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Title: Sea Ice Modeling in E3SM

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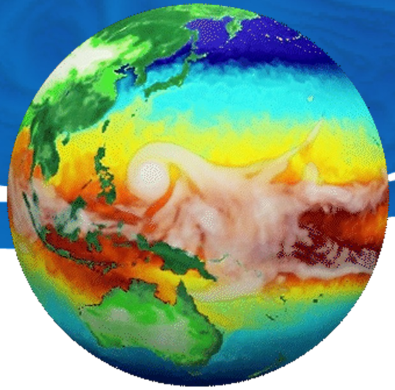
Sea Ice Modeling in E3SM

Elizabeth Hunke, Andrew Roberts, Darin Comeau and rest of Sea Ice Team



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E3SM Energy Exascale Earth System Model

Sea ice is frozen ocean water

Weddell Sea, Photo credit: Elizabeth Hunke

Photo credit: Hajo Eicken

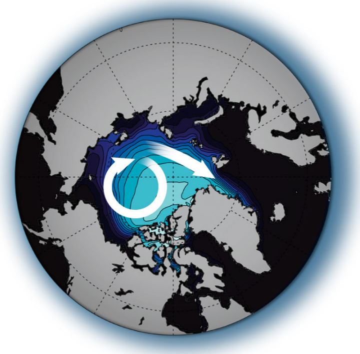
What's important? Albedo

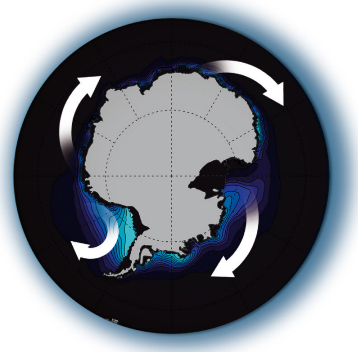
High ice/snow albedo reflects solar radiation.

Sea ice insulates atmosphere from ocean, influencing heat & moisture exchange.

