Los Alamos NATIONAL LABORATORY

Modeling ice and polar oceans

Highlights from the CICE Consortium and LANL

Elizabeth Hunke
T-3 Fluid Dynamics and Solid Mechanics
LANL Program Manager for DOE Earth and Environmental Systems Sciences Division
Lead, CICE Consortium

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LA-UR-22-31676

CICE Consortium

Outline

Sea ice modeling

Recent developments from CICE Consortium and DOE

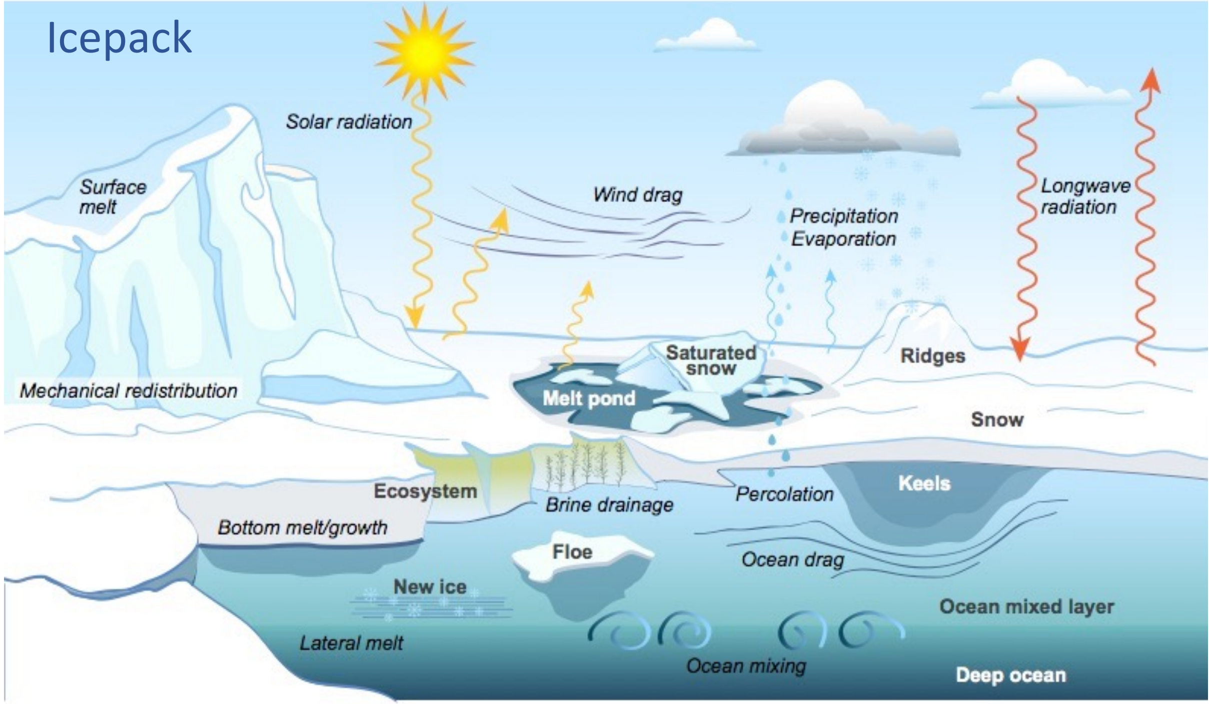
Modeling needs

Community surveys

Department of Energy / LANL efforts

Coastal, high resolution

Physical processes that affect the area and thickness of sea ice: thermodynamics / column physics



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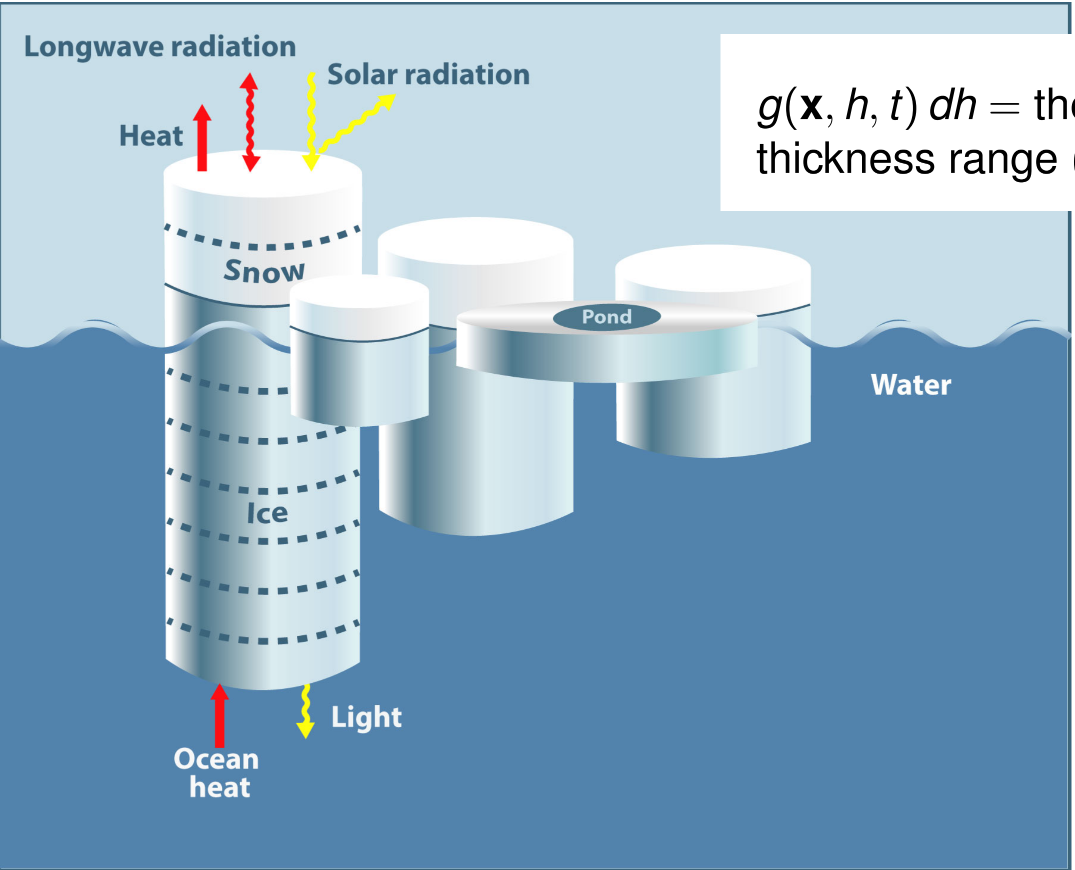
Sea ice thickness distribution



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

g evolves based on

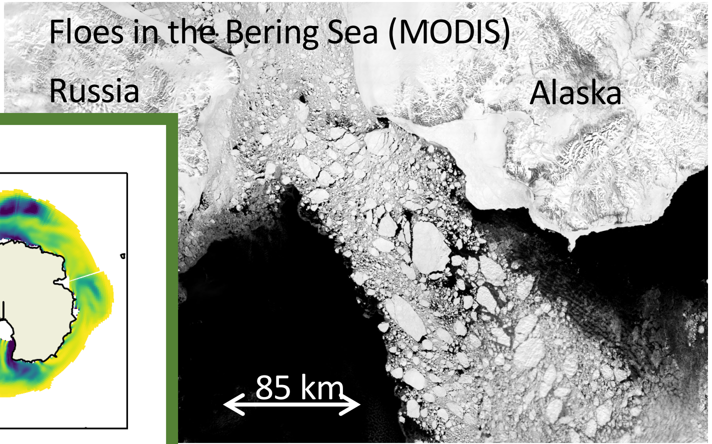
- Horizontal ice velocity
- Mechanical redistribution
- Rates of thermodynamic growth, melt

