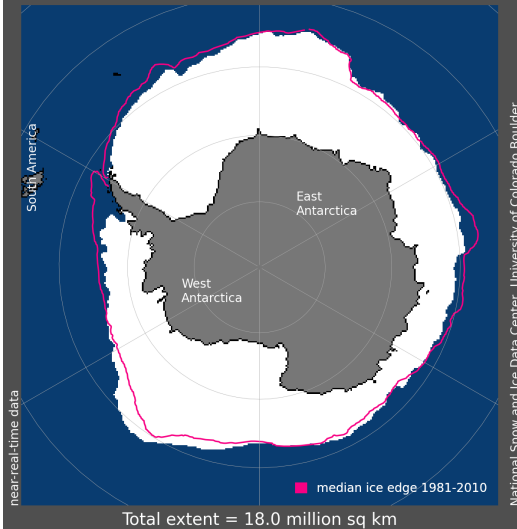


NCAR
UCAR

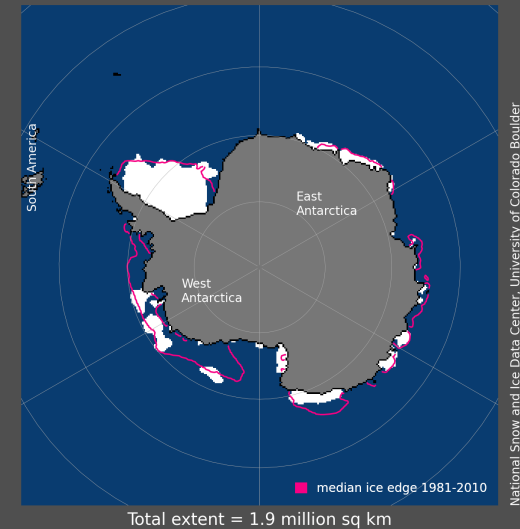
September (Maximum)

March (minimum)

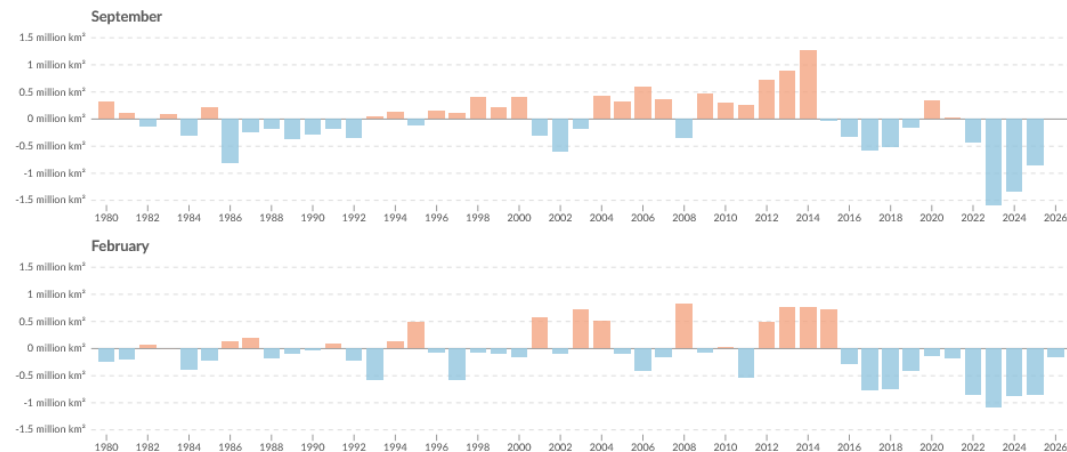
Sea Ice Extent, Sep 2022



Sea Ice Extent, Feb 2023

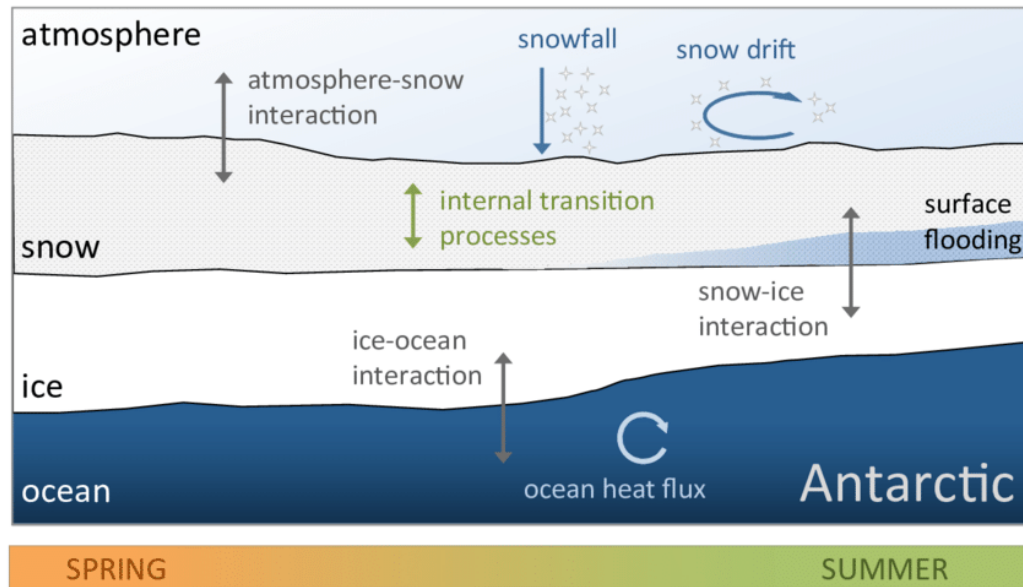
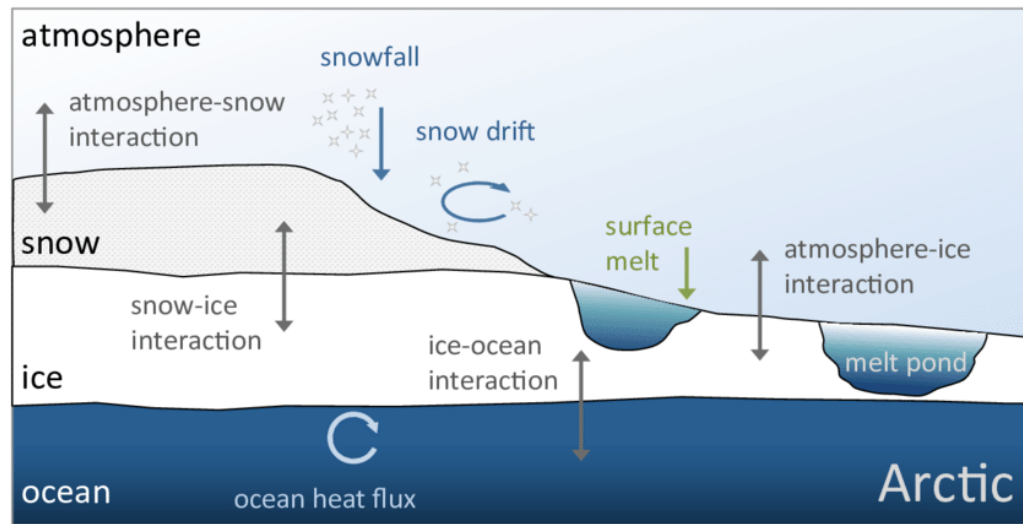


Anomaly relative to 1980-2010



National Snow and Ice Data Center - Sea Ice Index (2026) – with minor processing by Our World in Data

Arctic vs. Antarctic – seasonal evolution

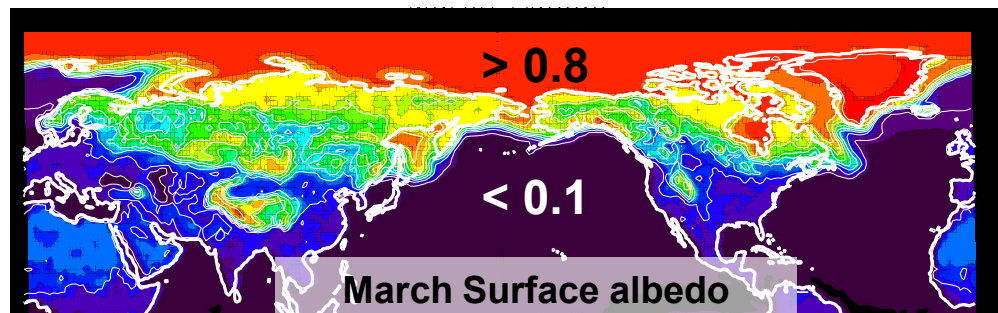


Arndt et al. 2017

Why sea ice matters in the Earth system

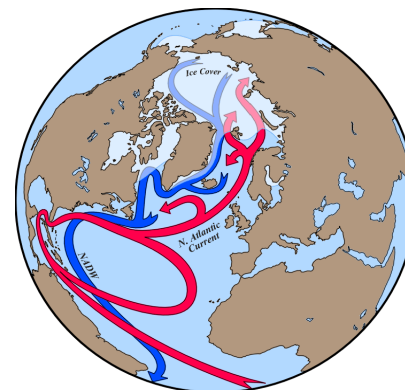
Surface energy budget

- Albedo
- Surface turbulent fluxes



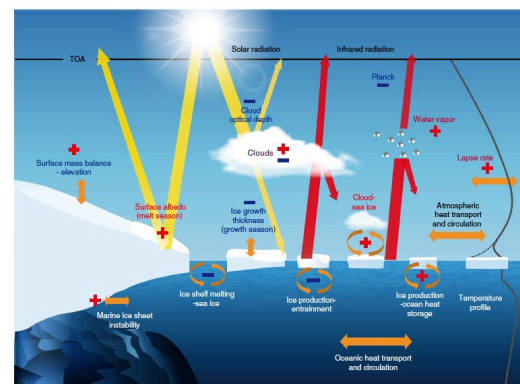
Hydrologic cycle/Ocean Circulation

- Ice formation
- Ice transport



Climate Feedbacks (e.g.)

- Albedo feedback
- Ice growth/thickness feedback
- Ice/Cloud feedback



Goosse et al. 2018

- 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.)

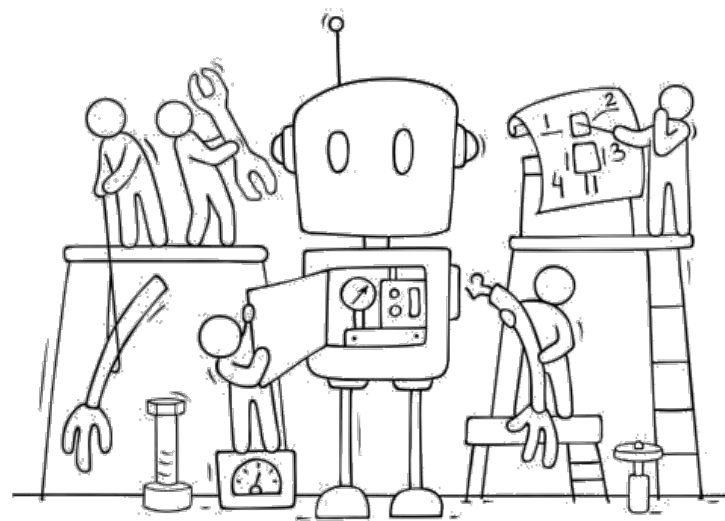
CICE (pronounced “sice”): The CICE Consortium Model

- 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 (horizontal)
2. Thermodynamics (vertical)
3. Subgrid-scale representation (heterogeneity, most notably the Ice Thickness Distribution a.k.a. ITD)



- 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)

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

Diagram illustrating the momentum balance equation for ice dynamics, with terms labeled below:

- Total derivative (points to $m \frac{D\mathbf{u}}{Dt}$)
- Coriolis (points to $-mf\mathbf{k} \times \mathbf{u}$)
- Air stress (points to $\boldsymbol{\tau}_a$)
- Ocean stress (points to $\boldsymbol{\tau}_w$)
- Sea Surface Slope (points to $-mg_r \nabla Y$)
- Internal Ice Stress (points to $\nabla \cdot \boldsymbol{\sigma}$)

$$m \frac{D\mathbf{u}}{Dt} = -mf\mathbf{k} \times \mathbf{u} + \tau_a + \tau_w - mg_r \nabla Y + \nabla \cdot \sigma$$

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

Air-Ice Stress

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

Ocean-Ice Stress

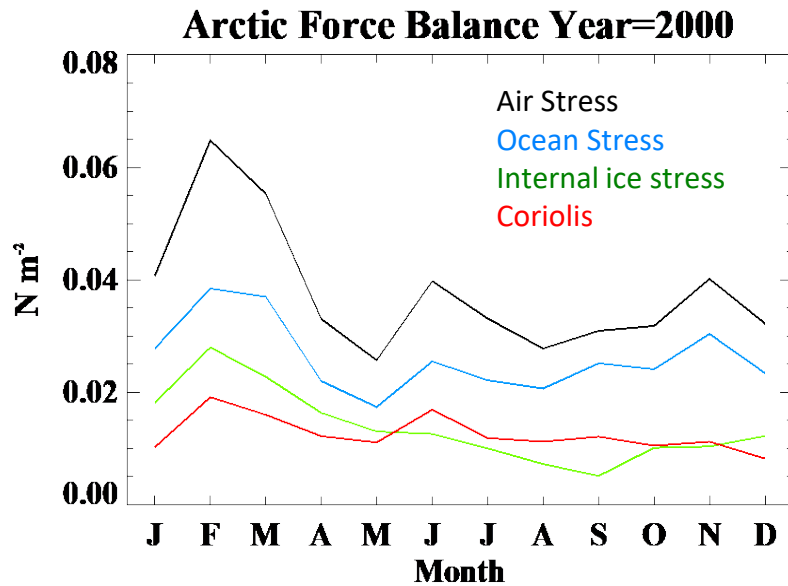
$$\vec{\tau}_w = c_w \rho_w |\vec{U}_w - \vec{u}| \left[(\vec{U}_w - \vec{u}) \cos \theta + \hat{k} \times (\vec{U}_w - \vec{u}) \sin \theta \right]$$