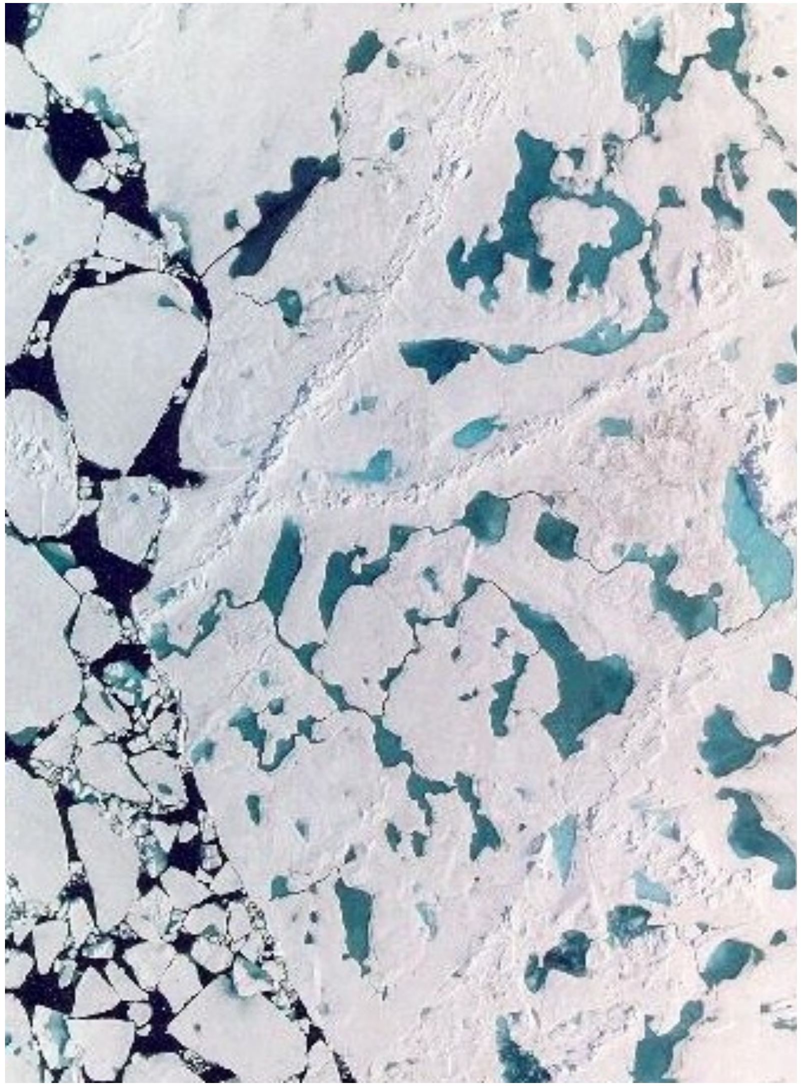
Elizabeth Hunke

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





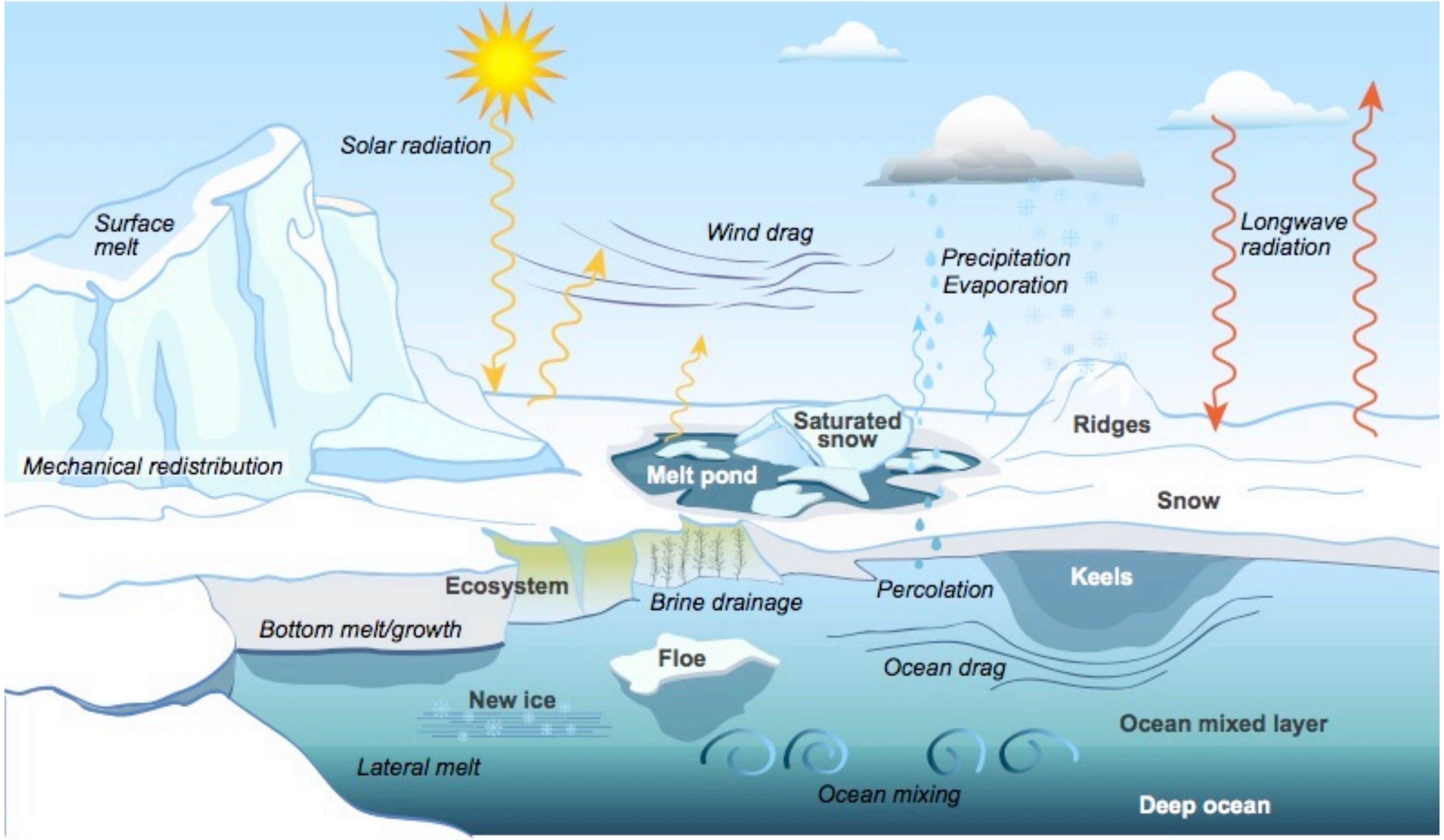
- Reasonable mean state, variability
  - Concentration, thickness, mass & energy budgets
- Realistic ice-ocean-atmosphere exchanges of mass and energy
- Realistic response to climate perturbations
  - Key climate feedbacks
  - Ice **thickness** determines sensitivity to melting and freezing



Arctic sea ice, ridges, melt ponds, open water. D. Perovich

MPAS-Seaice uses Icepack for column physics

Physical processes that affect the area and thickness of sea ice



github.com/CICE-Consortium/Icepack

E3SM implementation of Icepack from the CICE Consortium

- Icepack
  - Morphology
    - Thickness Distribution ↔ ∘
    - Floe Size Distribution ↔ ∘ V3
    - Snow Distribution ↔ ∘
    - Ridged Ice Distribution ↔ ∘ V4
    - Melt Pond Fraction ↔ ∘
    - Brine & Enthalpy Distribution ↔ ∘
  - Physics
    - Radiative Transfer ↓↑ ∘
    - Ice-Atmosphere Turbulent Fluxes ↓↑ ∘ ∘
    - Ice-Ocean Turbulent Fluxes ↓↑ ∘ ∘
    - Vertical Growth & Melt ↓↑ ∘
    - Lateral Growth & Melt ↓↑ ∘
    - Precipitation Hydrology ↓↑ ∘
  - Biogeochemistry
    - Skeletal Layer ↓↑ ↔ ∘
  - Data Fusion
    - Altimetric Emulator ⟳ ∘ V4

E3SM

CICE Consortium

Arrows indicate energy (↓↑) and mass (↓↑) flux exchange with the ocean and atmosphere, as well as horizontal advection (↔) using a dynamical core with Icepack. Small circles indicate the location of current (∘) Icepack calculations, and preferred (∘) column calculations in the case of a CD grid. ⟳ indicates observational emulation in run time.

Andrew Roberts

github.com/CICE-Consortium/Icepack

What does MPAS-Seaice do?

- Dynamics
  - Momentum
  - Stress
  - Transport
    - tracers
  - Mechanical redistribution (ridging)
- Thermodynamics
  - Radiation
  - Mushy layer
  - Melt terms
    - Top (surface) and bottom (basal)
  - Growth terms
    - Bottom accretion (congelation)
    - Frazil formation
    - Snow-ice formation

- Ice thickness distribution

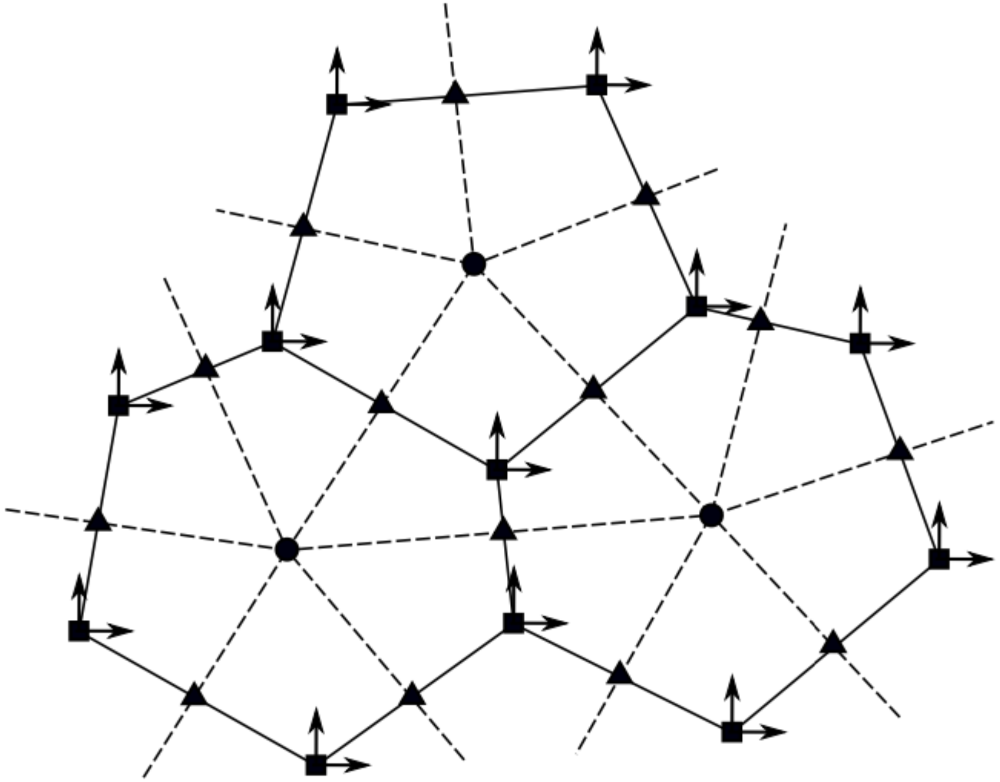
- Other physics
  - Melt ponds
  - Snow
  - Biogeochemistry
  - Floe size distribution (new!)
- Analysis members
- Driver (coupling interface)
- I/O

MPAS-Seaice

Icepack

MPAS-Seaice overview

- MPAS-Seaice is based on Multiple Prediction Across Scale (MPAS) framework
  - Unstructured mesh, Voronoi tessellation
  - Shares mesh with ocean
- Continuum model
  - Sea ice occupies a percentage of a grid cell, individual floes are not resolved.
- Uses a “B-grid”
  - Sea ice velocity is defined at cell vertices
  - Sea ice concentration, volume, and tracers defined at cell centers.