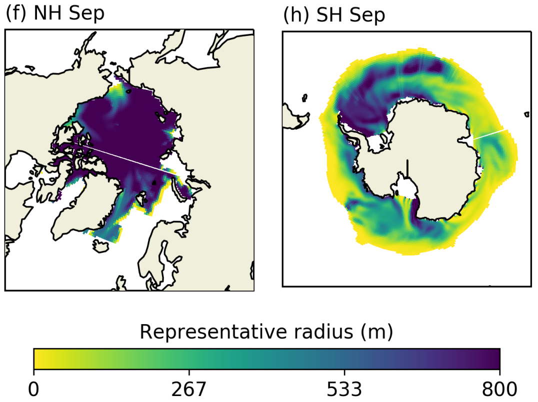
Enhances resolution of column-based physics within a grid cell

Wave-ice interactions

Floe size distribution *g(**x**, h, r, t)*

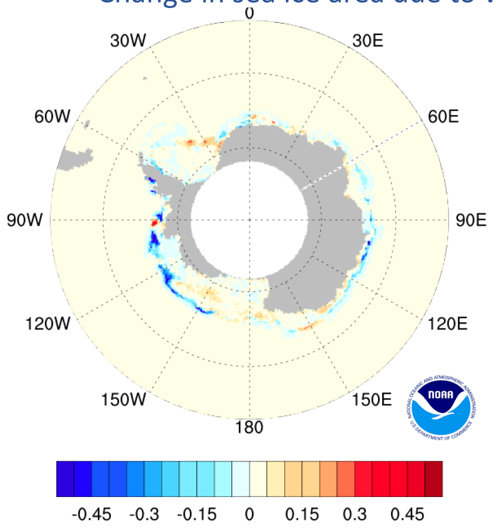
Waves are critical to FSD in the marginal ice zone.





Representative floe radius simulated by the FSD model in CICE5

Change in sea ice area due to waves



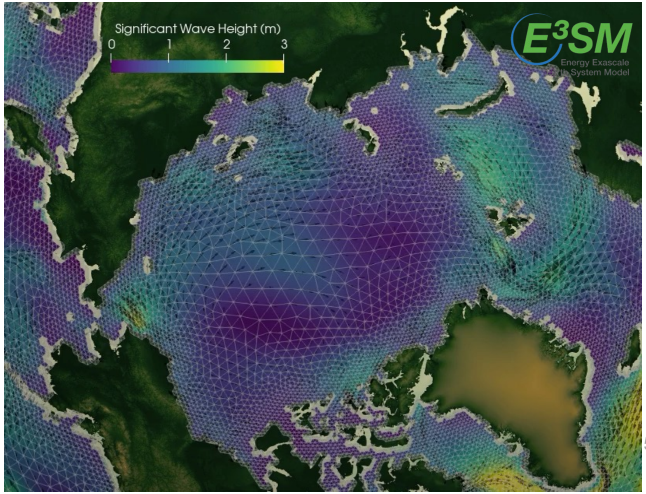
NOAA UFS 10-day test including CICE6 with FSD, MOM6, WW3

D. Worthen

Roach, Lettie, et al. (2018). An emergent sea ice floe size distribution in a global coupled ocean--sea ice model. *J. Geophys. Res. Oceans.*

WW3 running on an MPAS unstructured mesh

S. Brus



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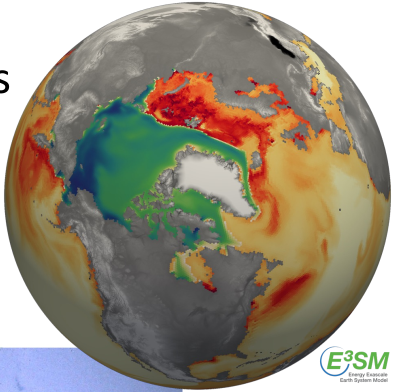
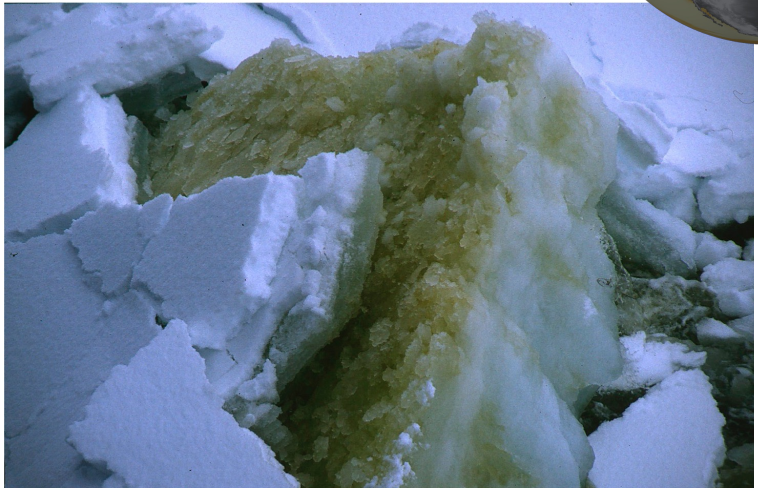
Sea ice ecosystem

Algae live in the liquid (brine) within sea ice and thrive where there are nutrients



April 2050 ice and ocean BGC

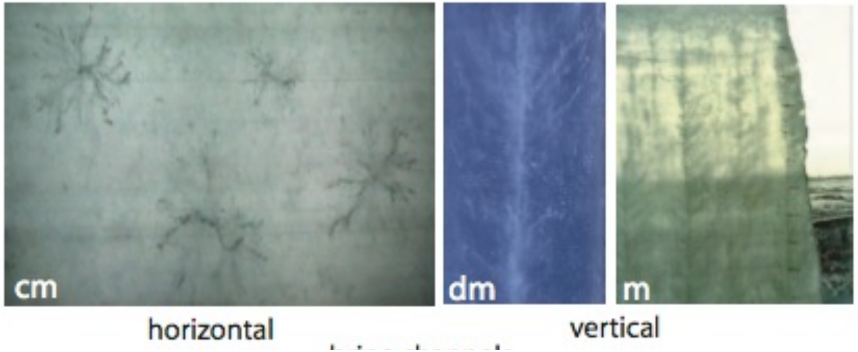


A photograph in natural light showing elongated tubes that form as brine pockets trapped between the ice crystals. The image is 5 millimeters in width. Photo courtesy of Ted Maksym, United States Naval Academy.