Dynamics

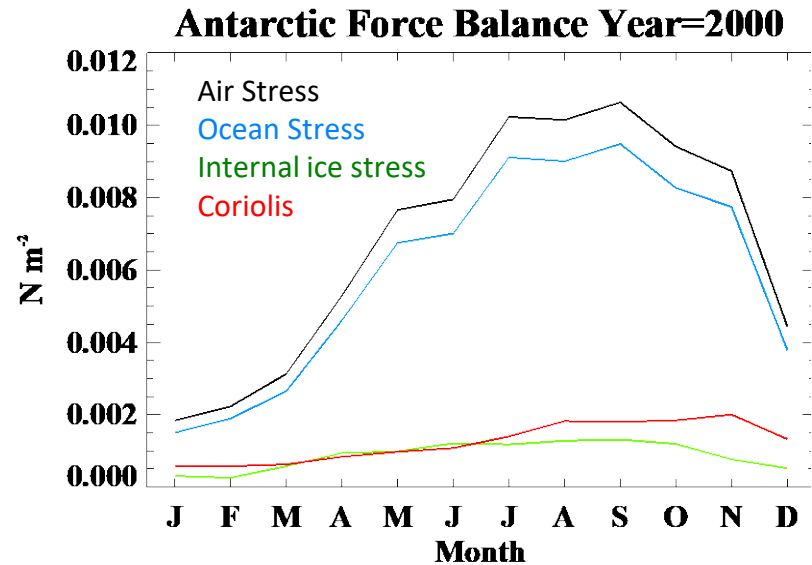
(e.g. Hibler, 1979)

$$m \frac{Du}{Dt} = -mf\mathbf{k} \times \mathbf{u} + \tau_a + \tau_w - mg_r \nabla Y + \nabla \cdot \sigma$$

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



Internal ice stress impactful in winter



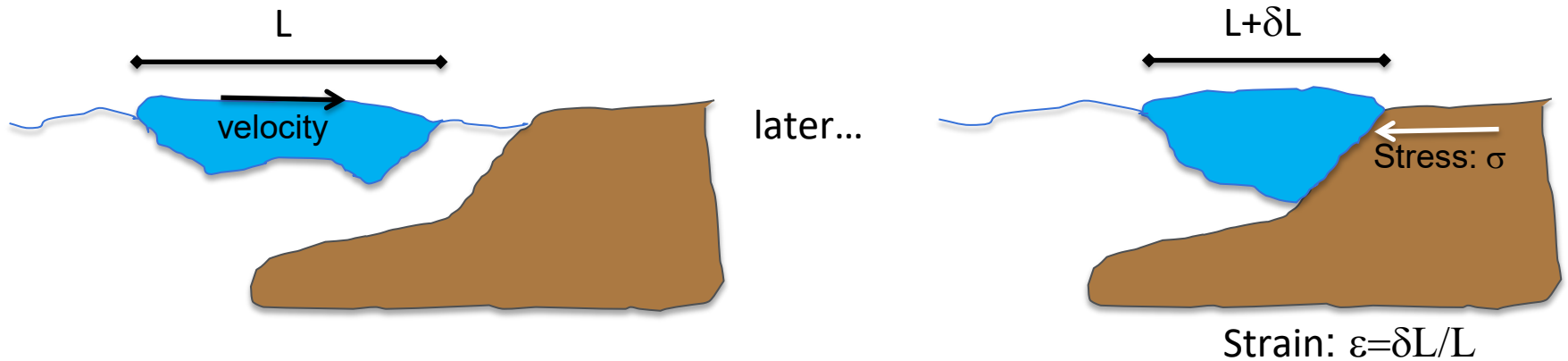
Free drift: Air stress $\approx$ Ocean stress

Dynamics

(e.g. Hibler, 1979)

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

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



(e.g. Hibler, 1979)

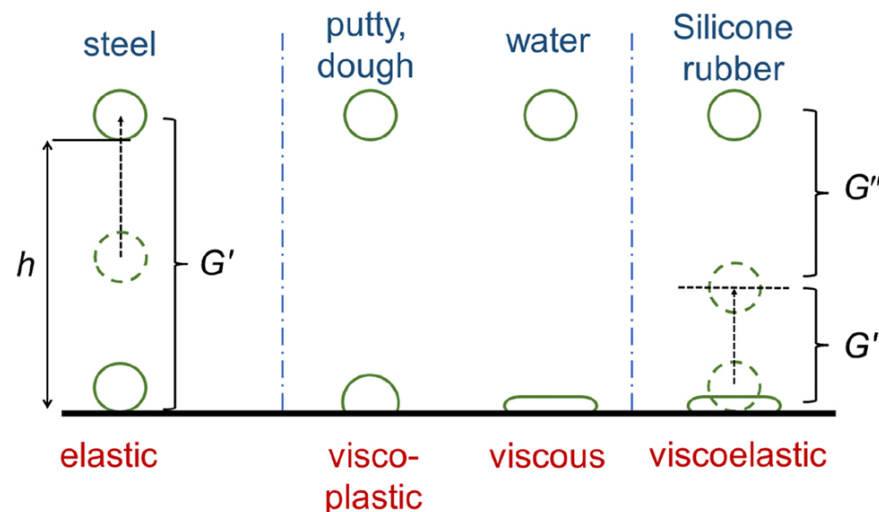
$$m \frac{Du}{Dt} = -mf\mathbf{k} \times \mathbf{u} + \tau_a + \tau_w - mg_r \nabla Y + \nabla \cdot \sigma$$

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

– ‘Rheology’ is defined as the relation between ice stress (σ) to ice strain rate (ε)

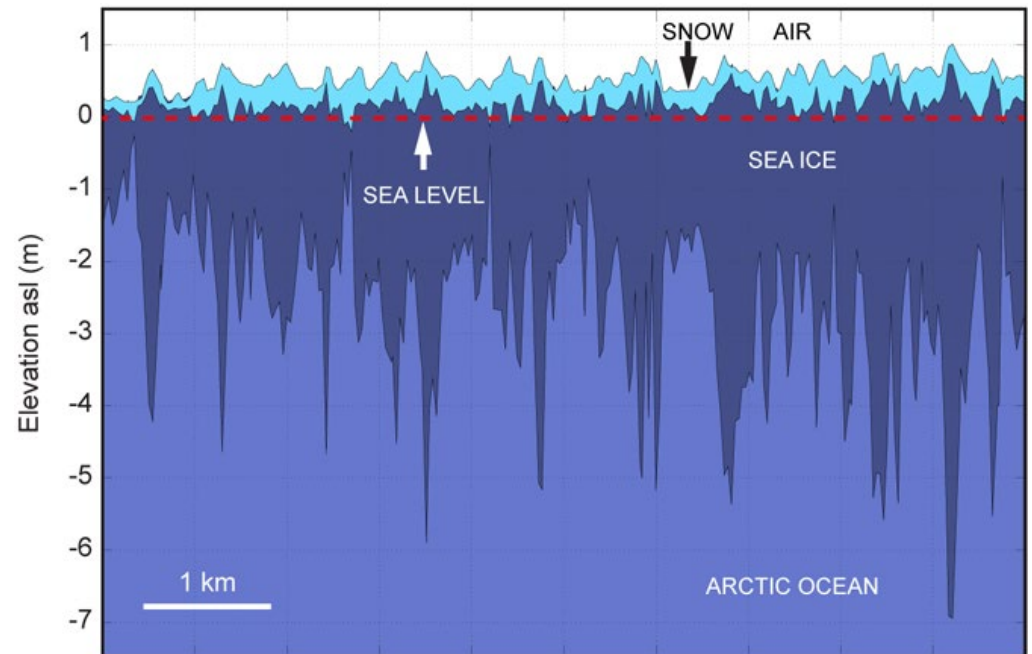
– CESM uses Elastic-Viscous-Plastic (EVP) scheme:

At large scales (>10 km, days) sea ice behaves like a visco-plastic (VP) fluid, however, VP parameterizations are numerically unstable at low strain rates (Hunke & Dukowicz 1997)