Sample from an MPAS mesh showing the primal mesh (solid lines), the dual mesh (dashed), and velocity components aligned with a locally Cartesian coordinate system (east/north).

Turner et al 2022, GMD

E3SM Energy Exascale Earth System Model

Sea ice dynamics

The sea ice momentum equation is:

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

- $m\frac{D\mathbf{u}}{Dt}$ → momentum
- $\nabla \cdot \sigma$ → internal stress
- $\vec{\tau_a}$ → wind stress
- $\vec{\tau_w}$ → ocean stress
- $k \times mf\mathbf{u}$ → Coriolis
- $mg\nabla H_o$ → sea surface tilt

Hibler 1979

Sea ice dynamics

The equation we actually solve (neglecting advective acceleration terms) is:

$$m\frac{\partial \mathbf{u}}{\partial t} = \nabla \cdot \sigma + \vec{\tau_a} + \vec{\tau_w} - k \times mf\mathbf{u} - mg\nabla H_o$$

- $m\frac{\partial \mathbf{u}}{\partial t}$: momentum
- $\nabla \cdot \sigma$: internal stress
- $\vec{\tau_a}$: wind stress
- $\vec{\tau_w}$: ocean stress
- $k \times mf\mathbf{u}$: Coriolis
- $mg\nabla H_o$: sea surface tilt

Hibler 1979

- The internal stress calculation comprises the bulk of the computational cost and is where elastic-viscous-plastic (EVP) rheology (Hunke & Dukowicz, 1997) for sea ice comes in.

Sea ice transport

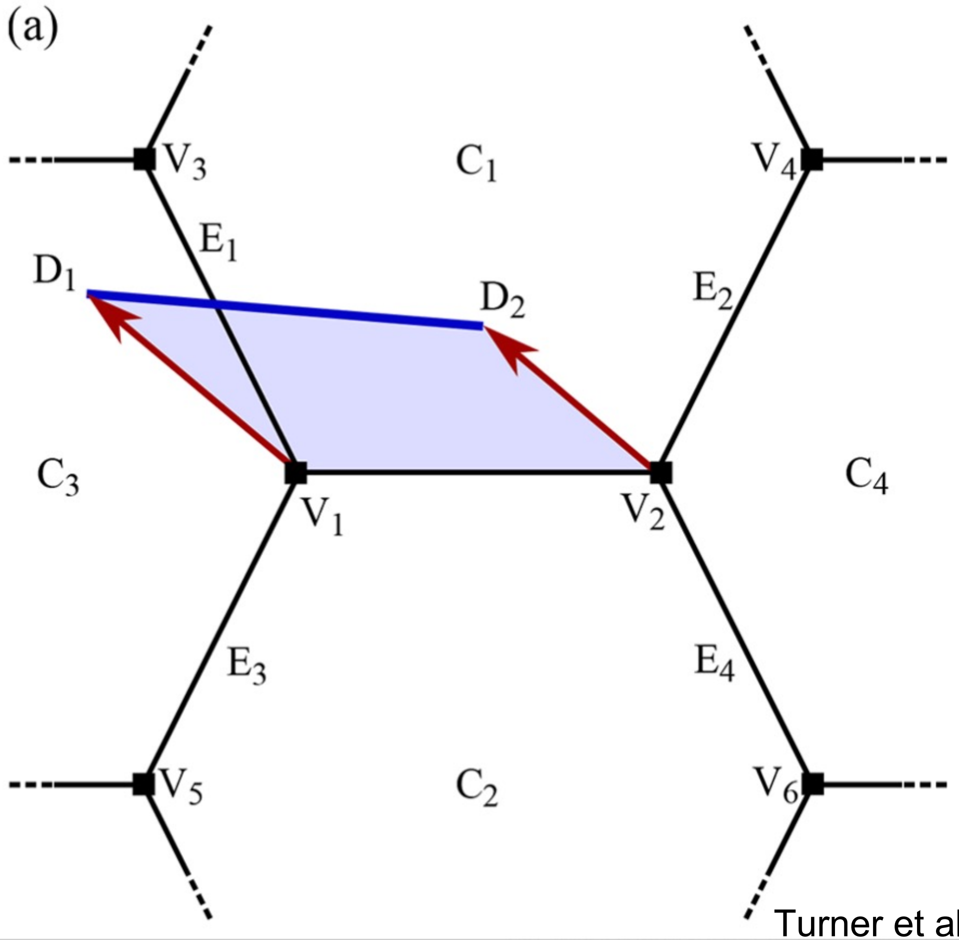
- Transport is done via incremental remapping (Lipscomb & Hunke 2004, MWR)
- Incremental remapping is designed to be conservative, i.e.

$$\frac{\partial c}{\partial t} + \nabla \cdot c\vec{u} = 0$$

- And for a tracer h (e.g. ice thickness)