"Mushy" Thermodynamics

Equations	Variables
Conservation of Energy	Enthalpy
Conservation of Salt	Salinity
Ice-brine liquidus relation	Liquid fraction
Darcy flow through a porous medium	Vertical velocity

Brine channels

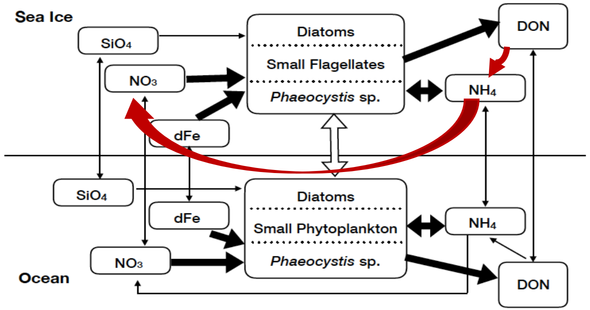


Courtesy K. Golden

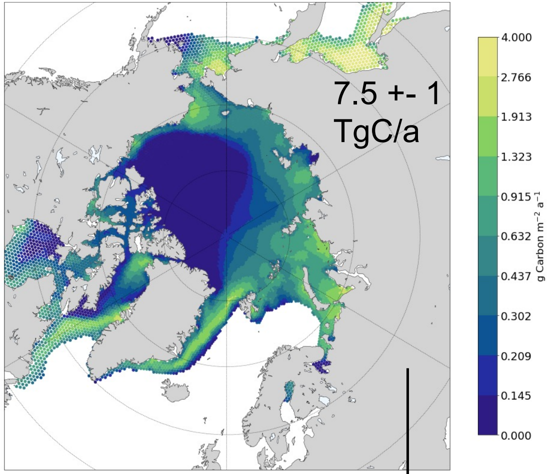
Ocean-sea ice BGC v2 simulations: Key Improvements

- v2 Physics: Redi-mixing parameterization was added, tuned, and validated, in order to resolve the (weak) ocean isopycnal mixing of tracers.

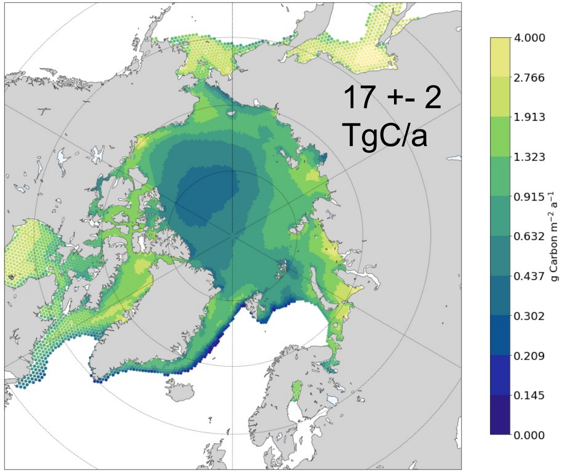
- Sea Ice eco-dynamics BGC developments. A world-leading capability.



E3SMv1.1 Sea ice Primary Production



E3SMv2 Sea ice Primary Production



Arctic Sea ice primary production: Well below observations of 9-73 TgC/a (Legendre et al 1992). Ocean surface nutrient biases play a significant role in this underestimation, we found that improved nitrogen cycling improved estimates to **17 +-2.1 TgC/a**

N. Jeffery

Advanced Snow Physics

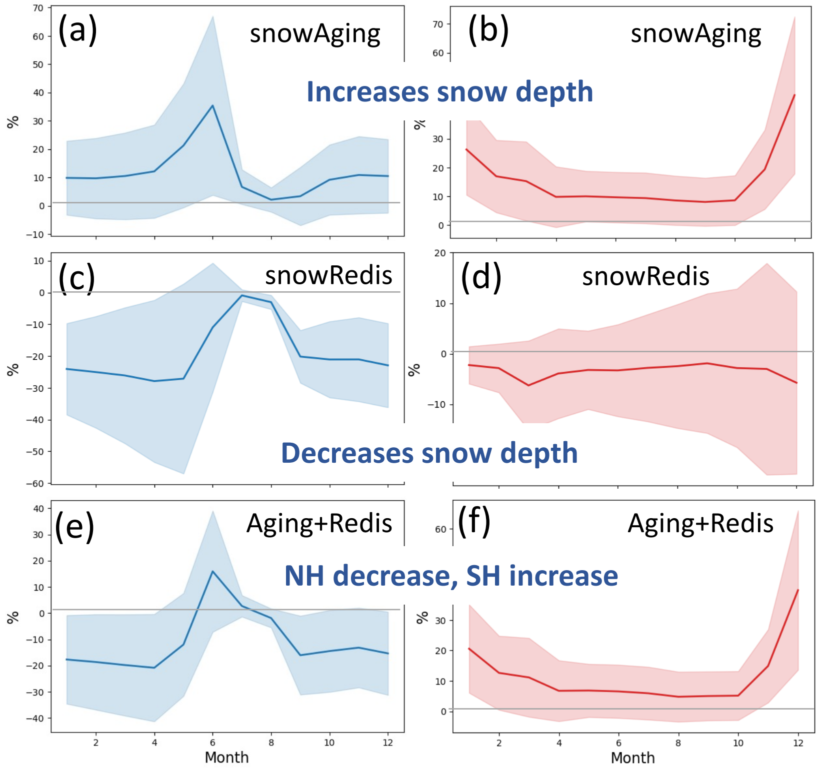
Impacts delta-Eddington radiation calculation

- Snow redistribution
  - Compaction by wind
  - Loss to leads
  - Interaction with ridges
  - Based on Lecomte et al. *Ocean Mod.* 2015

- Metamorphosis of snow grains (”aging”)
  - Grain size evolves as function of snow temperature, gradient, density
  - Wet and dry processes
  - Based on *NCAR/TN-478+STR* 2019
  - Use snow grain radius for dEdd radiation until ponds saturate snow

% Δ in Snow Thickness (Feature-Control)

Arctic | Southern Ocean



Shaded regions are the standard error in the monthly percent difference over the 102-year pre-industrial period.

N. Jeffery, E. Hunke

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E3SM Energy Exascale Earth System Model

Advanced Snow Physics

Impacts delta-Eddington radiation calculation

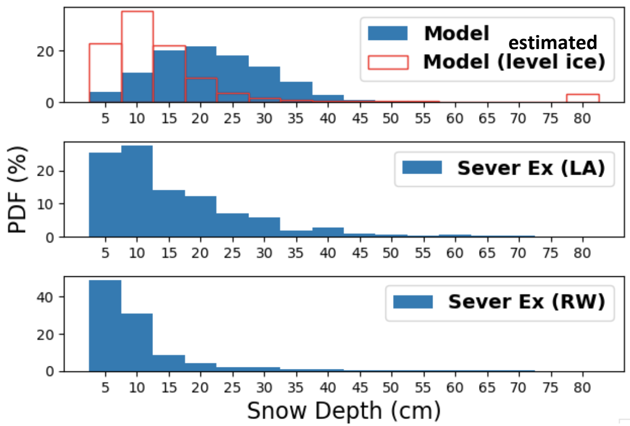
Comparison of modelled pre-industrial 102-year mean snow depth vs observations over level ice from the Sever Expeditions