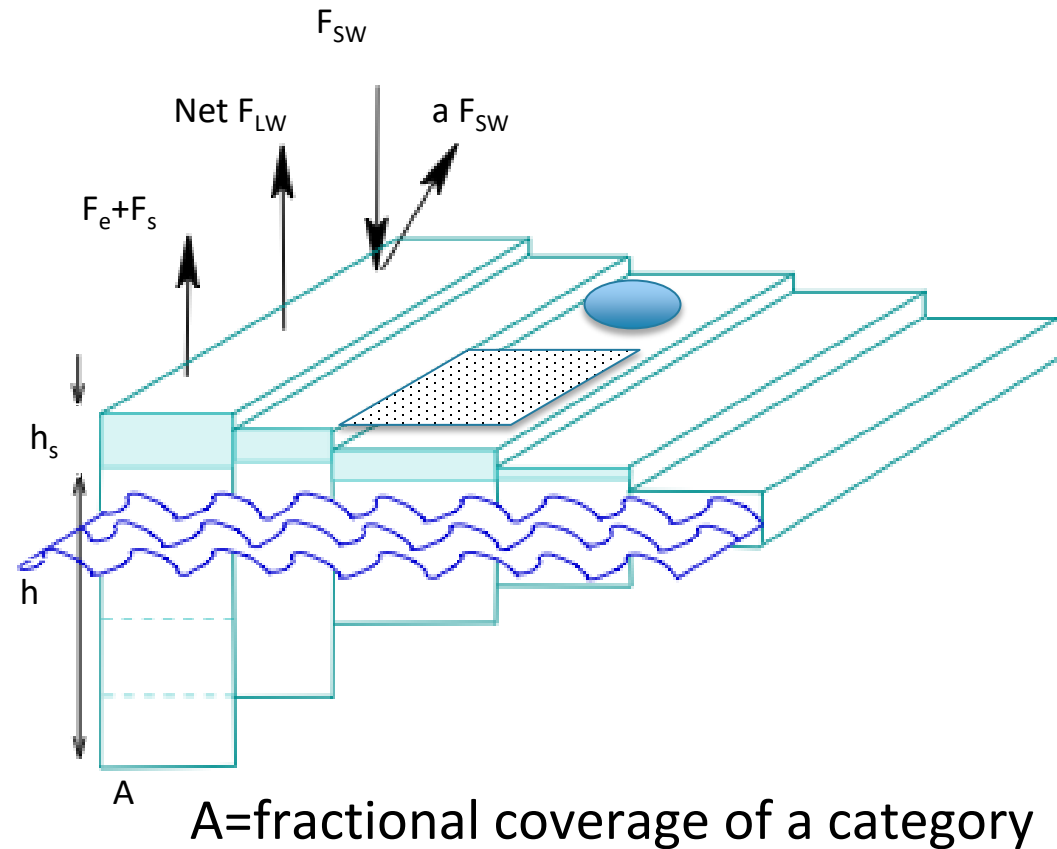
Ice Thickness Distribution

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



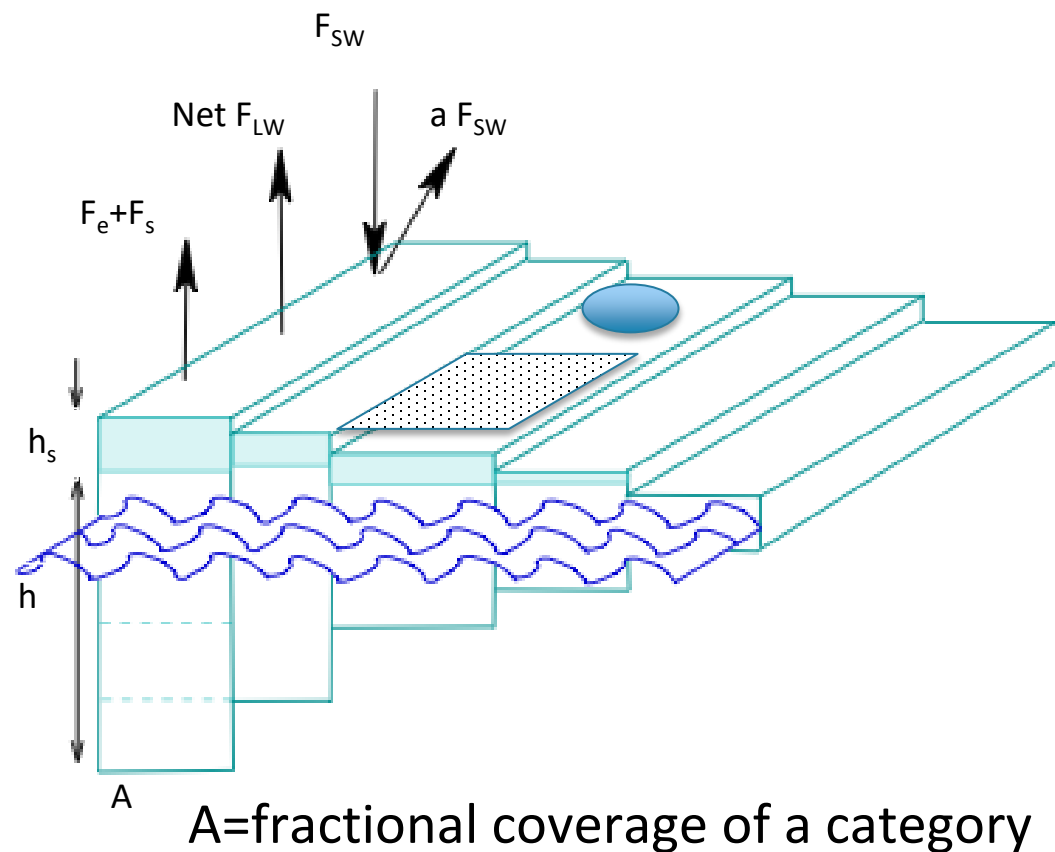
Ice Thickness Distribution

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



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

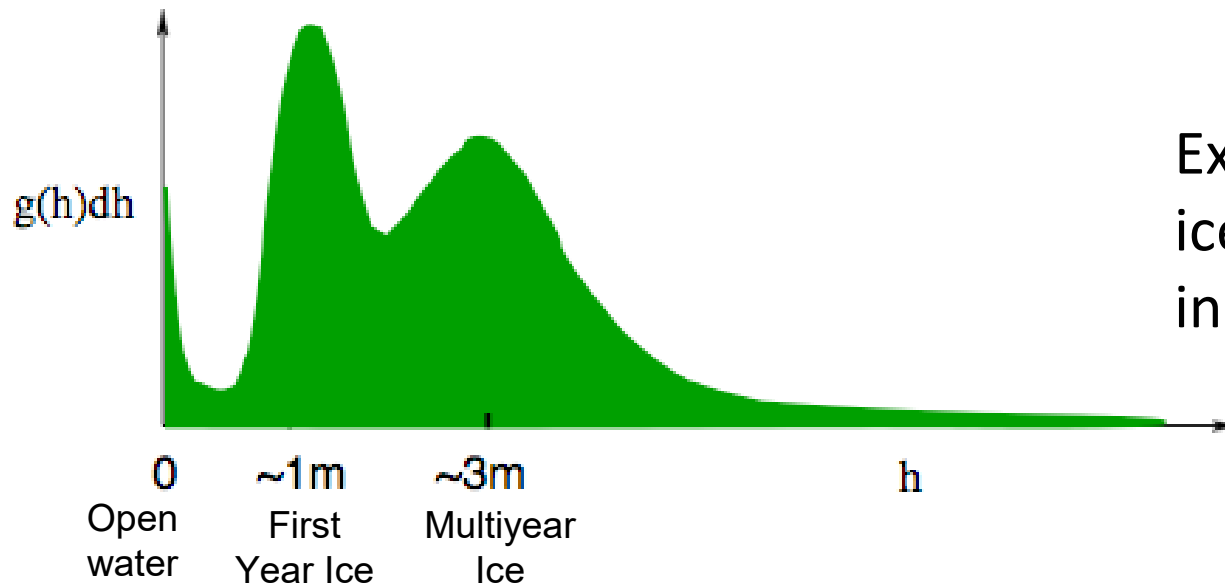


Ice Thickness Distribution

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

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

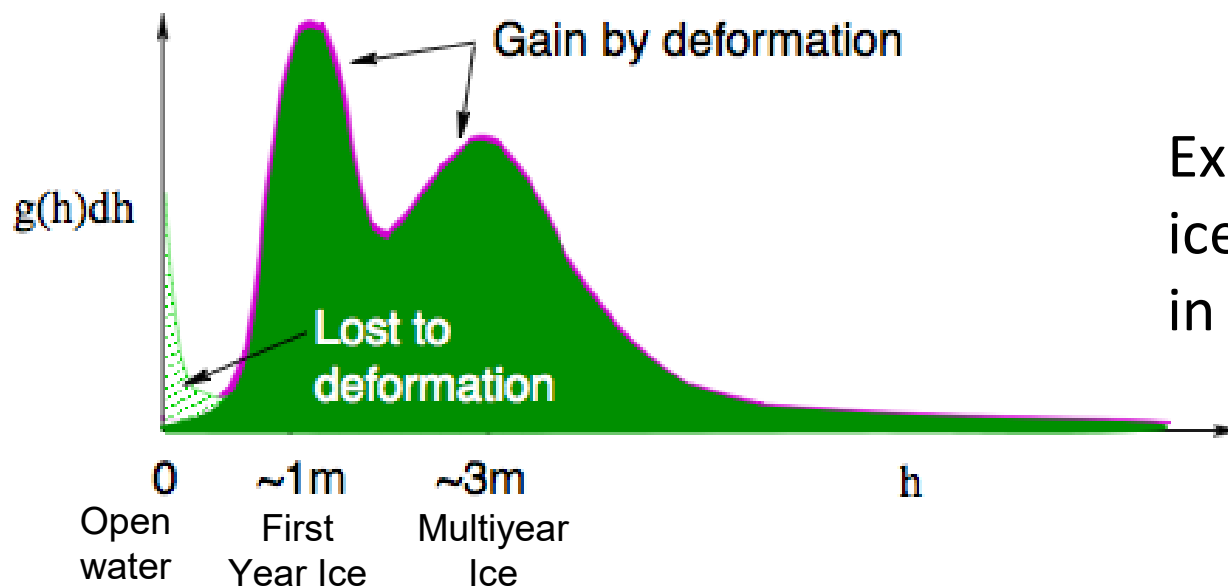
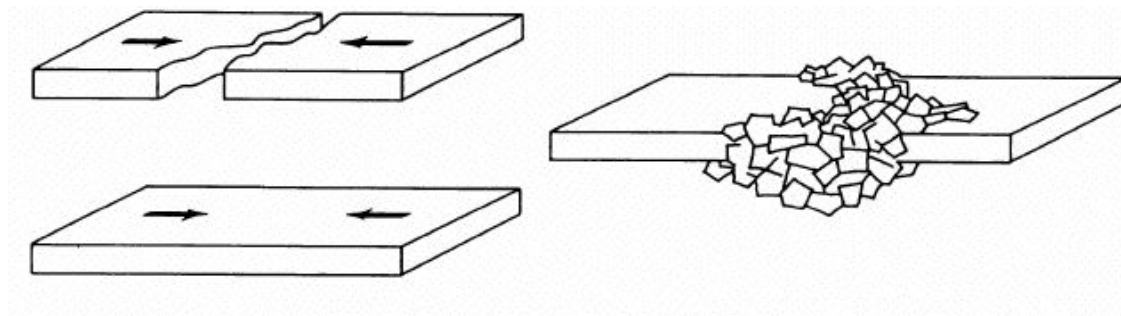
$\uparrow$ Ice Growth $\uparrow$ Lateral Melt $\uparrow$ Convergence $\uparrow$ Mechanical Redistribution



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

Ice Thickness Distribution: impact of convergence

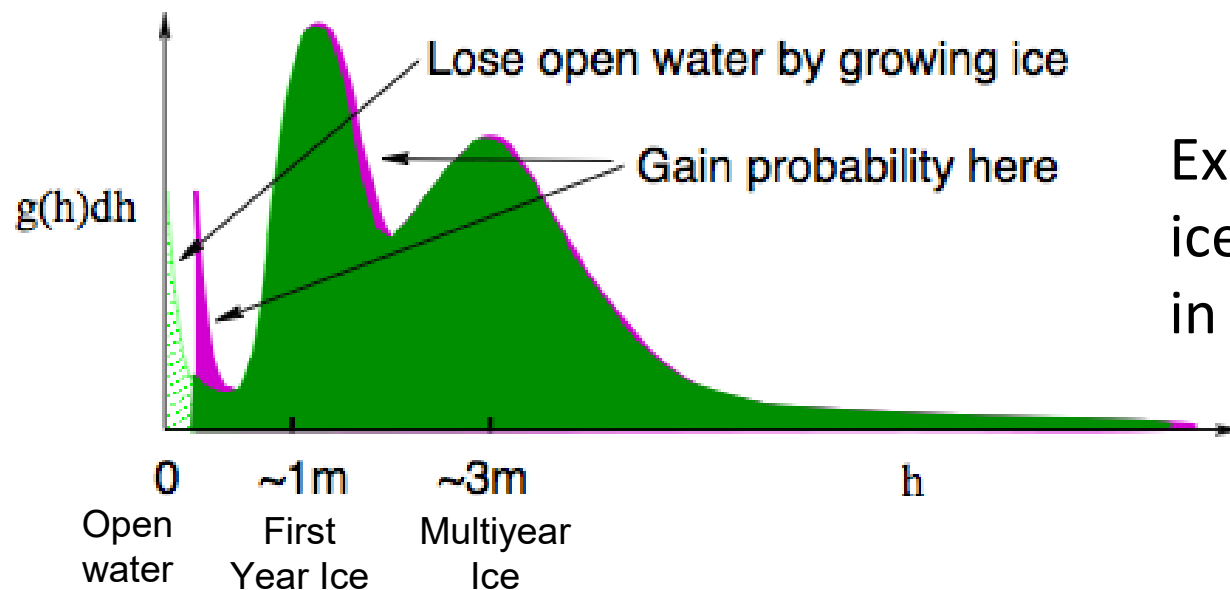
Mechanical redistribution: Transfer ice from thin part of distribution to thicker categories



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

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



Photo by Alice DuVivier



Photo by Robbie Mallett

Thermodynamics

Top surface flux balance

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

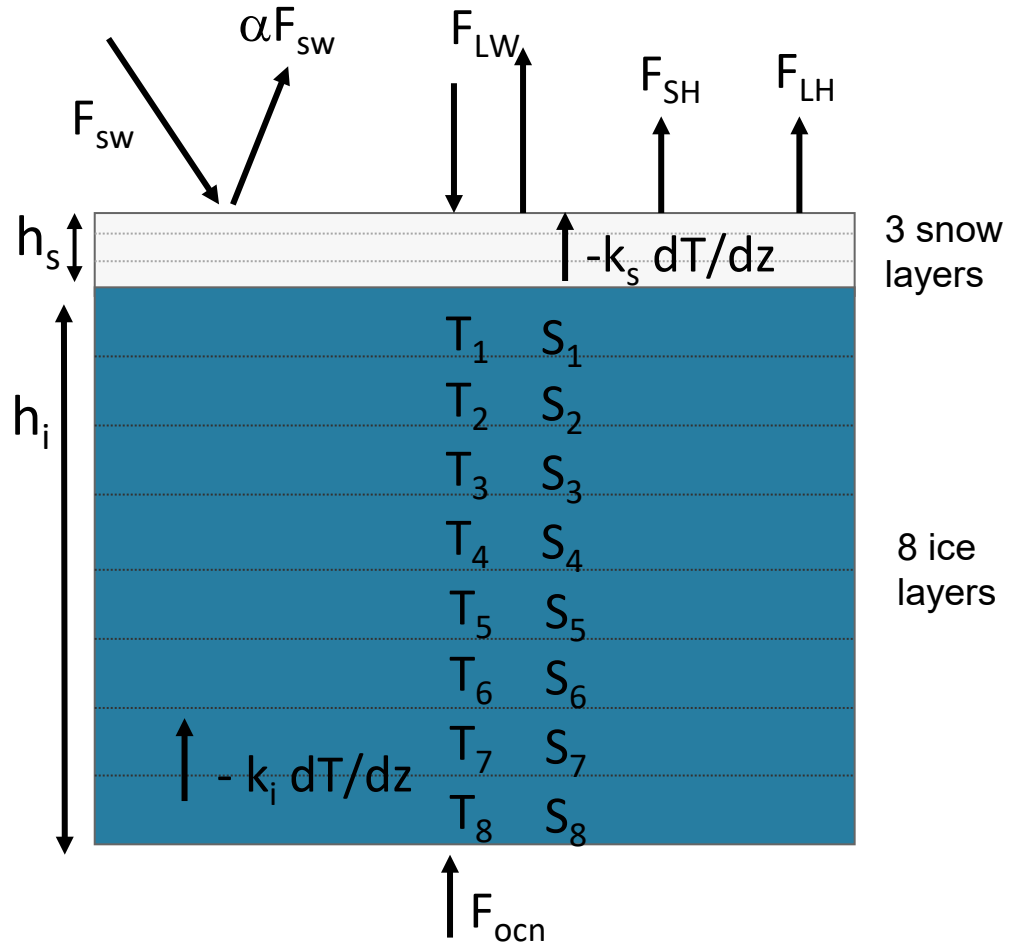
Vertical heat transfer (conduction)

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

SEA ICE

Bottom surface flux balance

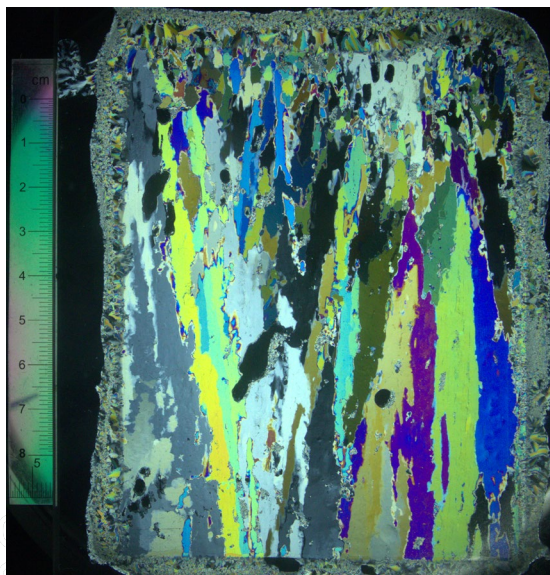
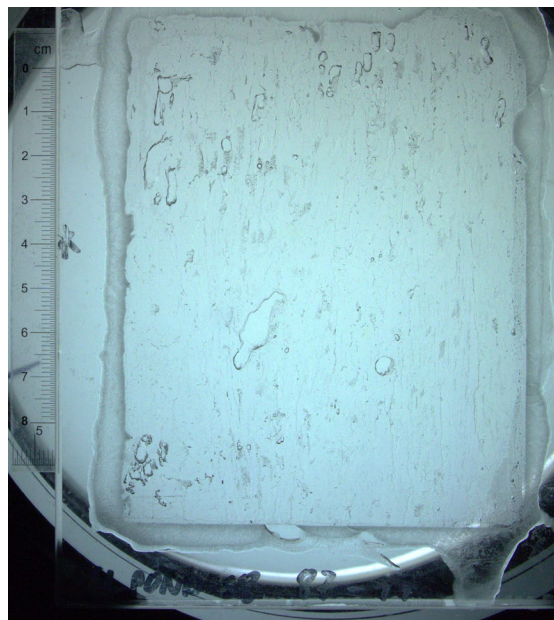
$$F_{ocn} - k \frac{\partial T}{\partial z} = -q \frac{dh}{dt}$$



k = conductivity

ρ = density (constant): $\rho_i = 917 \text{ kg/m}^3$; $\rho_s = 330 \text{ kg/m}^3$

Ice structure and heat fluxes



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 constants for brine and ice and snow.