$$\frac{\partial ch}{\partial t} + \nabla \cdot ch\vec{u} = 0$$

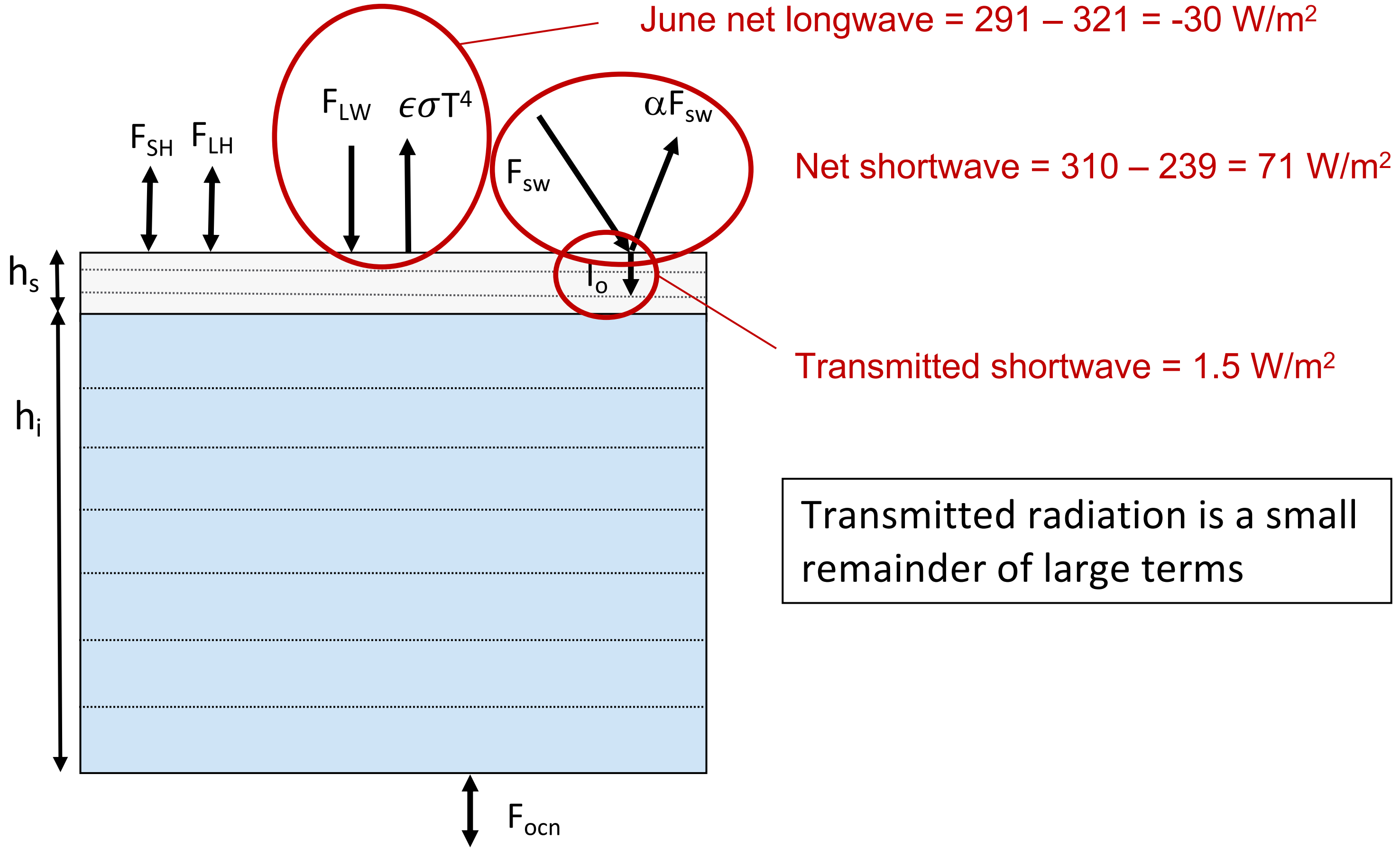
- IR is also monotonic, and scales well with additional tracers



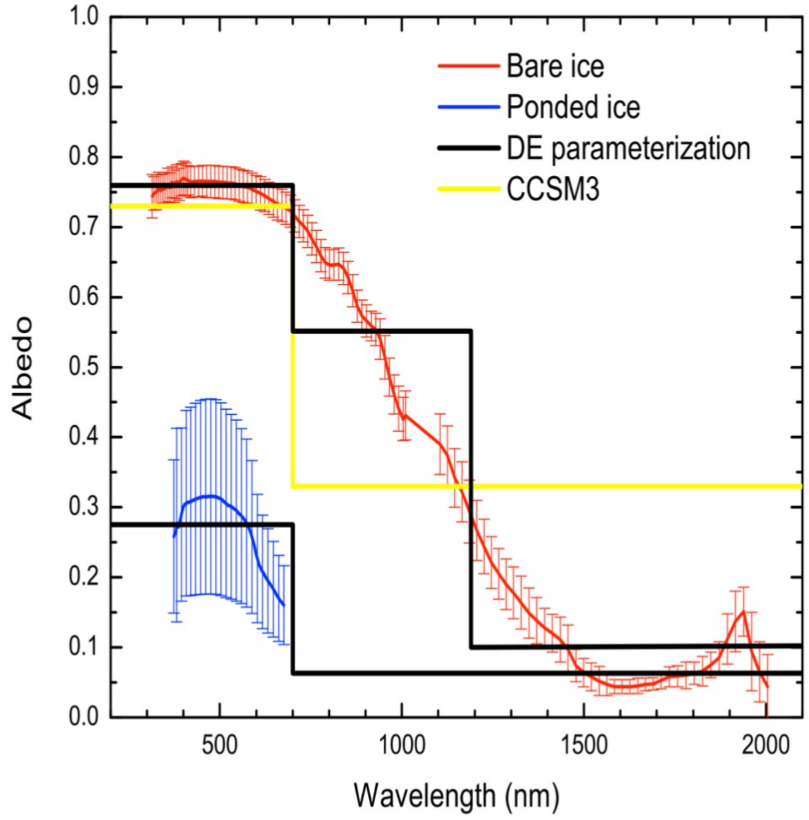
Turner et al 2022, GMD

Schematic showing transport across a cell edge on an MPAS mesh. Backward trajectories shown as red arrows to departure points D.