Arctic 1954-1991, Shalina and Sandven, TC 2017

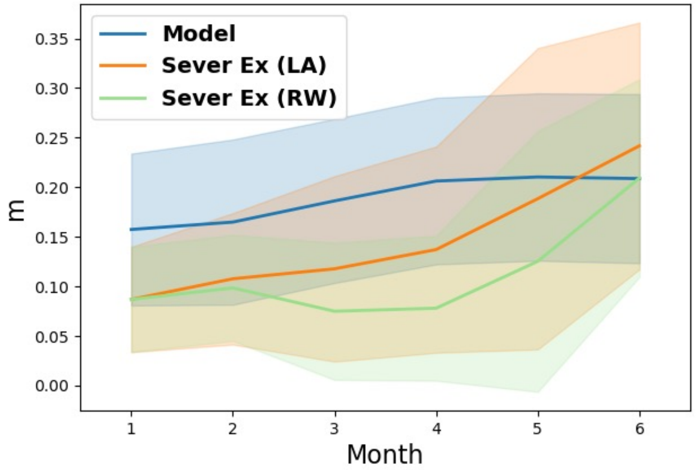
LA - Landing Area

RW - Runway

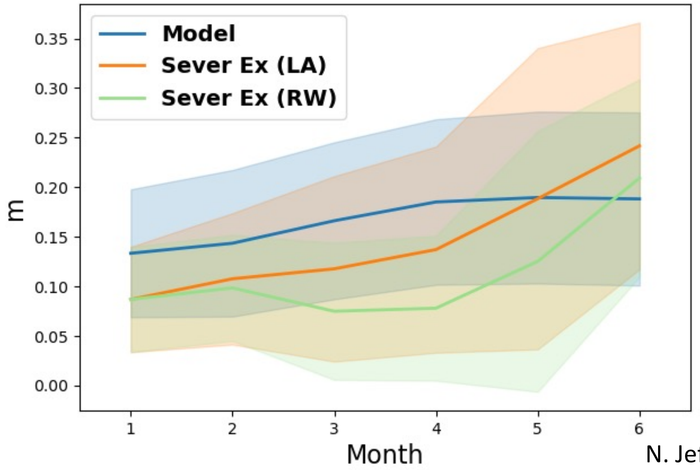
Snow Depth pdf (MAM,Russian Obs vs Aging+Redis)



Snow Depth Climatology (Russian Obs vs Control)



Snow Depth Climatology (Russian Obs vs Aging+Redis)



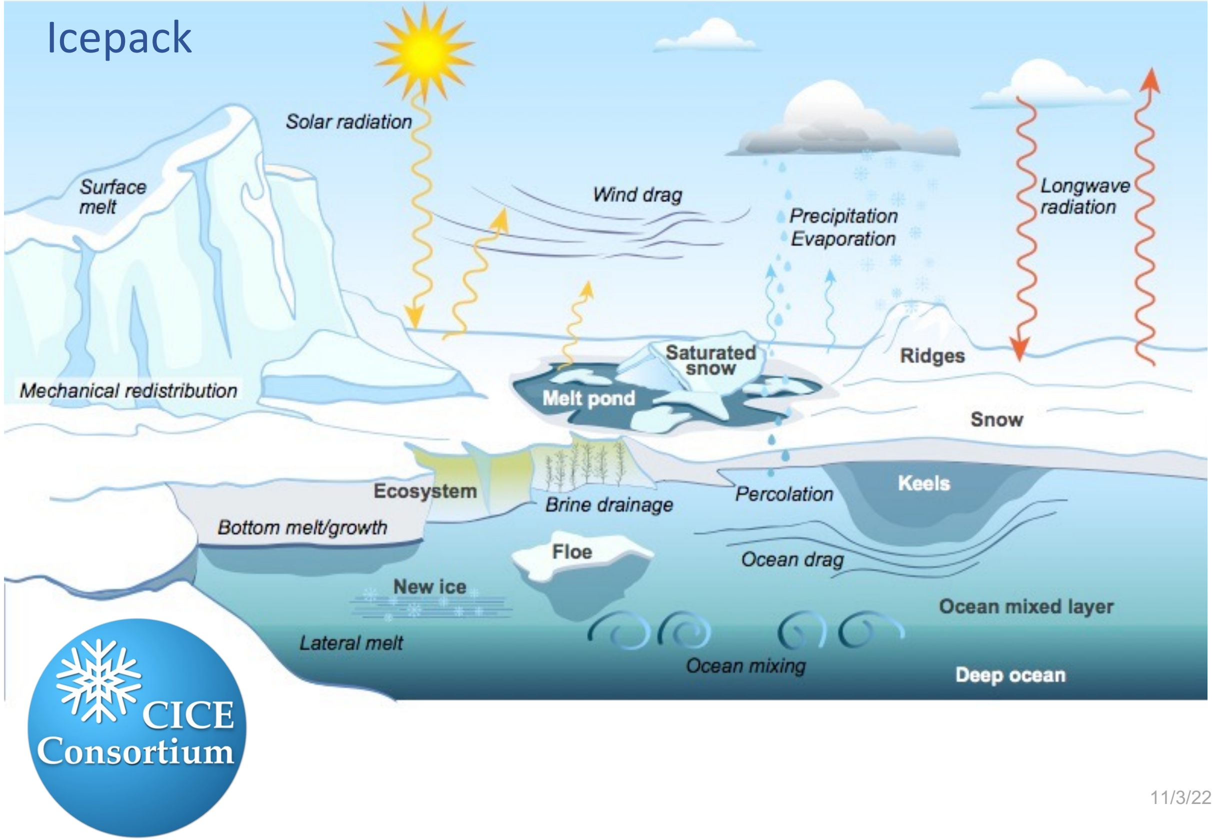
N. Jeffery

E3SM Energy Exascale Earth System Model

Physical processes that affect the area and thickness of sea ice: thermodynamics / column physics

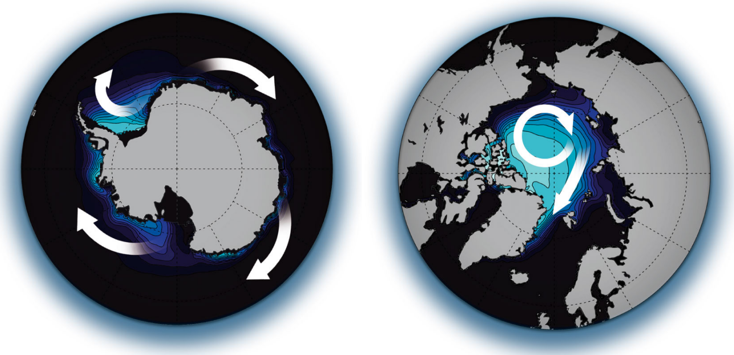
Major improvements for Icepack since 2019

- Floe size distribution
- Advanced snow physics
- Water isotopes
- Improved coupling mechanisms for under-ice drag, staggered atmospheric levels
- 5-band SNICAR / delta-Eddington radiation scheme for snow
- NetCDF history output
- Redesigned driver interface

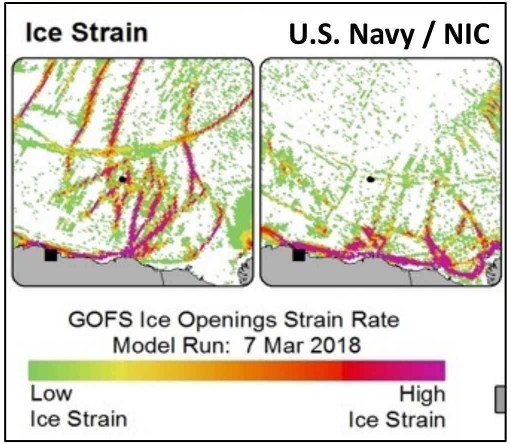


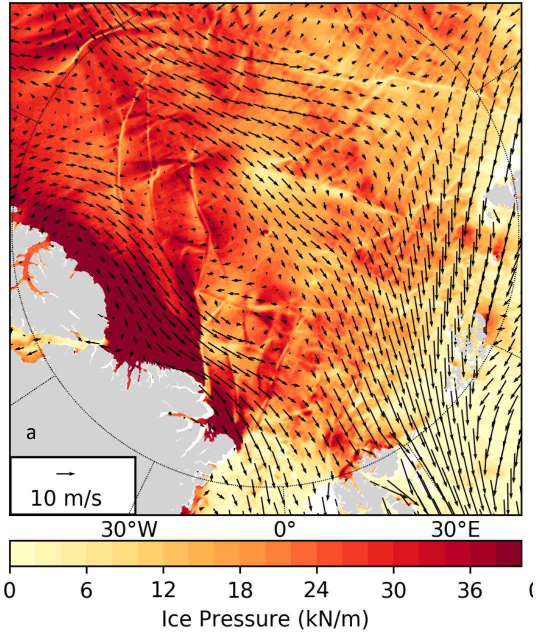
Quantities carried on or in the ice must be conservatively transported