Photos: D. Clemens-Sewall

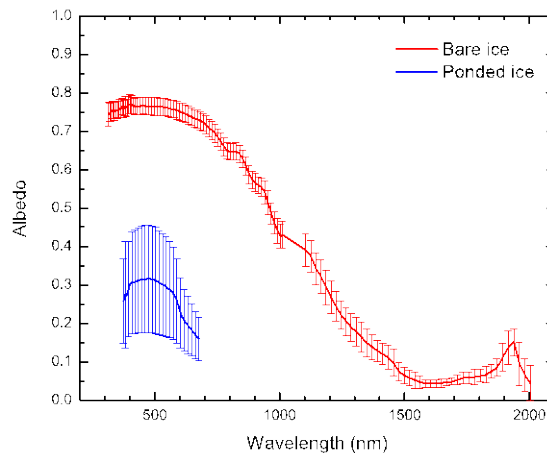
Delta Eddington Solar Radiation parameterization

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

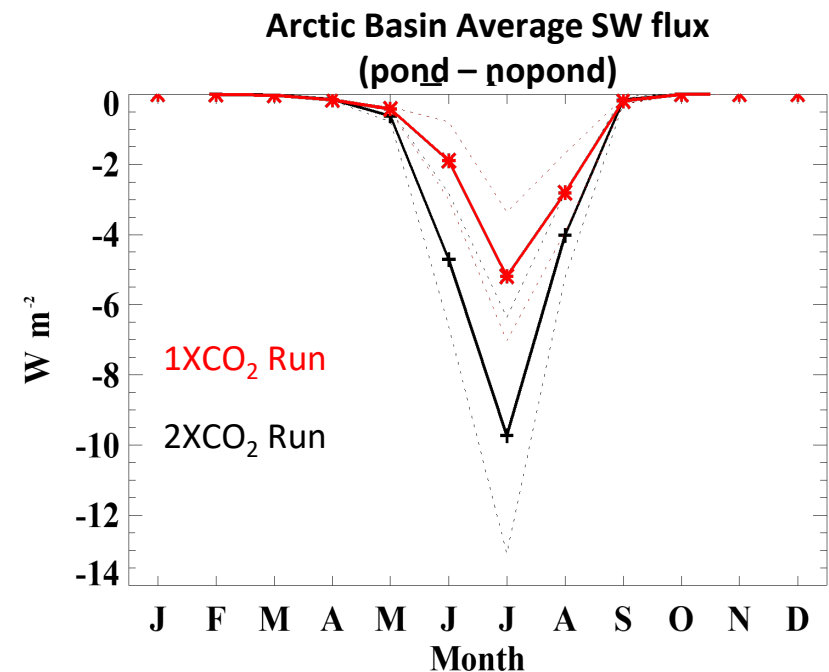
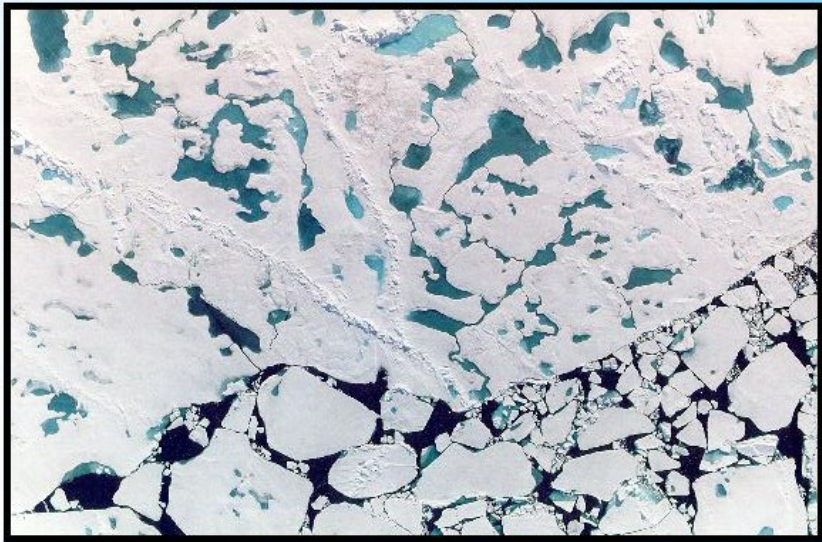
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

CESM1, CESM2, and CESM3: Delta Eddington Solar Radiation

- 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.

Melt Pond Parameterization

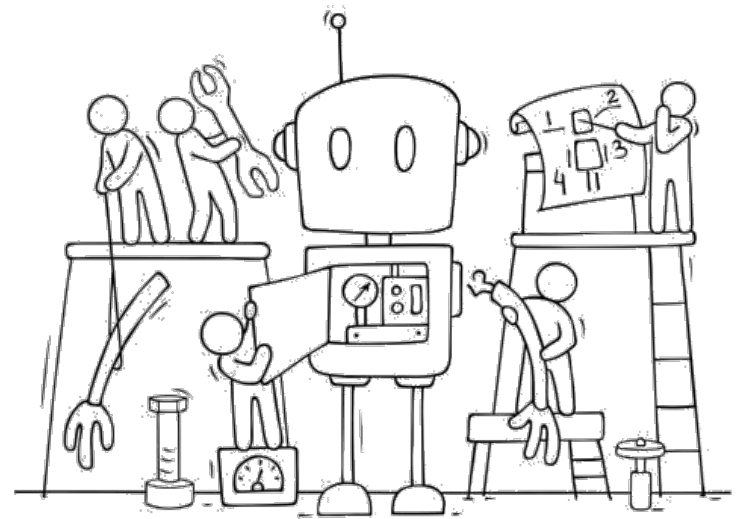
- Only influences radiation and has big influence on surface forcing and light transmission into ocean
- Ponds evolve over time and are carried as tracers on the ice



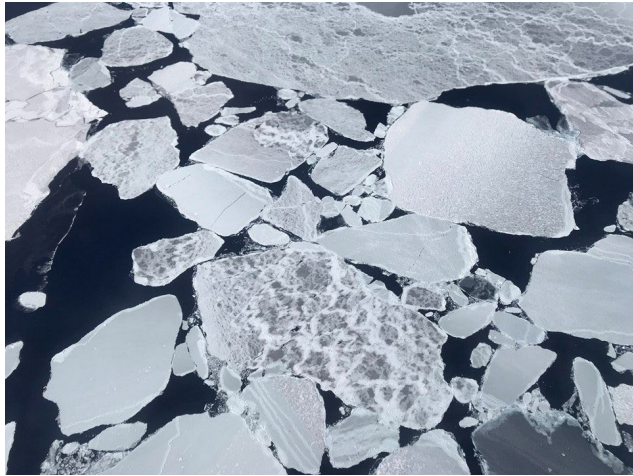
Holland, M. M., et al. 2012: Improved sea ice shortwave radiation physics in CCSM4

Sea ice models: what is in CESM3?

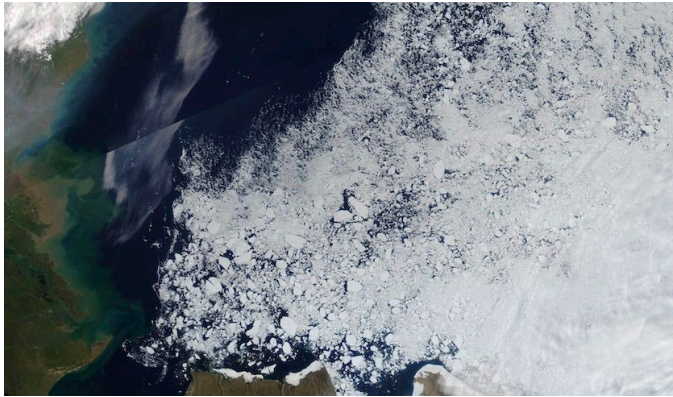
1. Dynamics
2. Thermodynamics
3. Ice thickness distribution
4. Waves
5. Floe size distribution
6. New melt pond parameterization



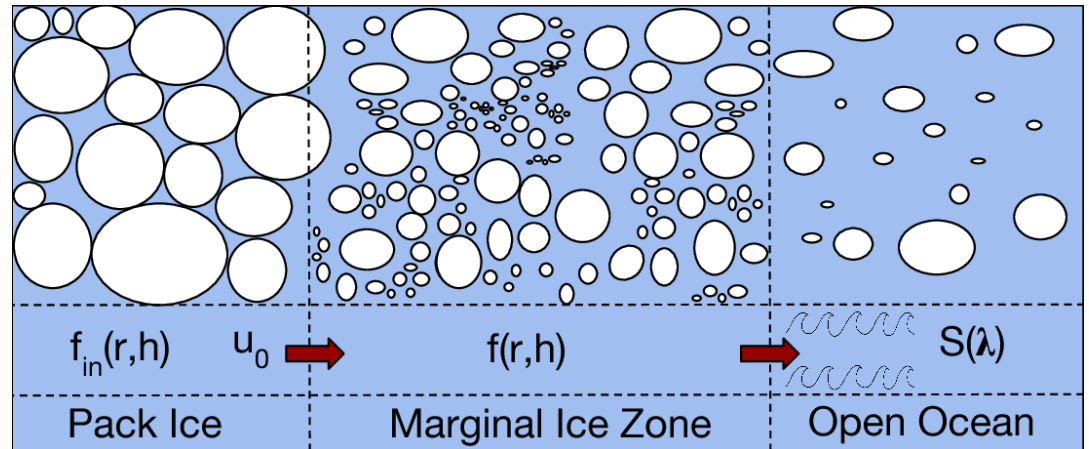
Floe Size Distribution



NASA Operation IceBridge (10/29/17)



MODIS satellite (7/27/19)

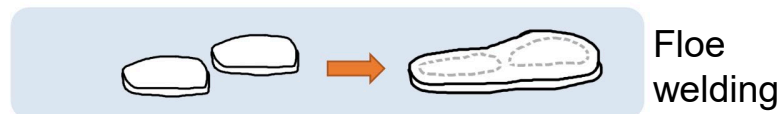
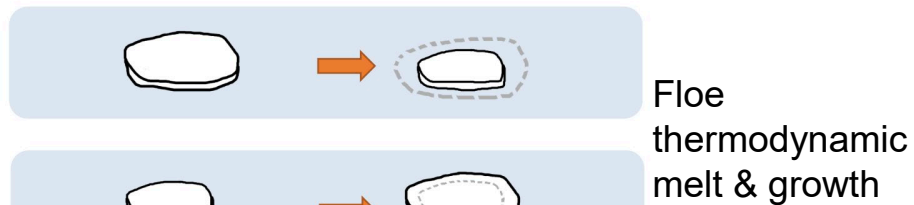


Floe Size Distribution

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

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

Thermodynamics Fracture

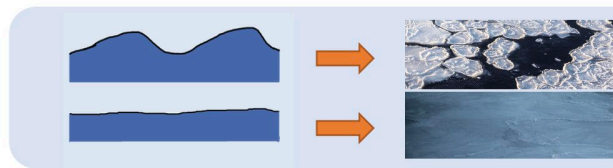


Floe Size Distribution

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

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

Thermodynamics Fracture



Waves
affect
sea ice



Floe
thermodynamic
melt & growth



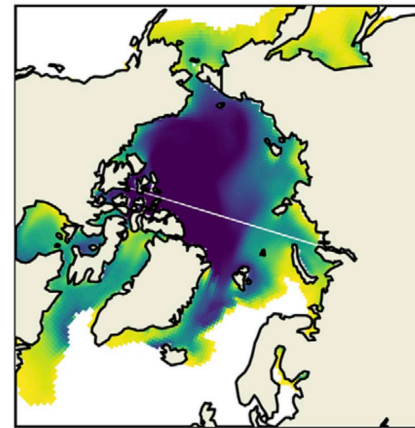
Floe
welding



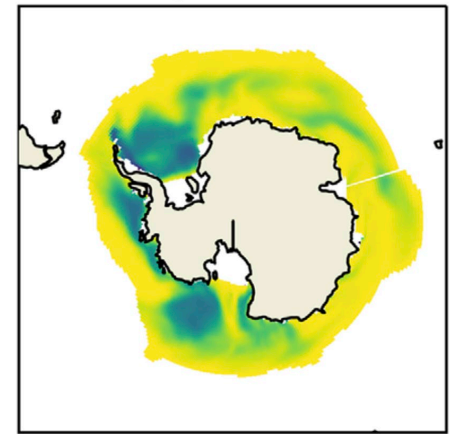
Floe
Fracture

CESM3 testing

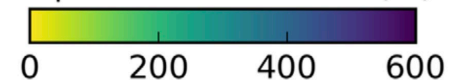
(a) NH Mar



(d) SH Sep

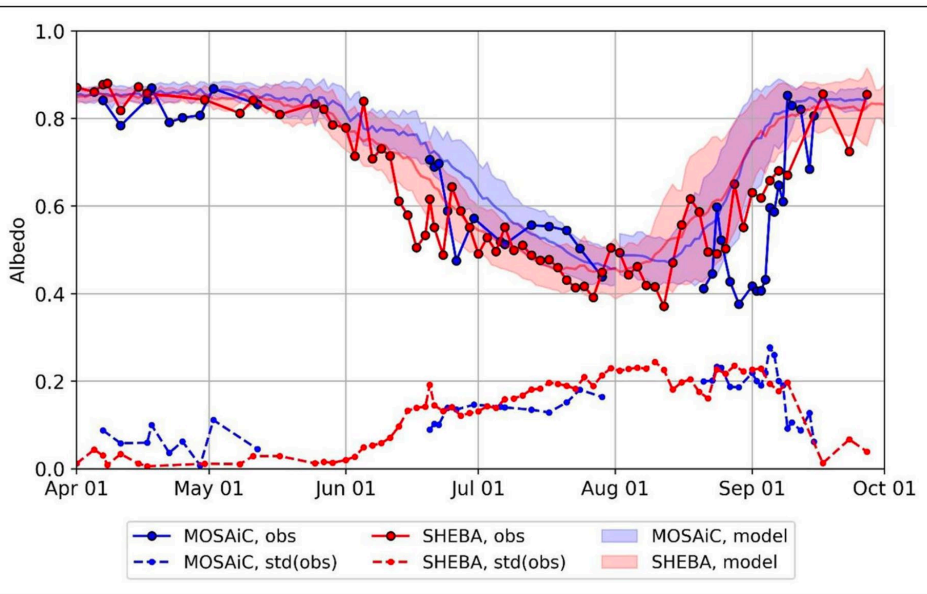


Representative radius (m)



Melt Ponds

CESM2 albedo looks great!