Sea ice thermodynamics – radiation

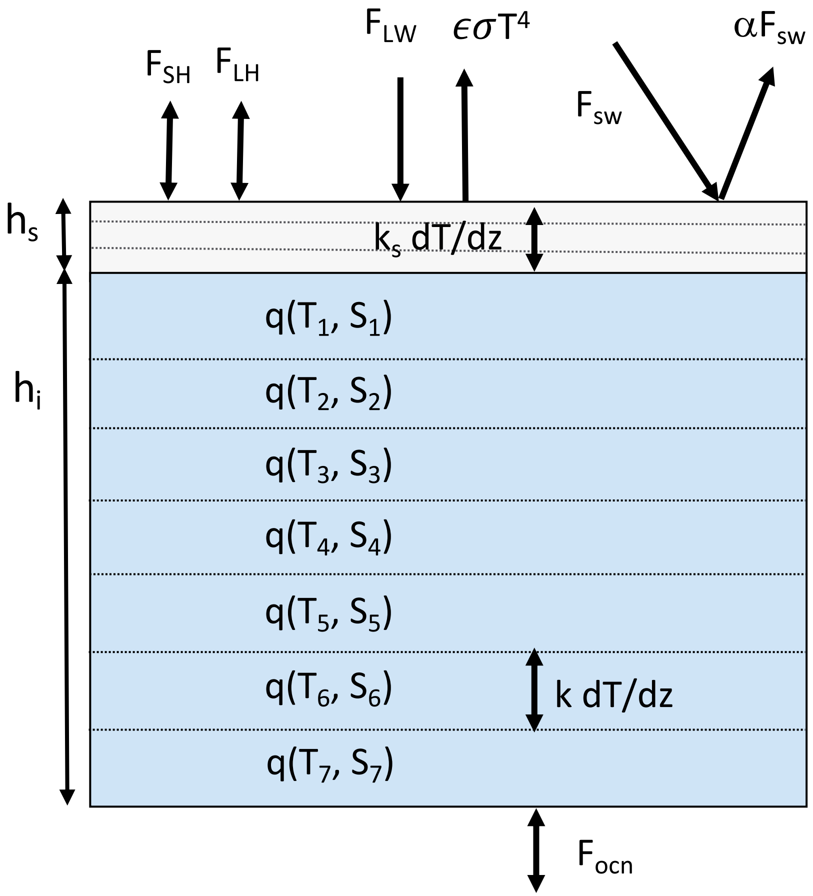


Transmitted radiation is a small remainder of large terms



Briegleb and Light, 2007

Sea ice thermodynamics – mushy layer



Sea ice is a multi-phase, multi-component material.

Calculate top, lateral, internal, and basal freezing and melting / dissolution

Top surface heat flux balance

$$(1-\alpha)F_{SW} + FLW - \epsilon\sigma T^4 + FSH + FLH - k\frac{\partial T}{\partial z} = q\frac{dh}{dt}$$

Vertical conduction of heat and salt

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) + w\frac{\partial q_{br}}{\partial z} + F$$

$$\frac{\partial S}{\partial t} = w\frac{\partial Sbr}{\partial z} + G$$

$$\phi = \frac{S}{S_{br}} \qquad K = \phi Kbr + (1-\phi)K_i$$

Bottom surface heat flux balance

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

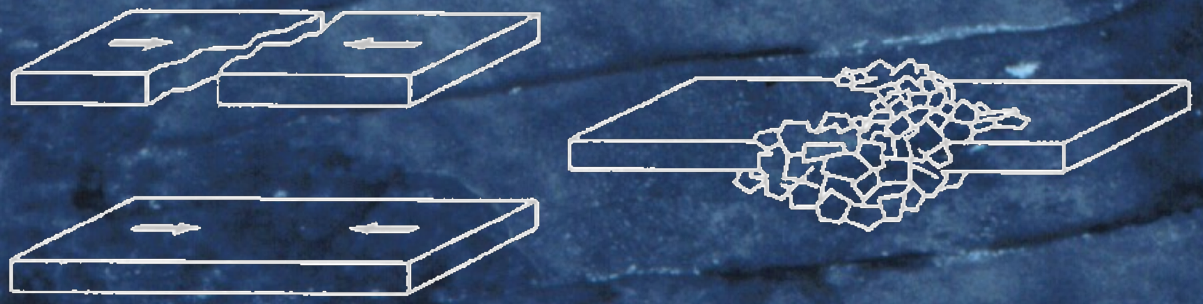
There are more equations for the brine quantities, forcing terms, etc.

Turner, Hunke, Bitz 2013, JGR: Oceans

Ice thickness is influenced by

- Thermodynamic growth and melt
  - Top and bottom melt
  - Bottom accretion (congelation)
  - Frazil formation
  - Snow-ice formation
  - “Mushy layer” with prognostic salinity

- Mechanical redistribution (ridging, rafting)

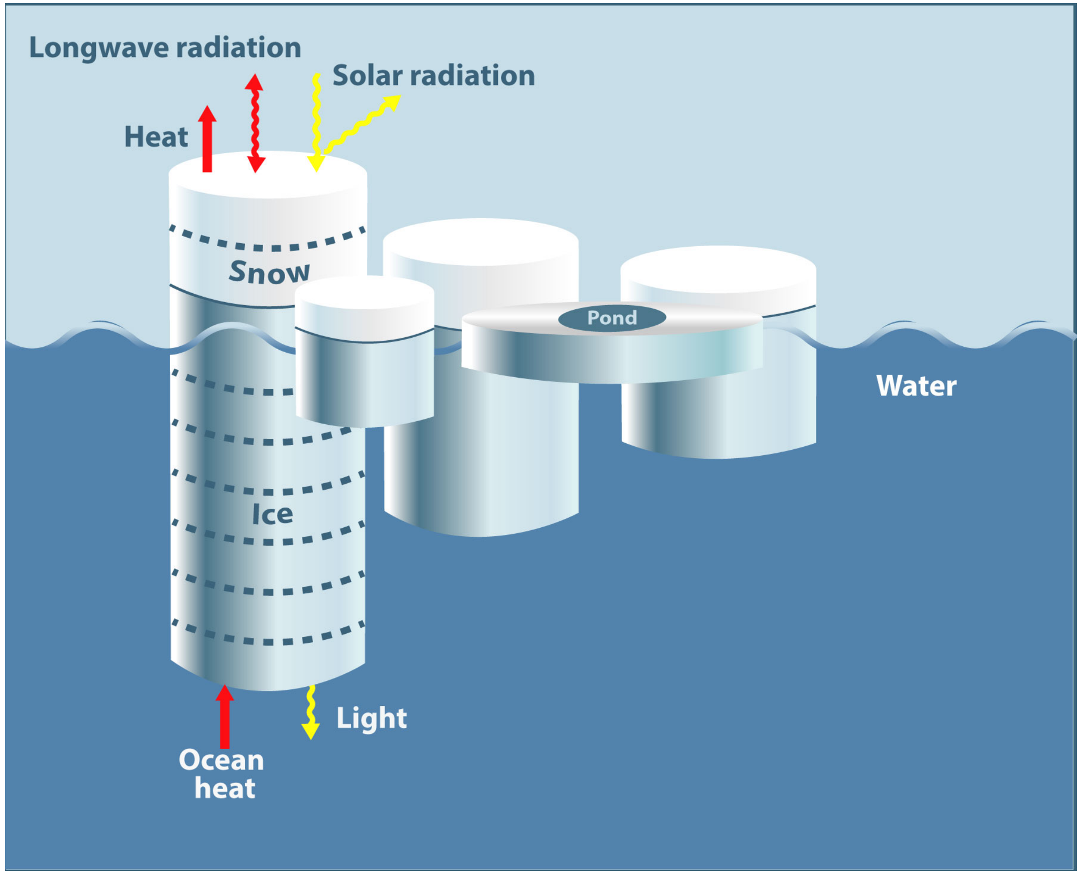


Sea ice thickness distribution

$g(\mathbf{x}, h, t)\, dh =$ the fractional area covered by ice in the thickness range $(h, h + dh)$ at a given time t and location $\mathbf{x}$

$$\frac{\partial g}{\partial t} = -\nabla \cdot (g\mathbf{u}) + \psi - \frac{\partial}{\partial h}(fg) + L,$$