Physical processes that affect the area and thickness of sea ice: dynamics



Momentum + rheology + conservation of transported quantities





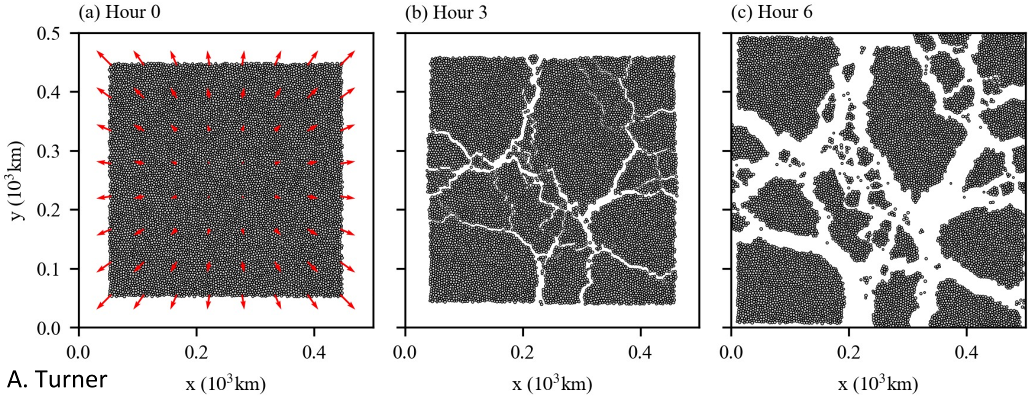
CICE

Canadian Arctic Prediction System

24 h forecast initiated at 00 UTC on 24 April 2020 in support of the MOSAiC expedition

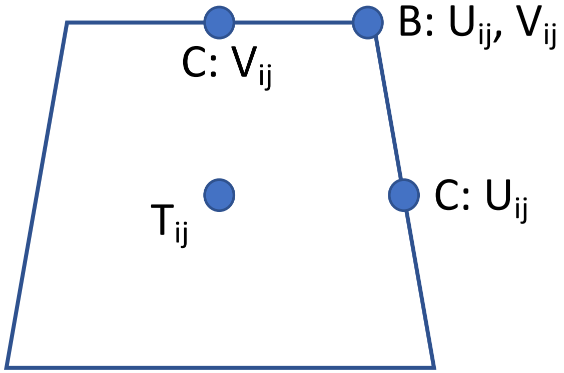
NEMO-CICE 4-5 km, GEM 3 km

Discrete Element Model for Sea Ice

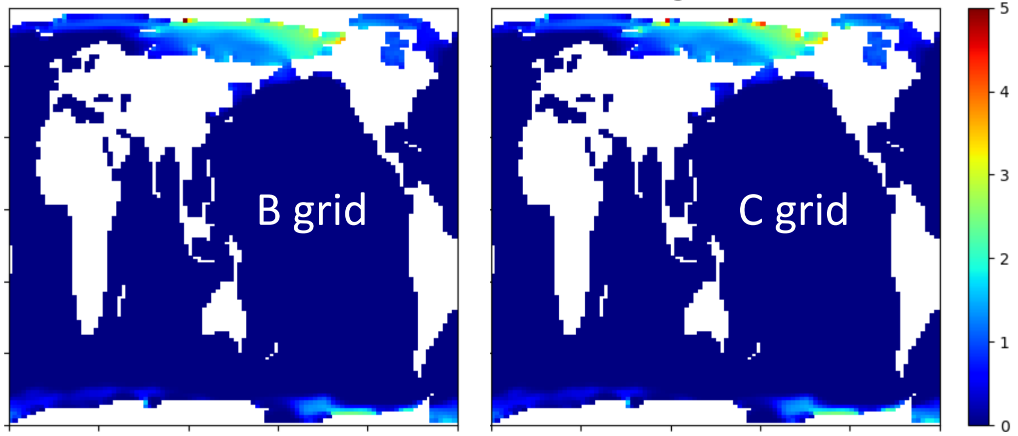


A. Turner

C-grid implementation



Sea ice thickness, 3° test configuration (m)



Alternative discretization for EVP dynamics for more direct coupling with C-grid ocean models

- Solves for velocity on cell edges rather than corners
- More flexible grid averaging, coupling
- Incremental remapping advection naturally uses edge velocities

Environment and Climate Change Canada

CICE Consortium

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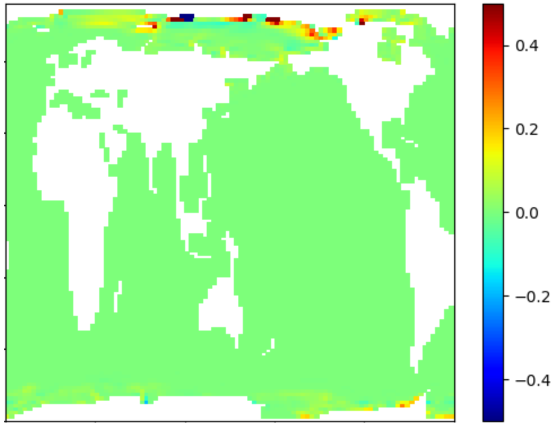
C – B difference (m)