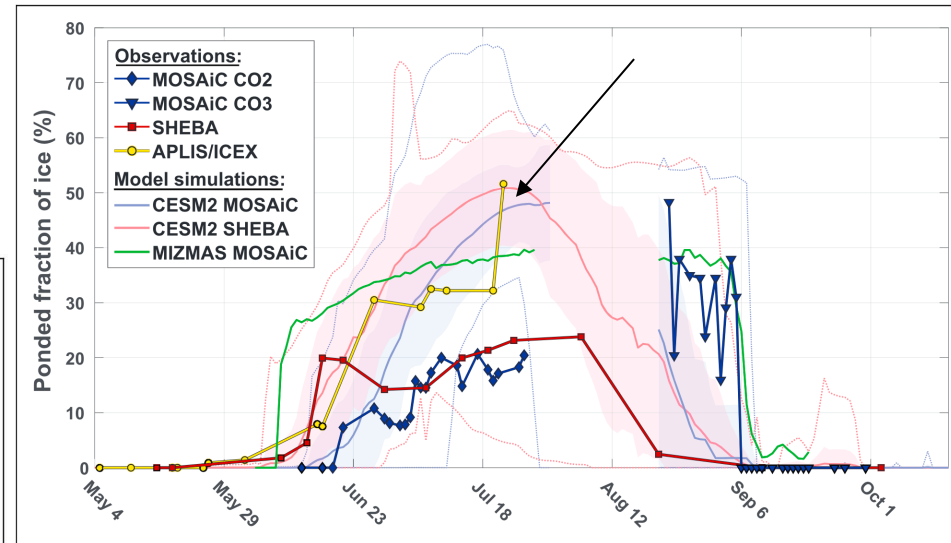


Light et al. 2022

Melt Ponds

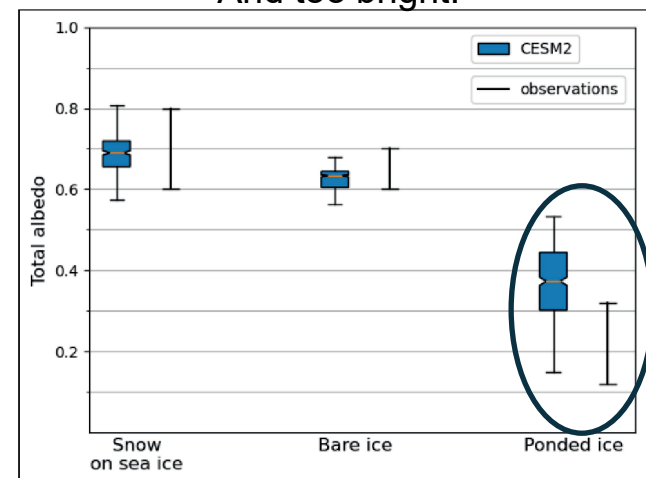
Ponds are too extensive...

CESM2 albedo looks great!



Webster et al. 2022

And too bright!

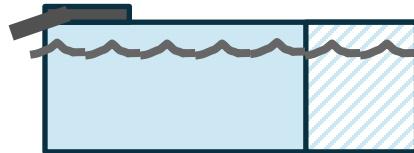


Light et al. 2022

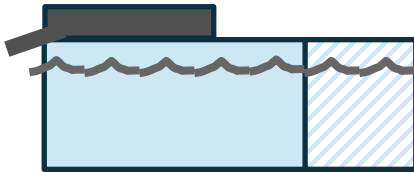
Melt Ponds

CICE: level ponds

Ponds are perched above the ice surface and exponentially decay.

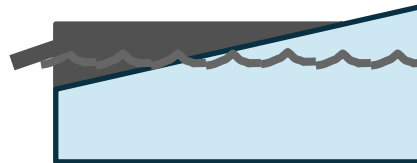


Pond area and depth grow by fixed ratio. Drainage only reduces depth.

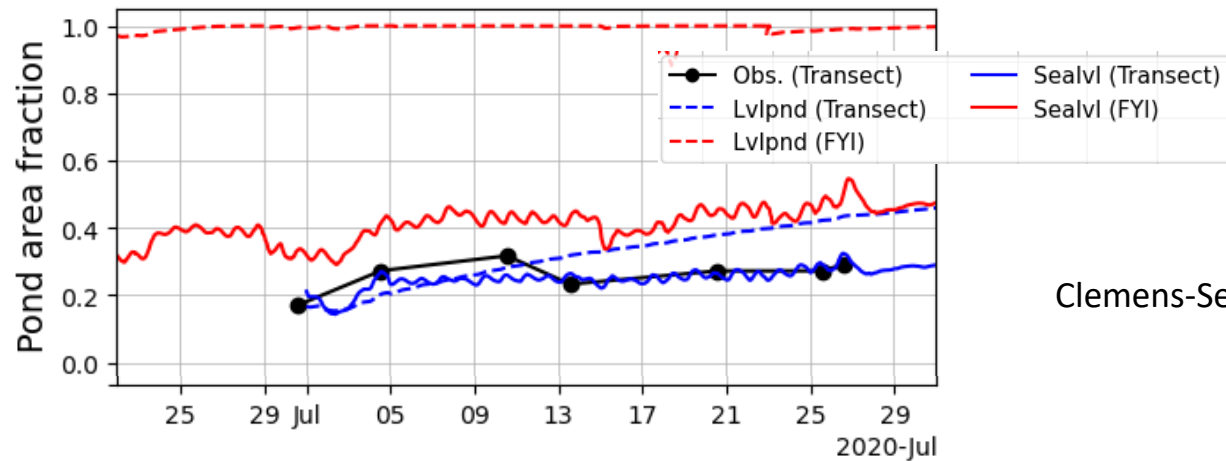
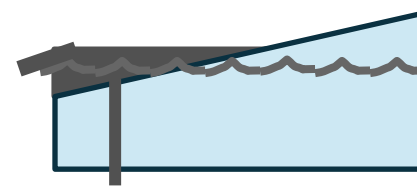


CICE: sealvl ponds (new)

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



Drainage reduces both depth and area based on hypsometry



Clemens-Sewall, in prep.

Thank you! – Questions?

Please get in touch!

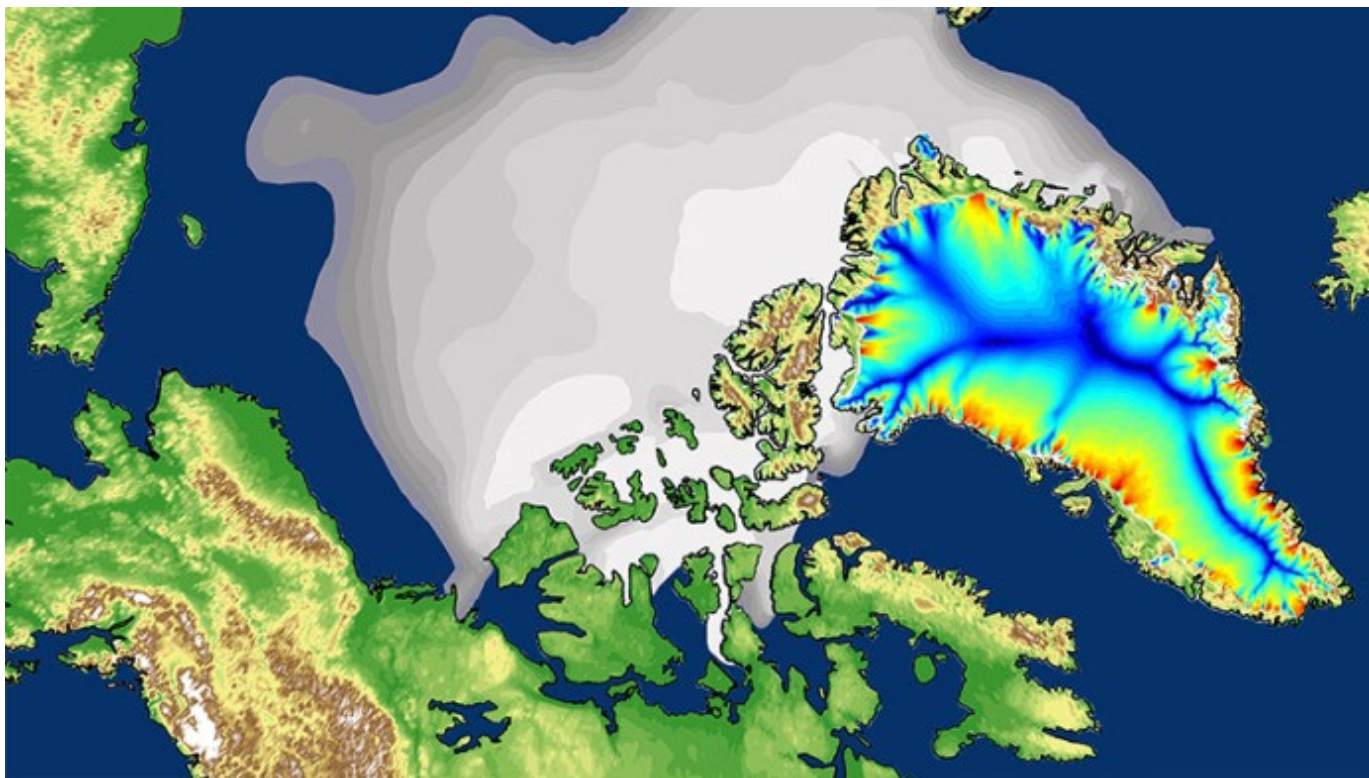
**David.Clemens-
Sewall@colorado.edu
duvivier@ucar.edu
dbailey@ucar.edu**

Photo:

D. Clemens-Sewall

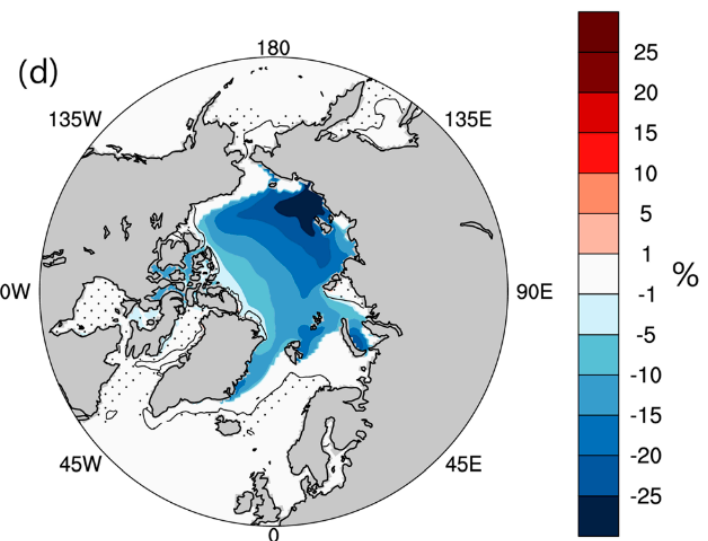
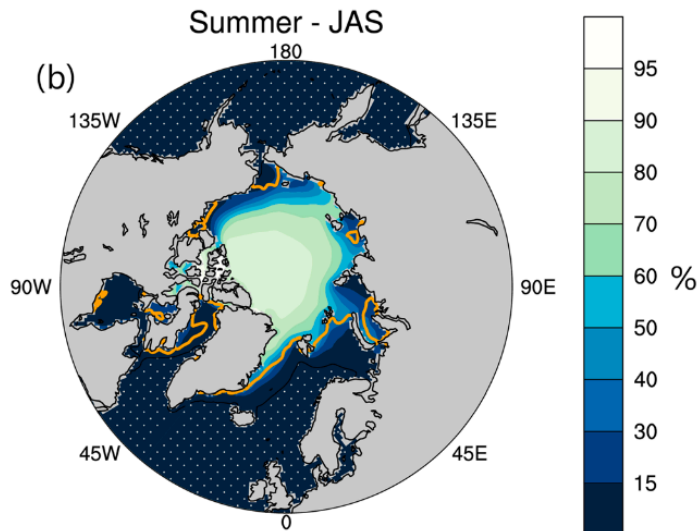
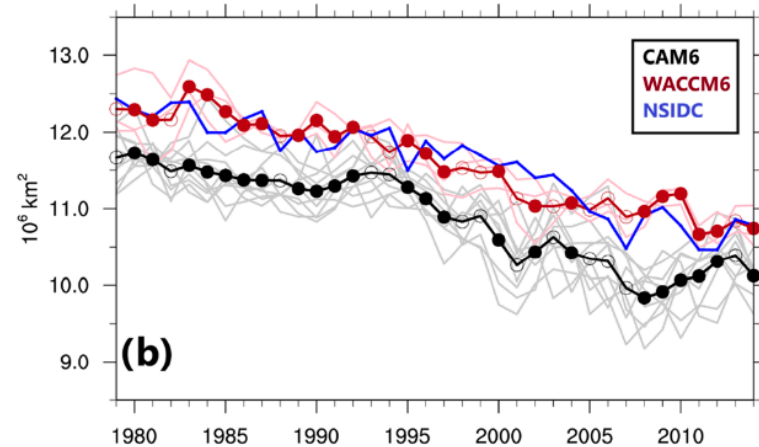
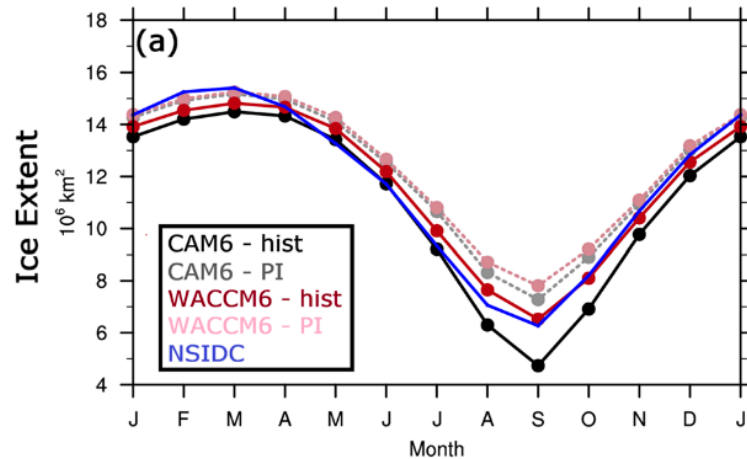