$\nabla = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y})$
$\mathbf{u}$ = horizontal ice velocity
ψ = mechanical redistribution function
f = rate of thermodynamic ice growth
L = lateral melting



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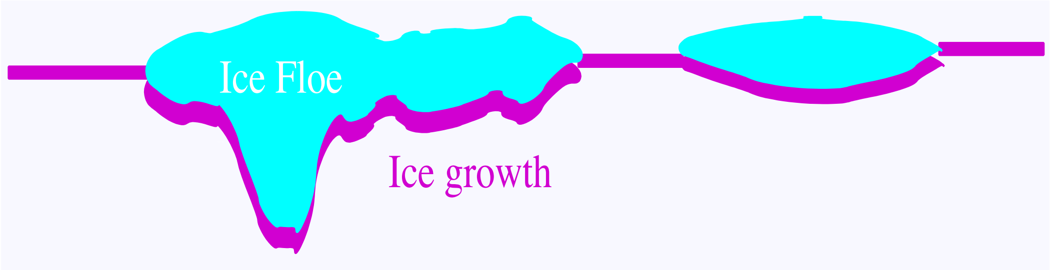
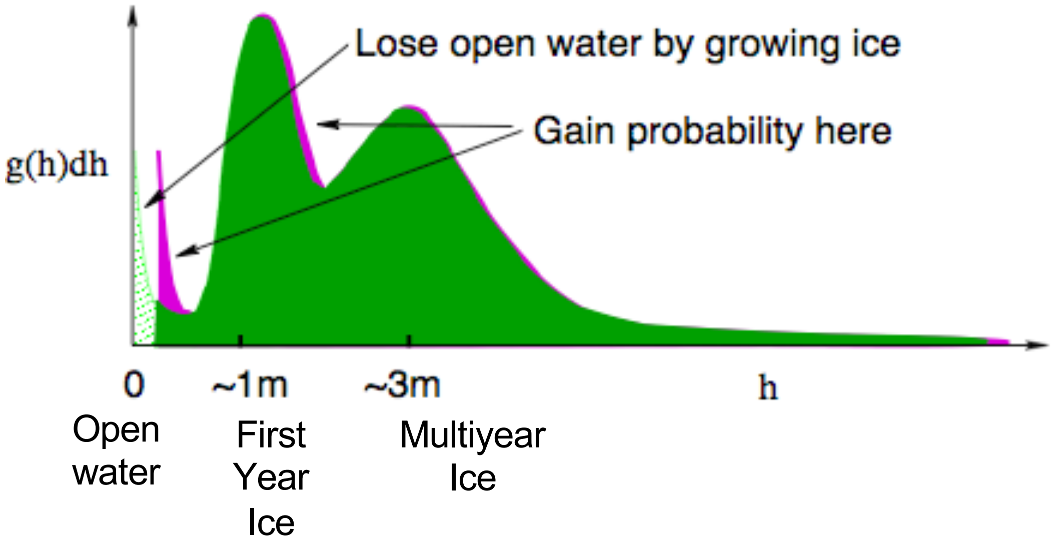
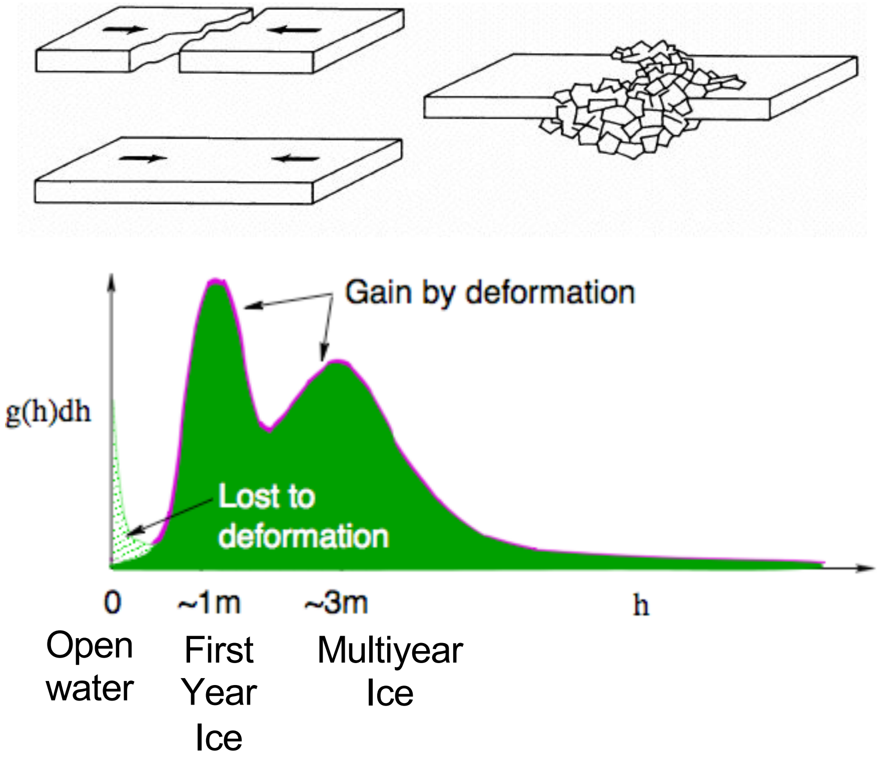