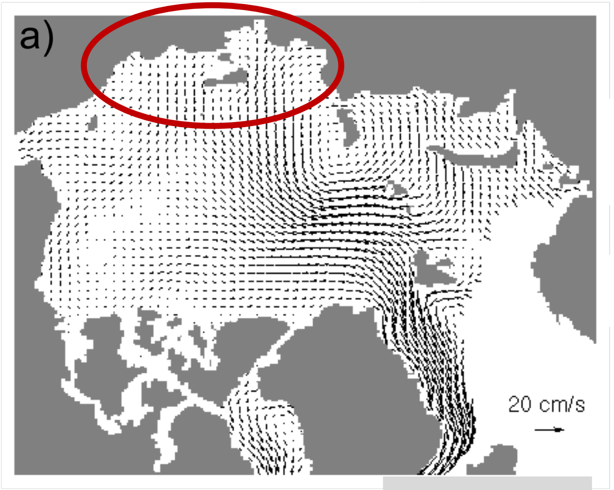


J. F. Lemieux and others

Differences accumulate in regions of convergence

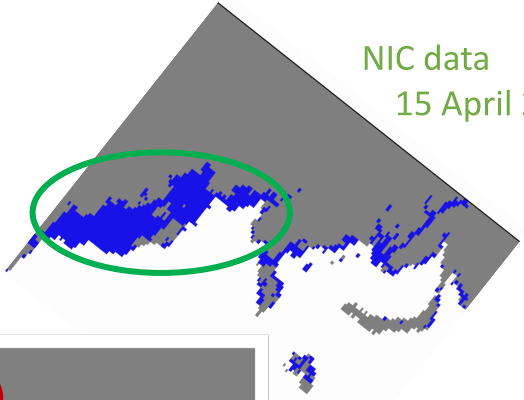
Landfast sea ice

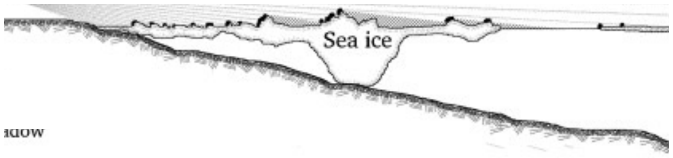
Simulation by a standard VP model



standard

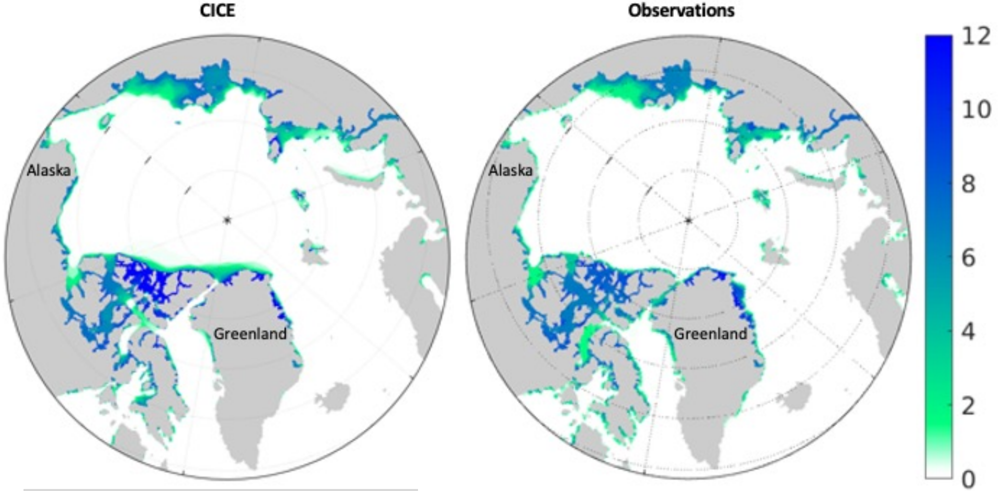
NIC data
15 April 2002





Mahoney et al., *Cold Reg. Sci. Technol.*, 2017

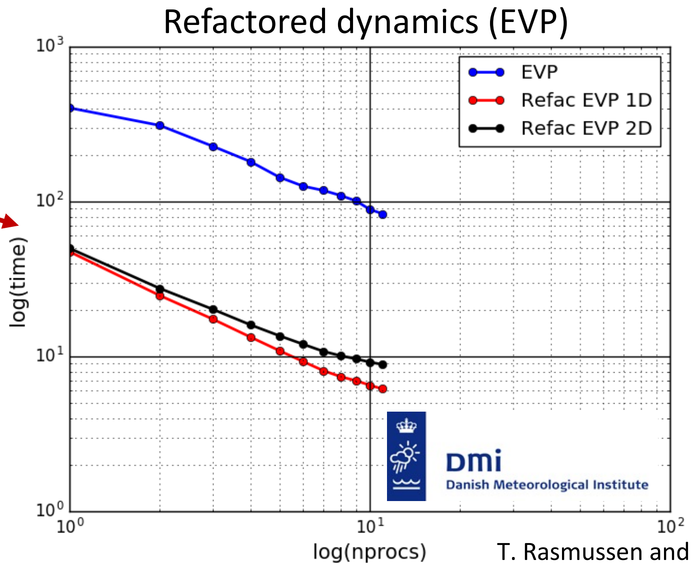
Number of months with landfast ice



parameterized

Major improvements for CICE dynamics since 2019

- Probabilistic grounding scheme for landfast ice
- Viscous-plastic (VP) dynamics solver
- Plastic potential for VP and EVP
- Vectorized (1D) EVP kernel
- C-grid discretization of dynamics
- Generalized grid infrastructure
- Transitioned to JRA-55 forcing
- Support for CMIP6 history variable output



T. Rasmussen and others

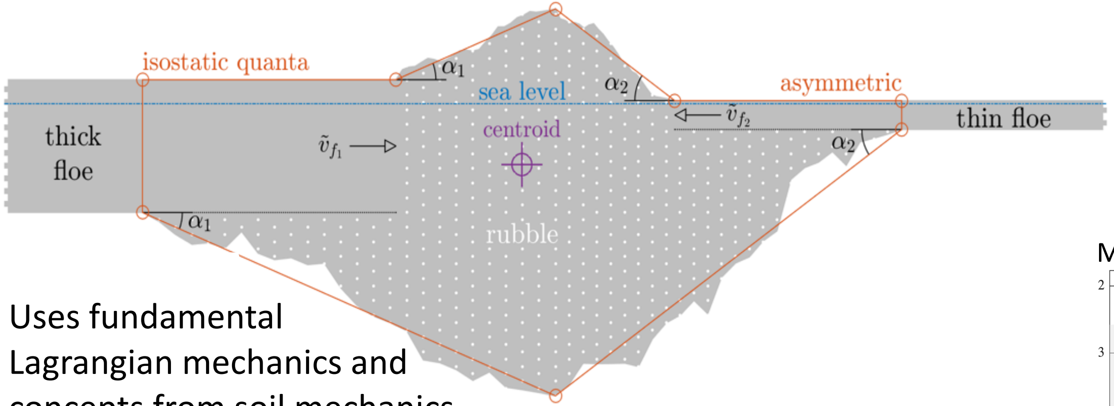
Software engineering upgrades include

- Quality Control testing
- Dynamic array allocation
- New CICE time manager
- Improved OpenMP threading performance
- Developed methods to support compilation of CICE into a library
- Increased code testing coverage to 76% (was 68% in summer 2000)
- Github Actions for automated testing on Pull Requests and Pushes
- Conda environments for user-friendly machine ports

https://github.com/CICE-Consortium

Sea ice macroporosity

A variational formulation for sea ice ridging

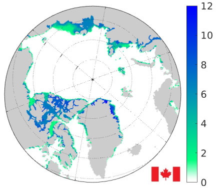


Uses fundamental Lagrangian mechanics and concepts from soil mechanics

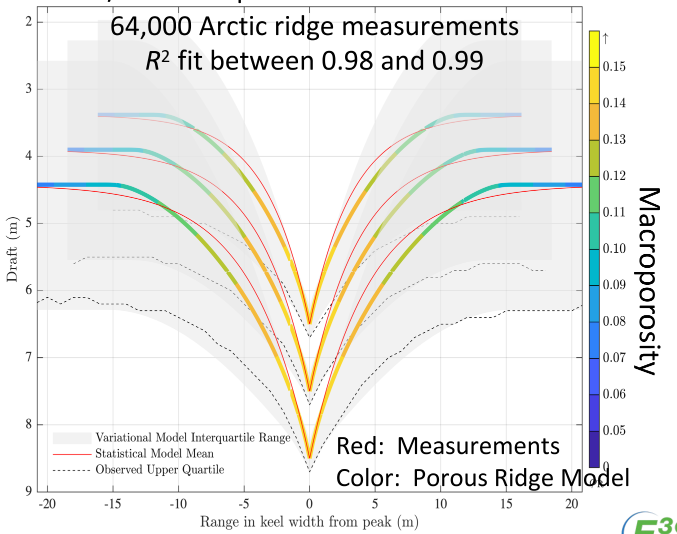
Ridge morphology is a major model structural bias that we know how to fix!