CESM2 Sea Ice Validation



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

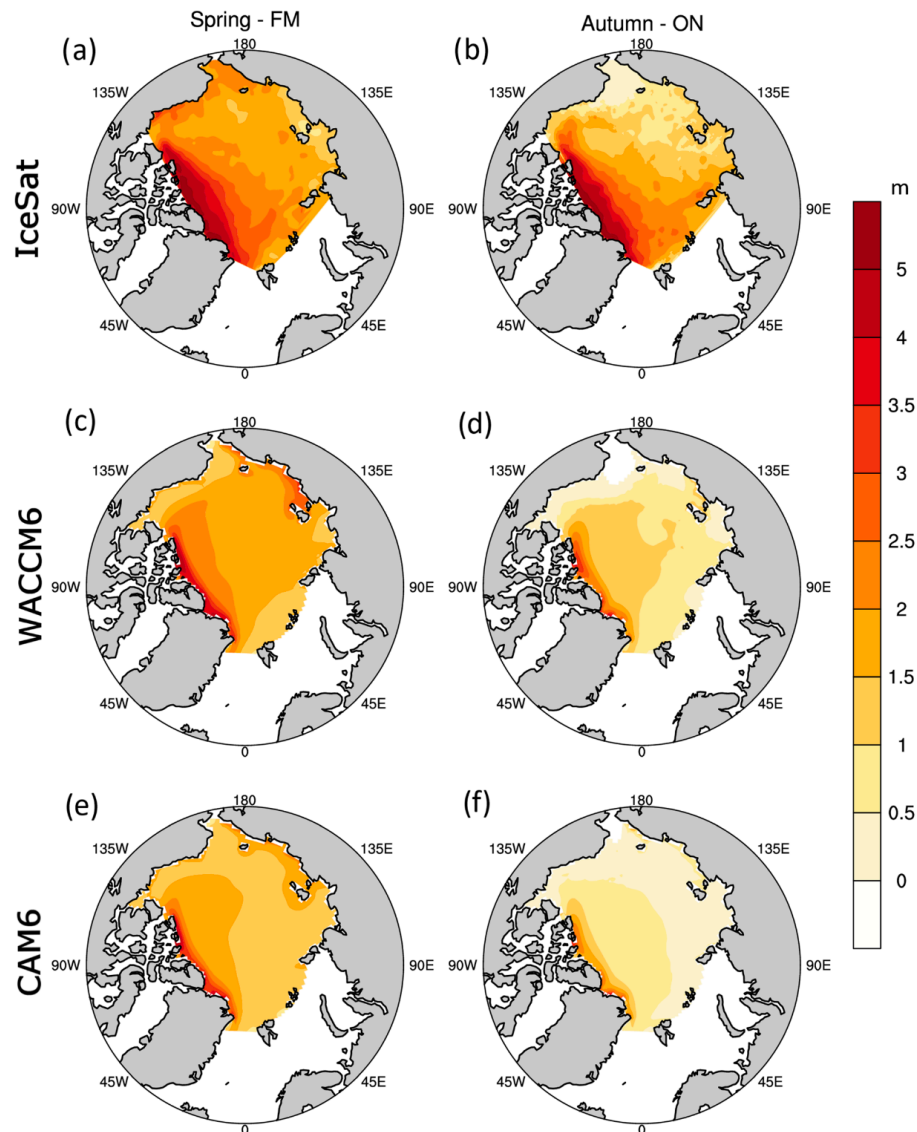
CESM2 Historical (1979-2014) Arctic Sea Ice Extent



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.

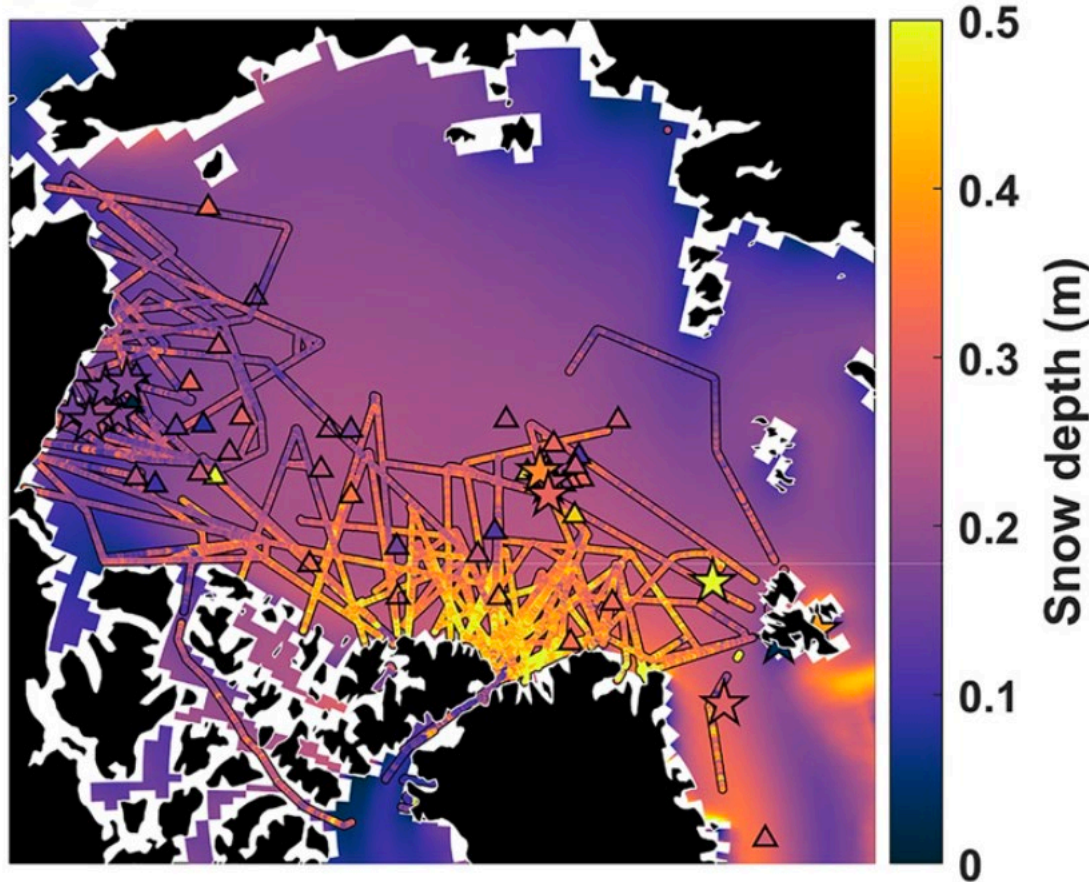
CESM2 Historical (2001-2005) Arctic Sea Ice Thickness



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

CESM2 Historical Arctic Sea Ice Snow

(c)



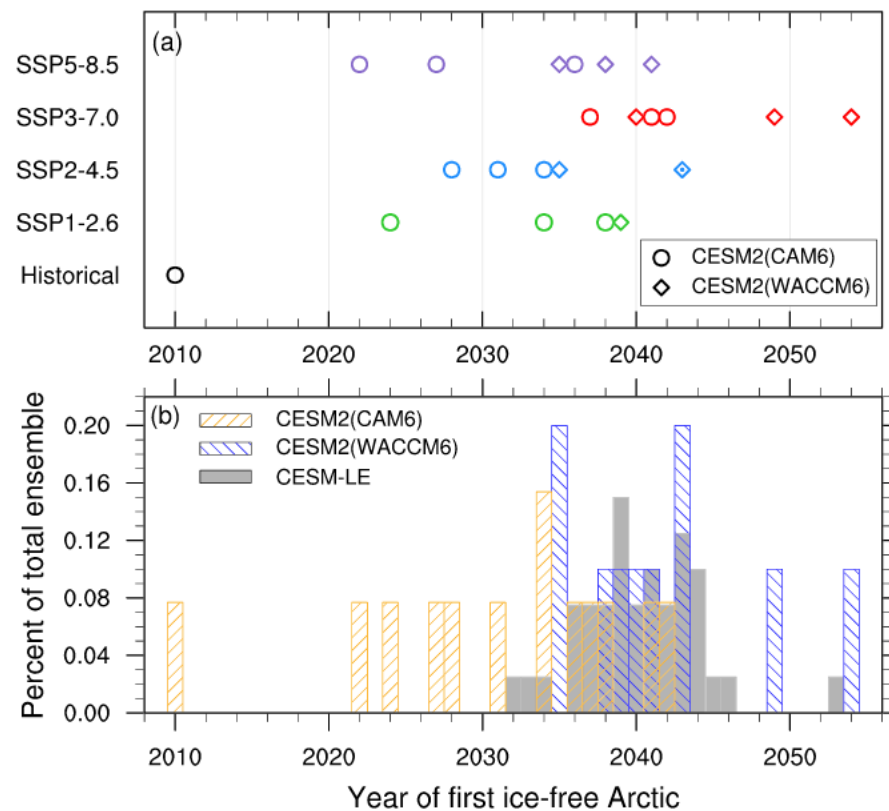
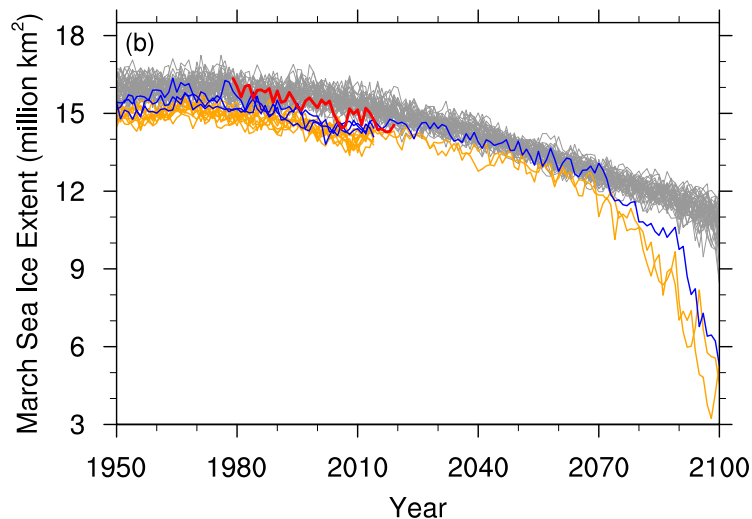
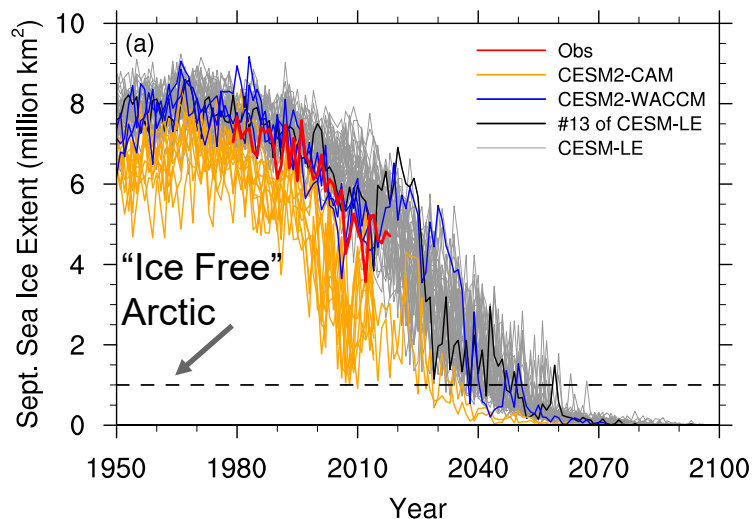
CESM2-WACCM6

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

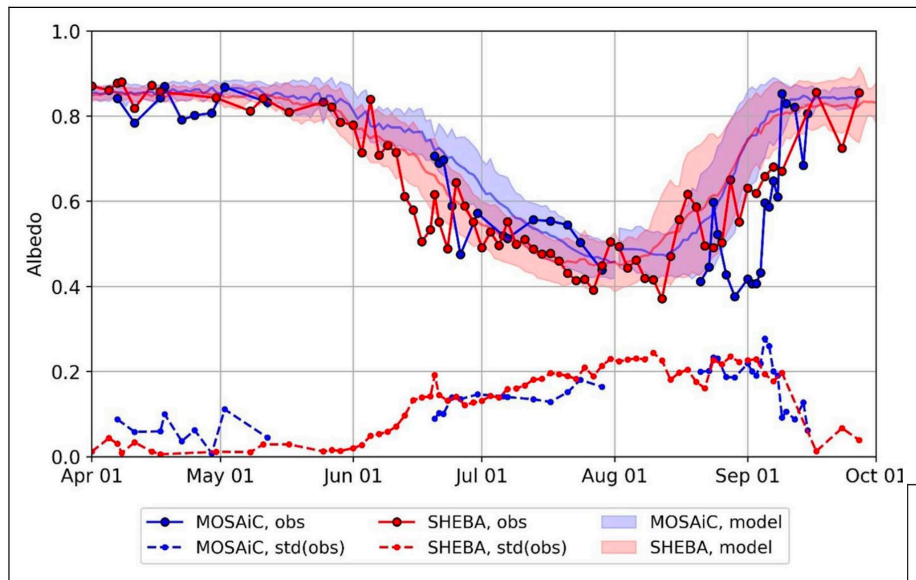


CESM2 with WACCM6 vs. CAM6 have similar ice-free dates and these are independent of scenario.