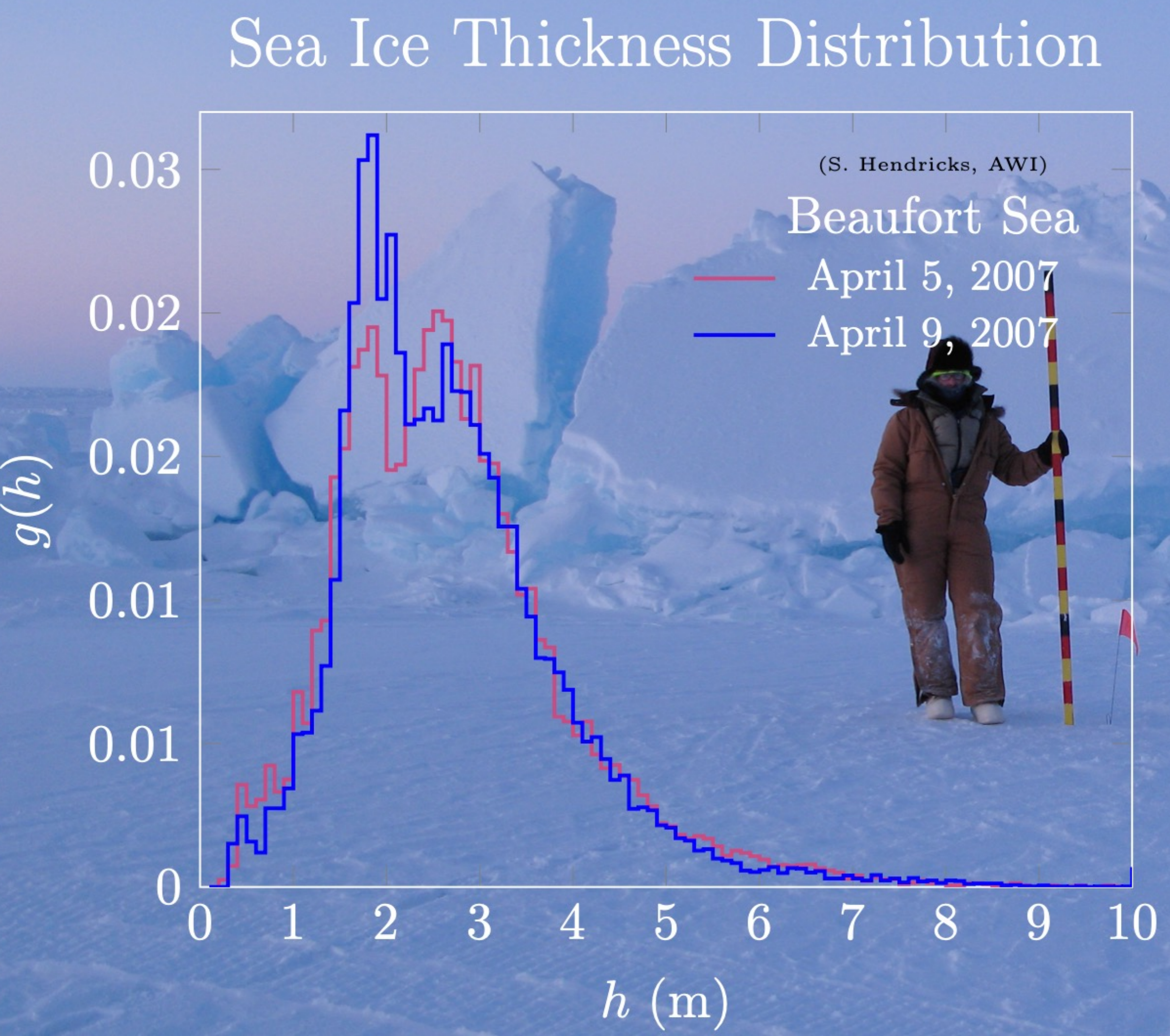


Sea ice thickness distribution

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

Hajo Eicken





$$m = \rho \int_0^\infty g(h)\, h\, dh$$

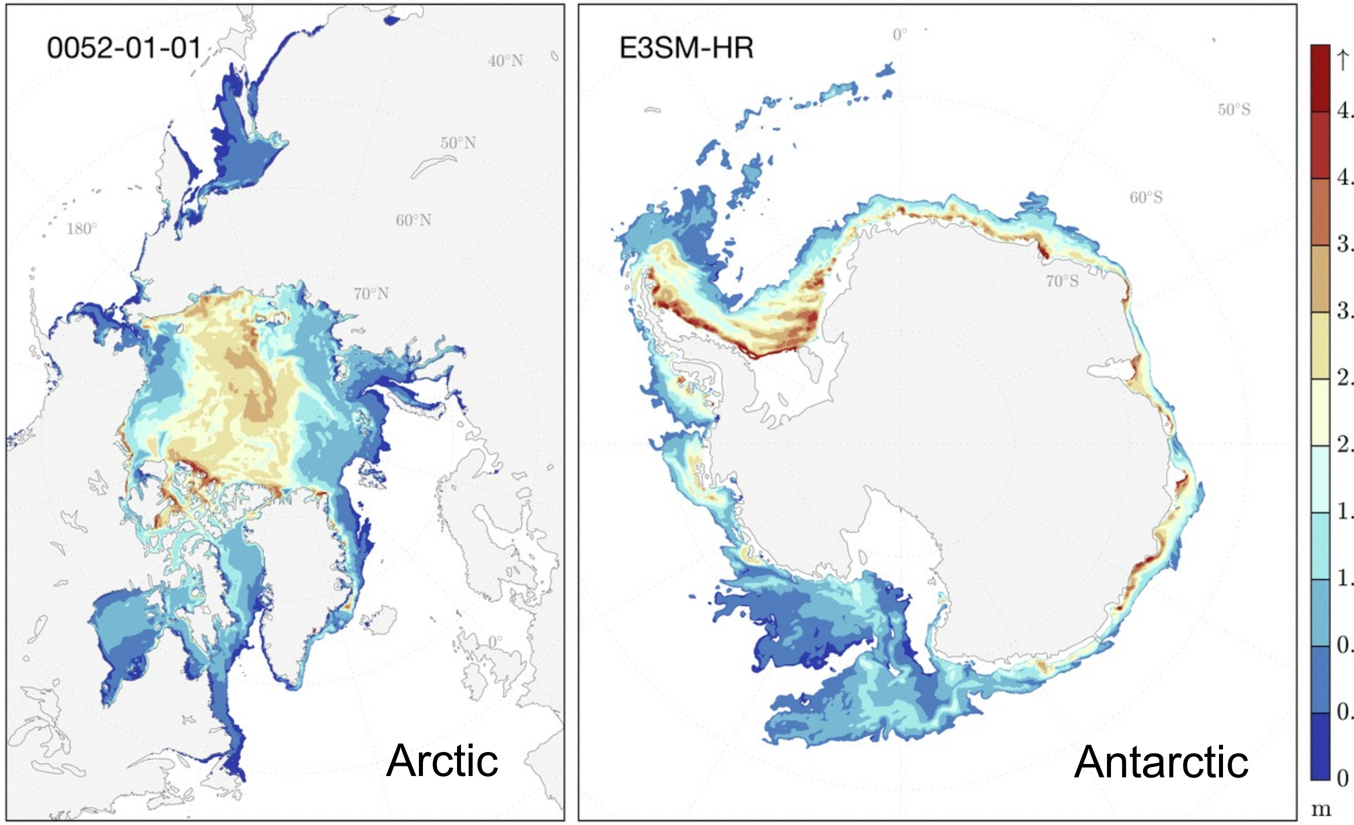
$g(h)$ is used to describe mass conservation in sea ice models:

$$\frac{dg}{dt} = \Psi + \Theta - g(\nabla \cdot \dot{\boldsymbol{x}})$$

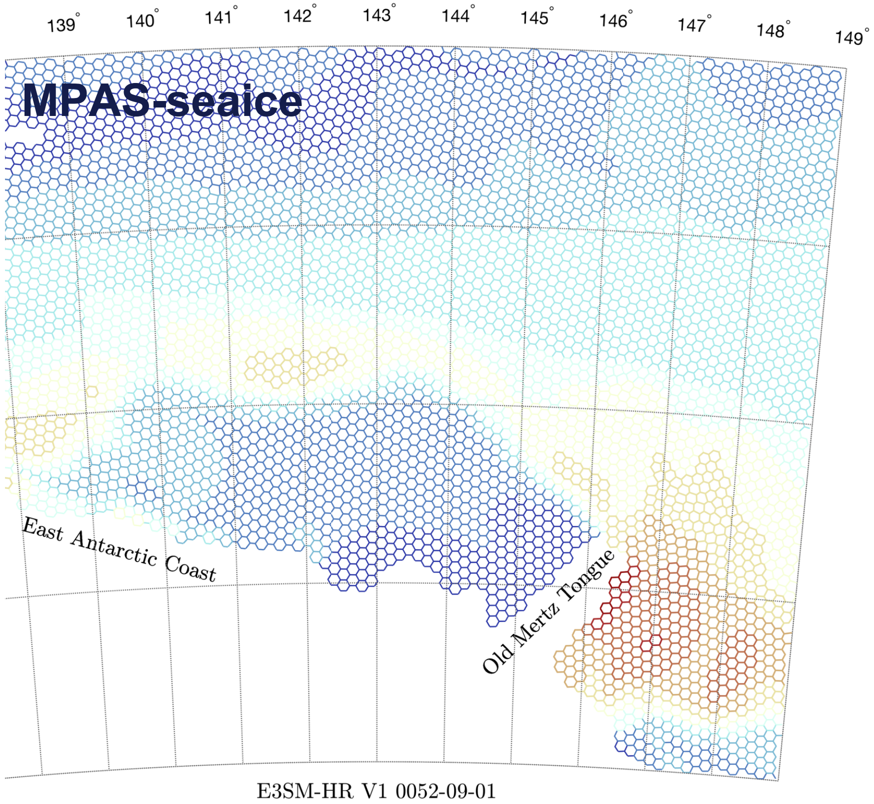
Ψ Dynamic Redistribution,
Θ Thermodynamic Redistribution

Andrew Roberts

Fully Coupled High-Resolution E3SM V1



Single annual cycle of sea ice thickness from a 50+ year fully coupled simulation using the HighResMip 1950 repeated year protocol



E3SM unstructured grid surrounding the Mertz Glacier Polynya in the East Antarctic, colored according to ice thickness.

Resolution:

- atmosphere, land 25 km
- ocean, sea ice: 6 km near the poles expanding to 18 km near the equator

E3SM Energy Exascale Earth System Model

Key Contributors: Peter Caldwell, Luke VanRoekel, Azamat Mametjanov, Adrian Turner, Chris Golaz, Milena Veneziani, Wuyin Lin, Mat Maltrud, Jon Wolfe, Andrew Roberts

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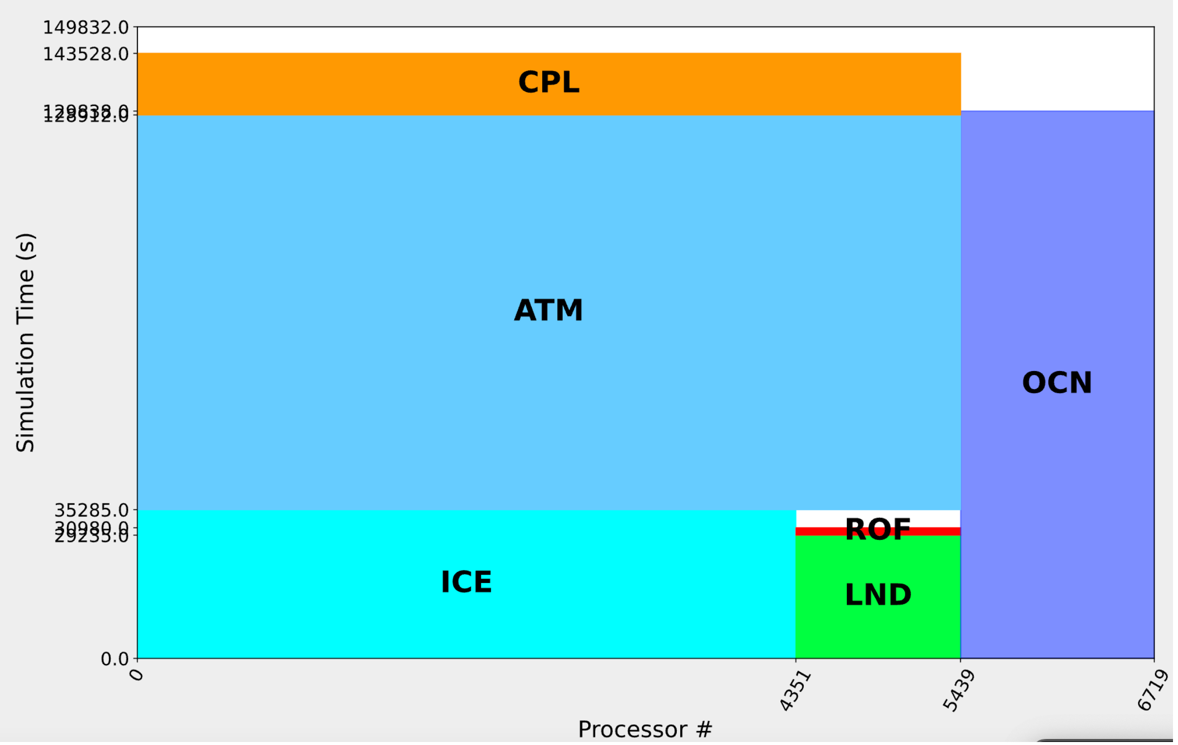
Documentation & References

- https://docs.e3sm.org/E3SM/MPAS-seaice
- https://cice-consortium-icepack.readthedocs.io/en/main/
- MPAS-Seaice overview manuscript: Turner, A.K., Lipscomb, W.H., Hunke, E.C., Jeffery, N., Engwirda, D., Ringler, T.D. and Wolfe, J.D., 2022. MPAS-Seaice (v1. 0.0): sea-ice dynamics on unstructured Voronoi meshes. *Geoscientific Model Development*, *15*(9), pp.3721-3751.



v3 performance by component

e3sm.org