Crucial for

- **Ridge/keel density, volume**
- **Dynamics: form drag, landfast ice**
- **Thermodynamics: melt ponds, conductivity**
- **Biological communities**



Model / data comparison shown for 3 keel drafts



Metzger, Mahoney, and Roberts, GRL 2021

A. Roberts

Sea ice modeling needs

an informal survey

"What's important" naturally depends on the application

- sea ice rheology / dynamics / mechanics
- wave-ice dynamics
  - floe size distribution, evolution
- biogeochemistry
- near-coastal physics
  - icebergs
  - landfast ice
  - sea ice's buttressing effect for ice shelves
- sea ice ridging and morphology
- understanding sea ice predictability and improving skill for seasonal forecasting
  - improving coupled atmosphere and ocean models
- seamless incorporation of observations (e.g. via simulators or emulators)
- computational efficiency, including scalability, use of GPUs
- Ice-ocean coupling other than waves; melt ponds; mass balance; other thermodynamics…

CICE Consortium

2021 R&D 100 WINNER

2021 R&D 100 GOLD

Environment and Climate Change Canada

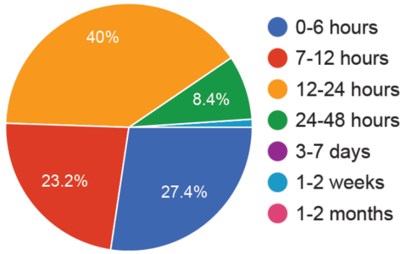
and participants of the Mathematics of Sea Ice Workshop
Isaac Newton Institute, Cambridge UK

IICWG mariner survey 2019

- IICWG undertook a “mariner survey” to ascertain user needs
  - Majority of responses from ships captains with 10+ years polar navigation

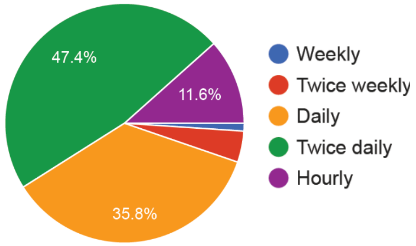
<u>Some requirements will prove very challenging for sea ice models!!</u>

Which ice forecasting time scale is most critical for you in/near ice?



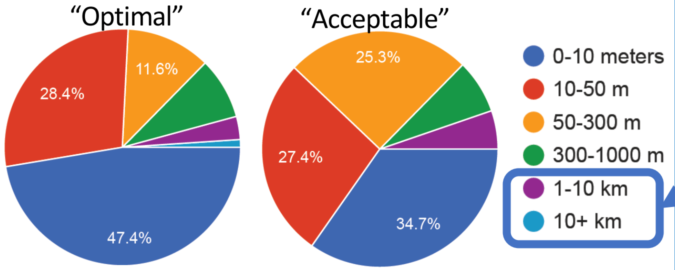
90% want <= 24 hours

What is the optimal ice information update frequency for your needs?



58% want >daily update

What is the minimum size of any ice (floe, ridge, lead) you need information about?



75% want < 50m; 87% want < 300m

Typical model resolution currently

(effective resolution much higher!)

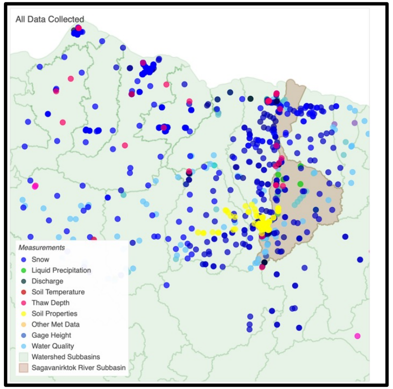
[**acknowledgement:** IICWG; EU-KEPLER; Nick Hughes, Norwegian Ice Service]

Slide courtesy of Ed Blockley, UKMO

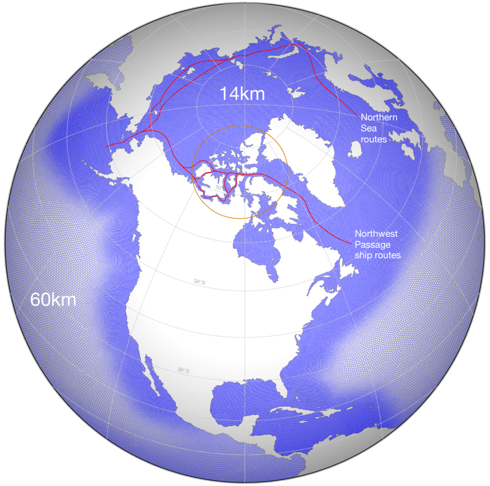
Interdisciplinary Research for Arctic Coastal Environments

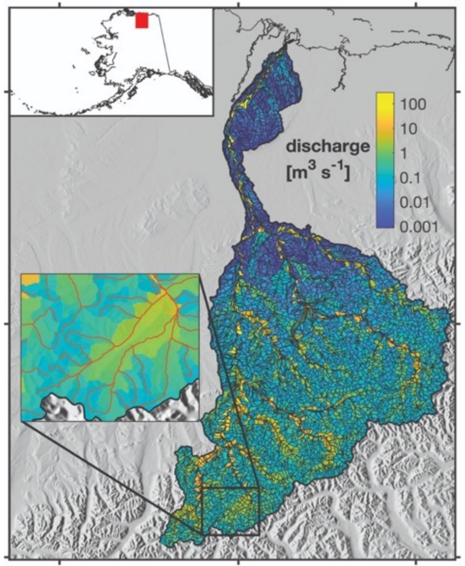
Evaluating, developing, and testing integrated models to quantify human and environmental change across the coastal Arctic

- Data analysis, multi-scale model hierarchy, and ESM development
  - Coastal biogeochemistry and change and their impacts to infrastructure and resources
  - Hydrological drivers for terrestrial and ocean feedbacks in coastal watersheds
  - Global and regional controls on Arctic shipping and development
    - E3SM advances for Arctic resolution, waves, ocean mixing, and landfast ice
    - Shipping model in GCAM
- Expanded Arctic research resources, data
  - Identification, acquisition, and curation of long-term orphaned data to support watershed analysis and modeling