DeRepentigny et al. 2022

<https://doi.org/10.1126/sciadv.abo2405>

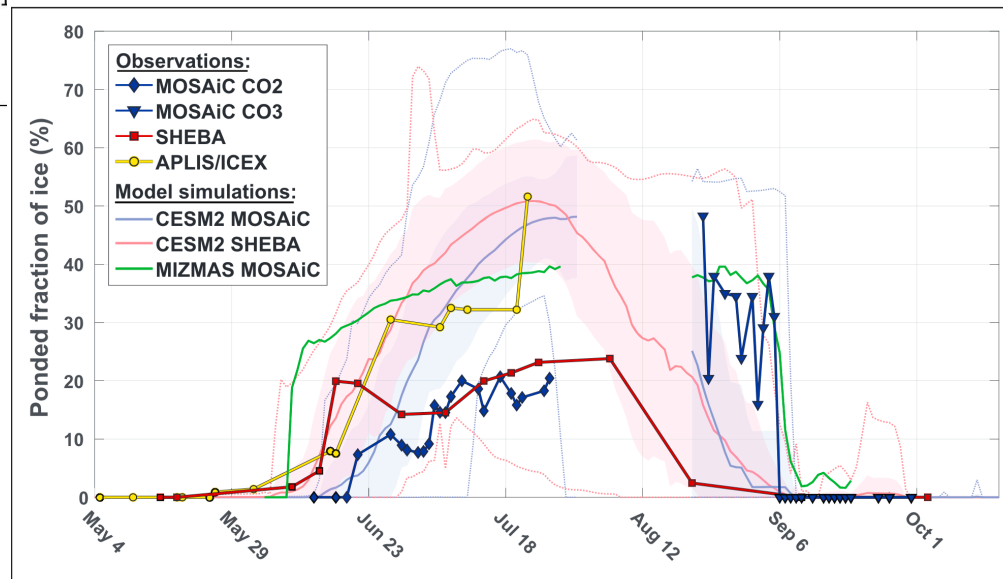
CESM2 Arctic Sea Ice – Melt ponds



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

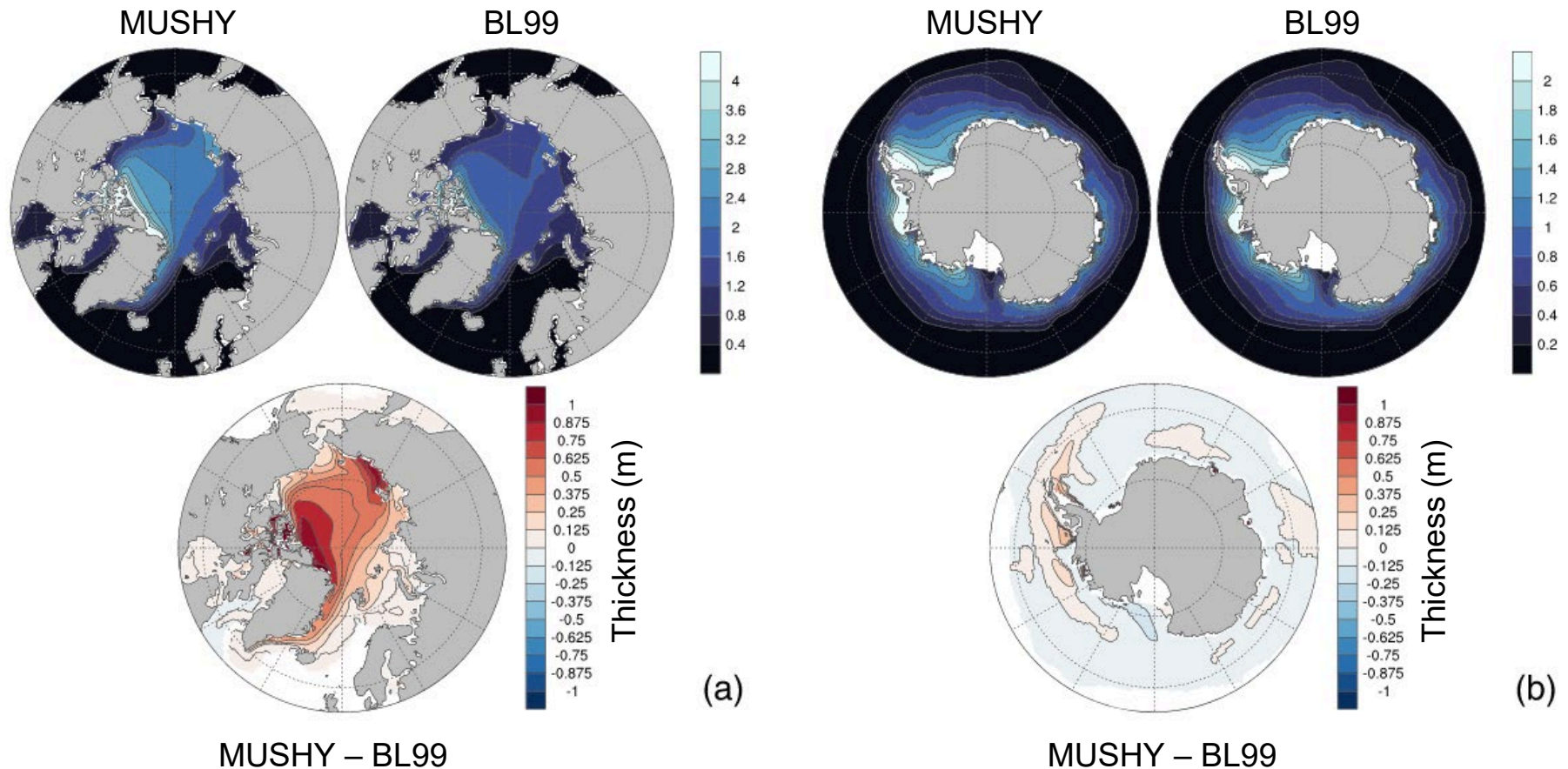
CESM2 Ponds are too extensive, but not deep enough.

→ Compensating biases lead to reasonable albedo.



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

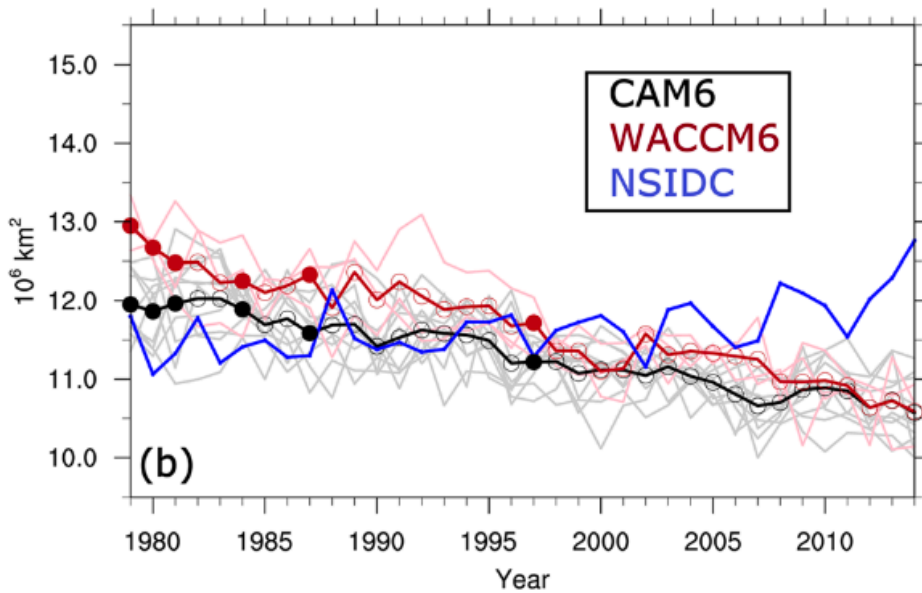
CESM2 – Mushy thermodynamics



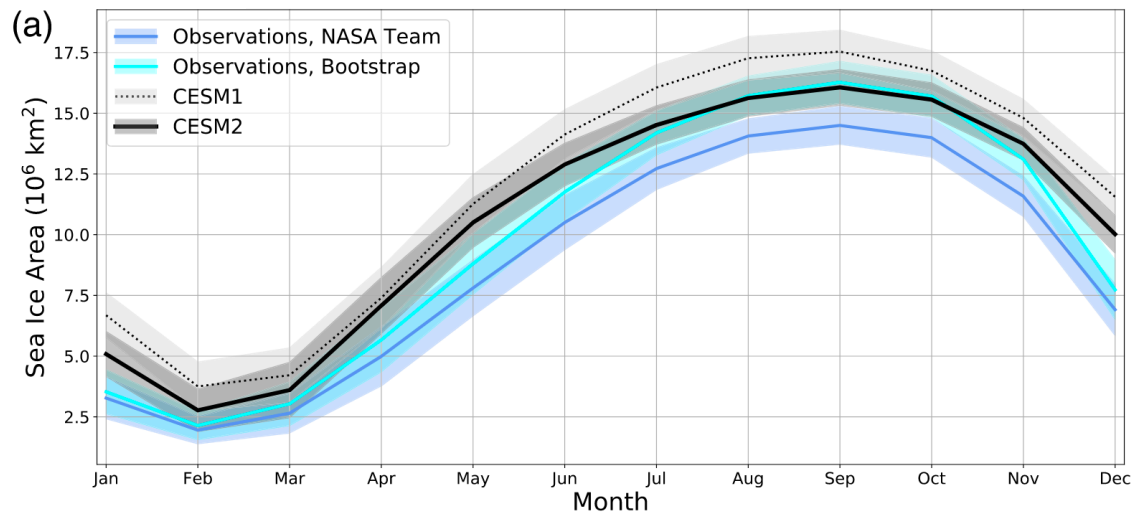
CESM2 tested with MUSHY (new) and BL99 thermodynamics shows that MUSHY leads to thicker and more extensive sea ice. Impacts are larger in the Arctic.

CESM2 Antarctic Sea Ice

Historical



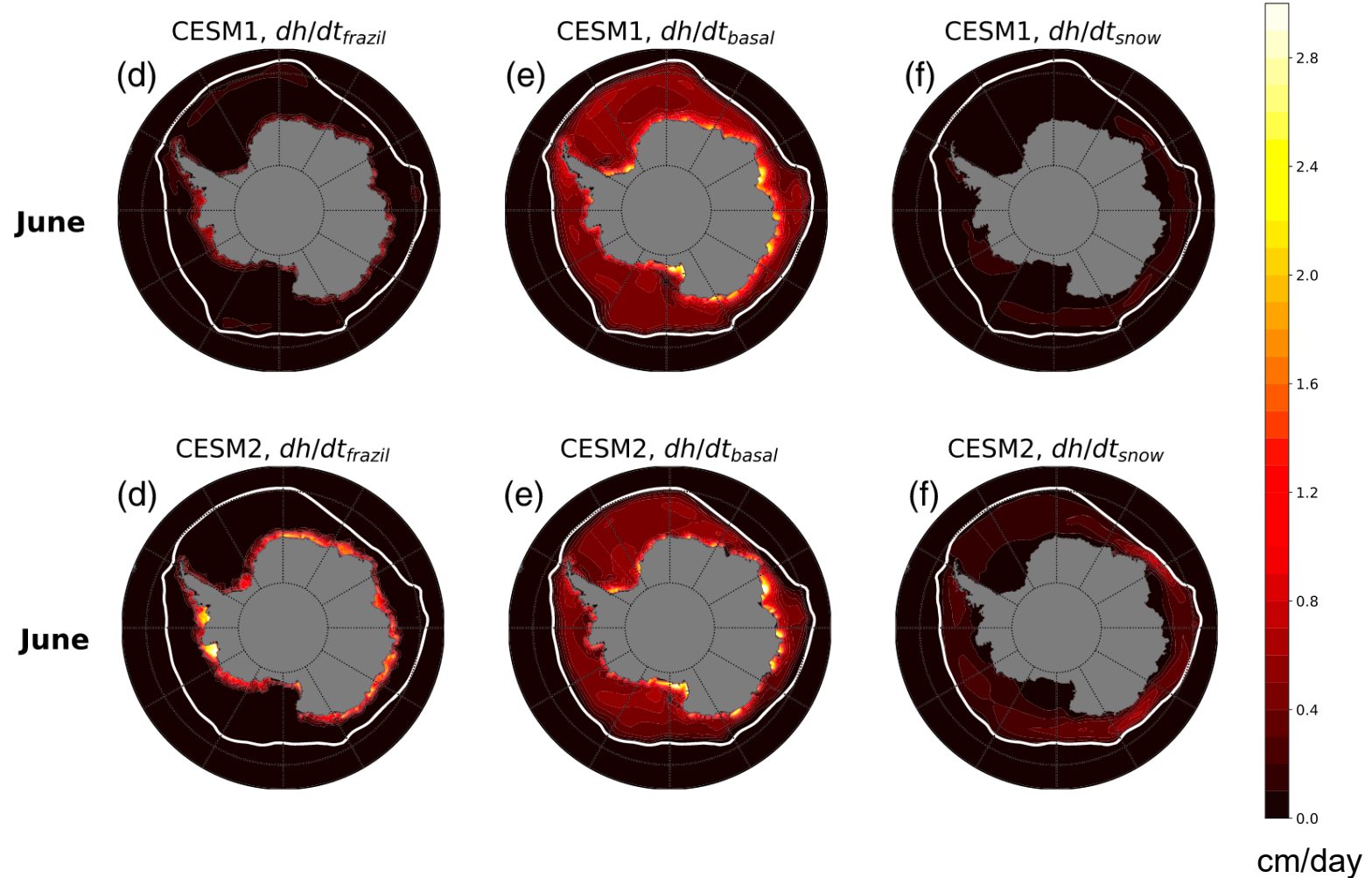
CESM2 mean Antarctic state is



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

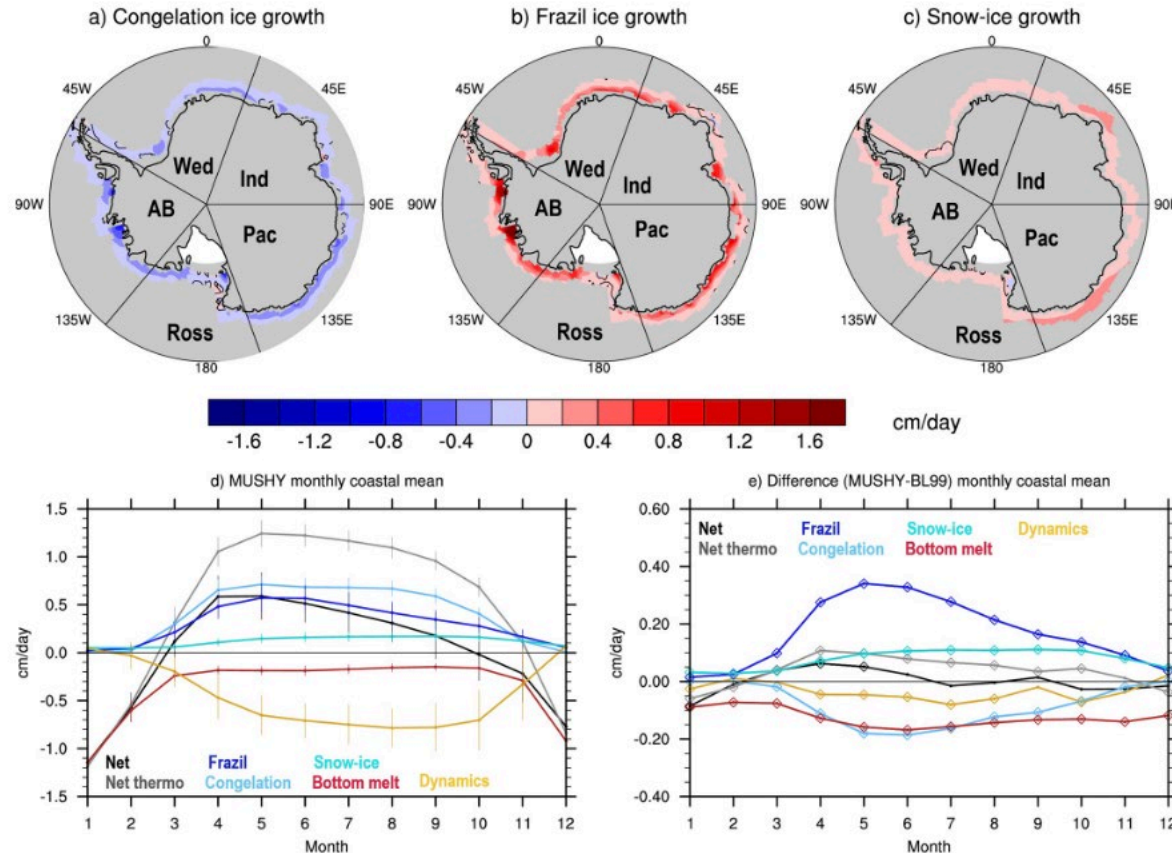
Singh et al. 2020
<https://doi.org/10.1029/2020MS002143>

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.

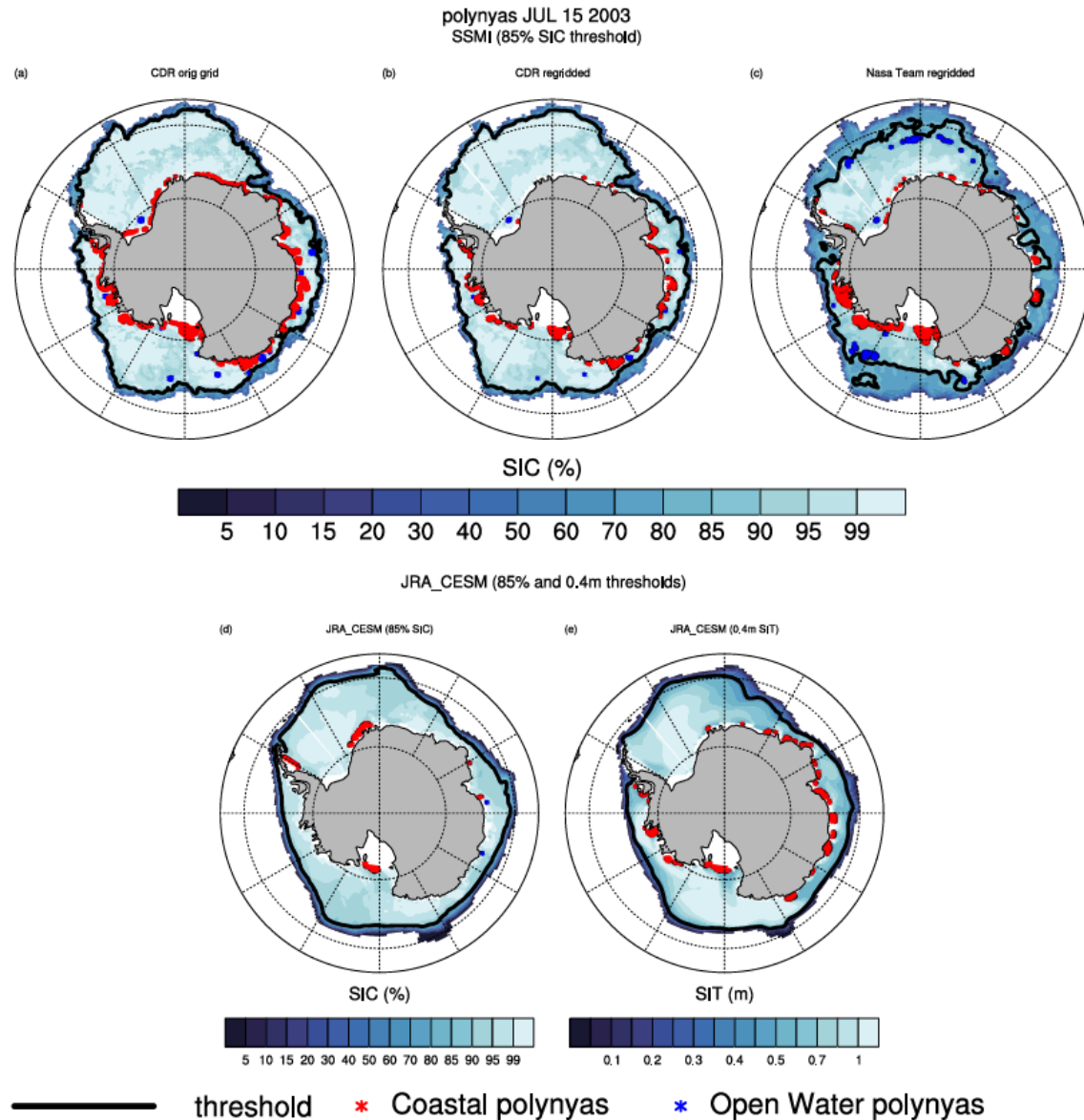
CESM2 Antarctic Sea Ice – growth processes are changing



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.

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.



Thank you! – Questions?

Please get in touch!

duvivier@ucar.edu
dbailey@ucar.edu

From: ChatGPT

“Sea Ice party”



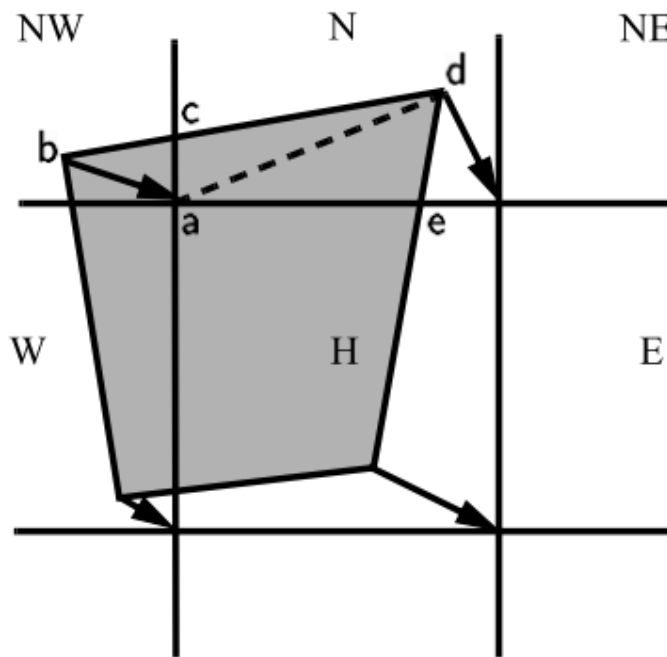
Extra Slides

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.

Advection

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



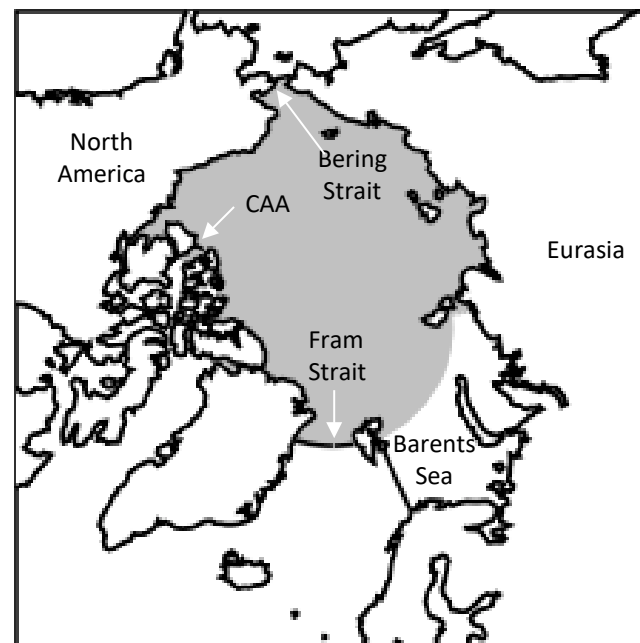
Conserved quantities are remapped from the shaded “departure region”, which is computed from backward trajectories of the ice motion field.

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

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

Ice volume change Thermodynamic source Divergence

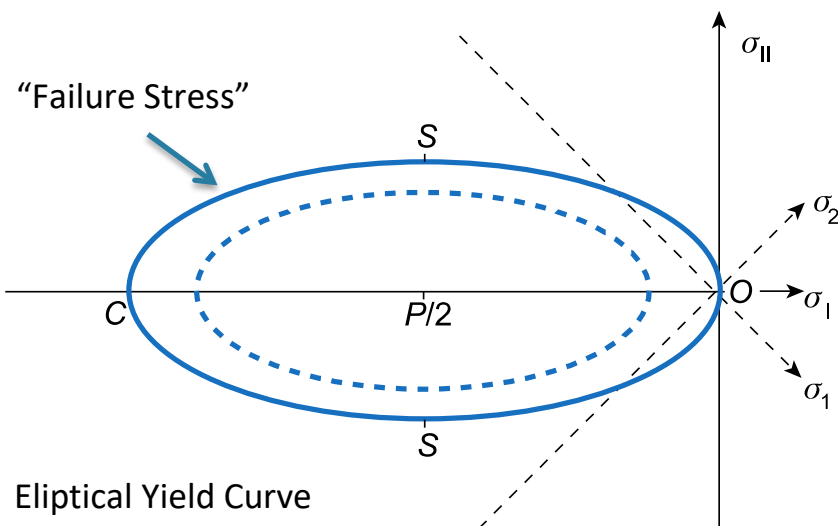


Climate model archive of monthly averaged ice thickness and velocity

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

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)

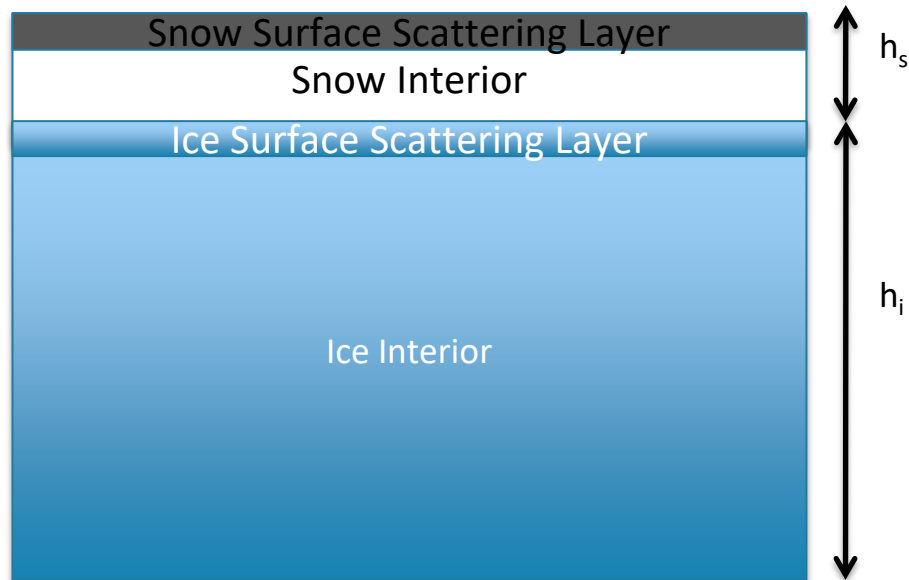


Elastic-Viscous-Plastic Model

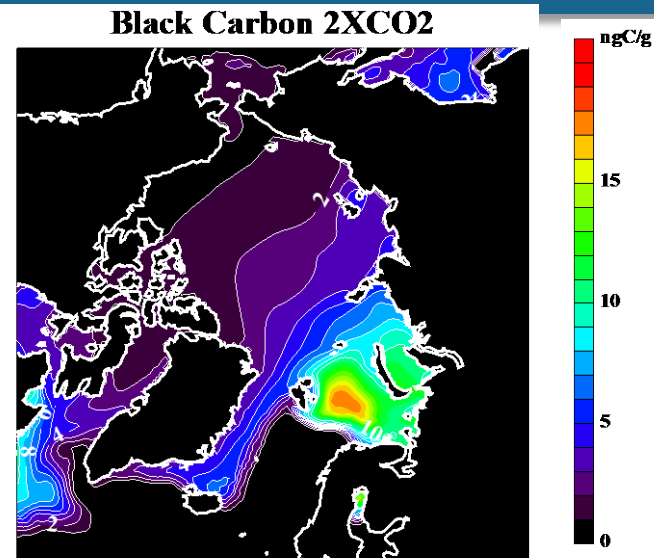
EVP model uses explicit time stepping by adding elastic waves to constitutive law (Hunke and Dukowicz, 1997)

Aerosol deposition and cycling

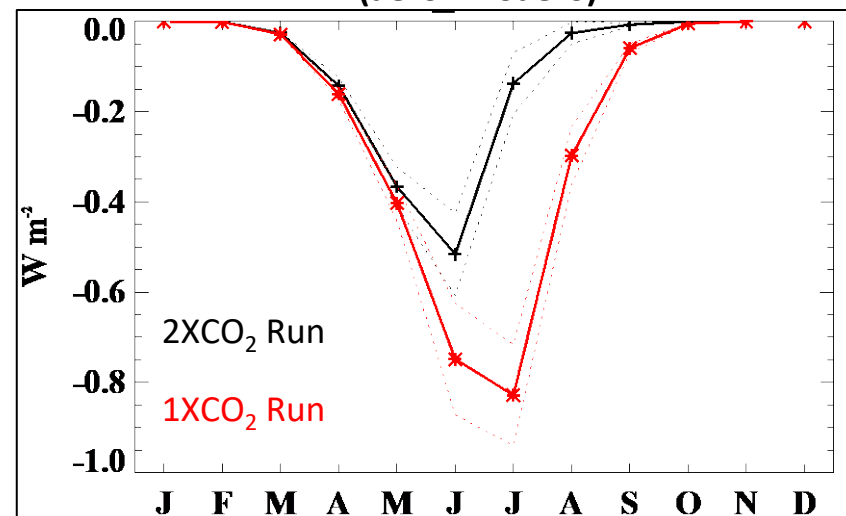
- Aerosol (e.g. dust, black carbon) deposition and cycling now included.
- These are deposited from the atmosphere and modified by melt and transport
- ~10% of the impact of melt ponds



With 1850
Aerosol
Deposition



Arctic Basin Average SW flux
(aero – noaero)



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