Multiscale integrated hydrology coupled to E3SM to enable watershed simulations





J. Rowland, A. Roberts and others

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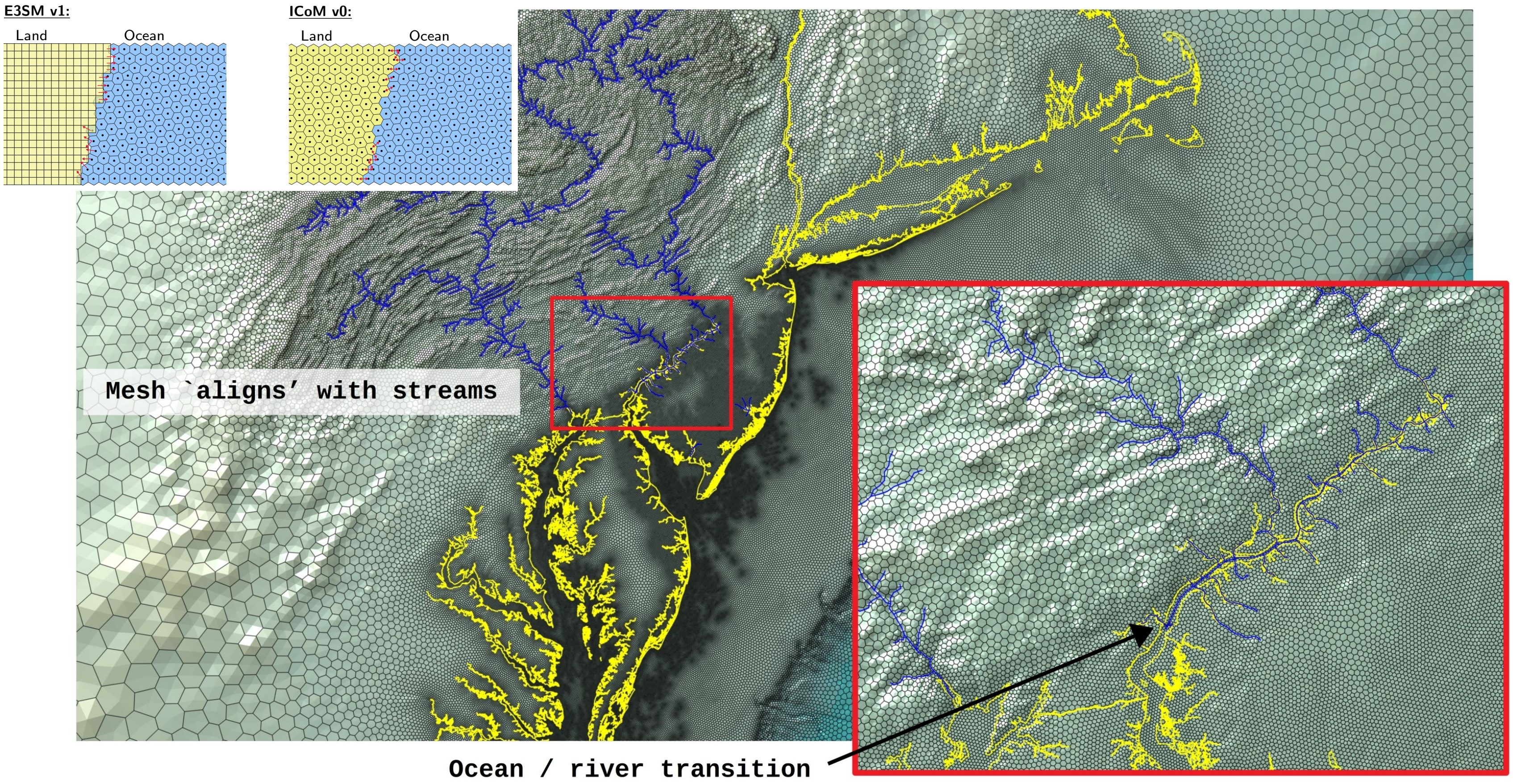
Overcoming land-river-ocean coupling challenges

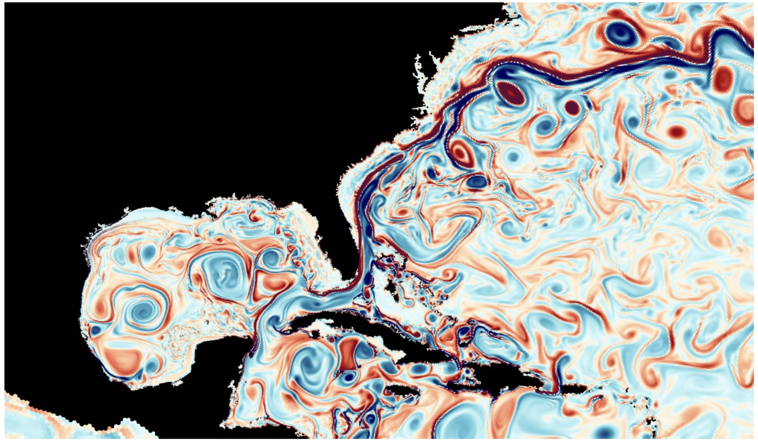


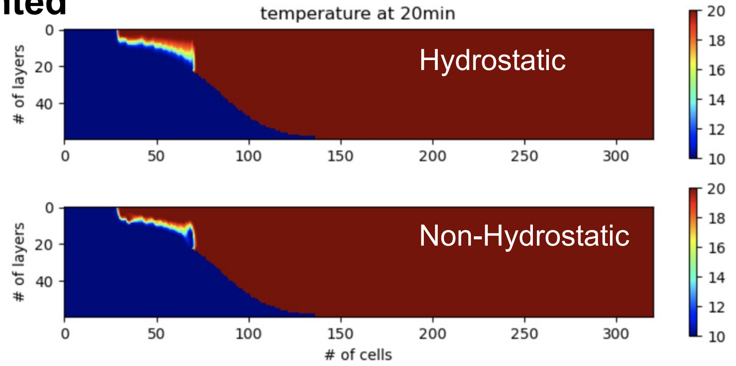
Advancing ocean turbulence modeling across scales

A new, nonhydrostatic capability for MPAS has been implemented

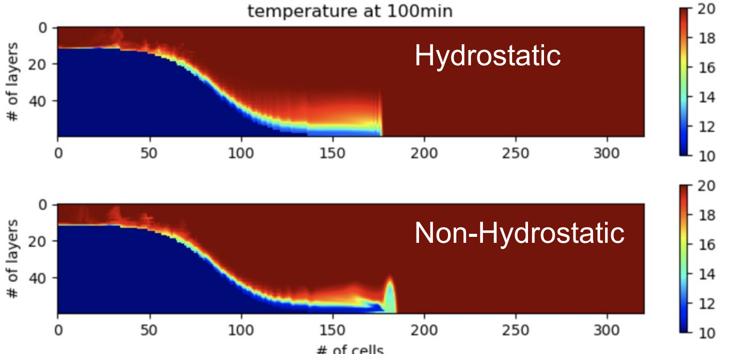
Grand challenge simulations are underway to examine the impact of nonhydrostatic dynamics on eddies

5km MPAS eddy-rich hydrostatic simulation. New simulation will be 1km and include nonhydrostatic dynamics.





Gravity current simulation for hydrostatic and non-hydrostatic simulations with MPAS. Hydrostatic simulation cannot form the downslope current correctly impacting dense water overflows.



Results inform Partially Averaged Navier Stokes closure

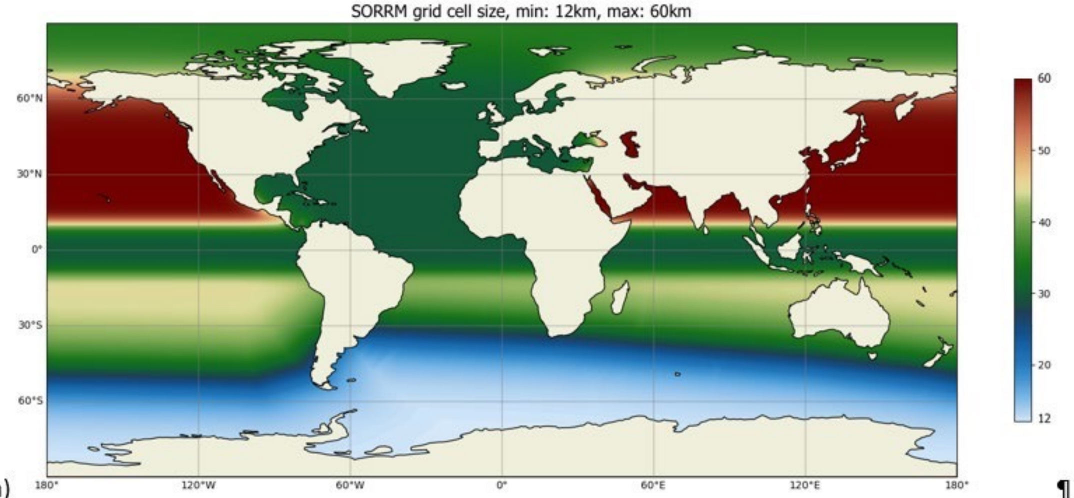
- can directly simulate flow where chosen
- becomes a high-fidelity turbulence closure outside this region

Regionally refined meshes

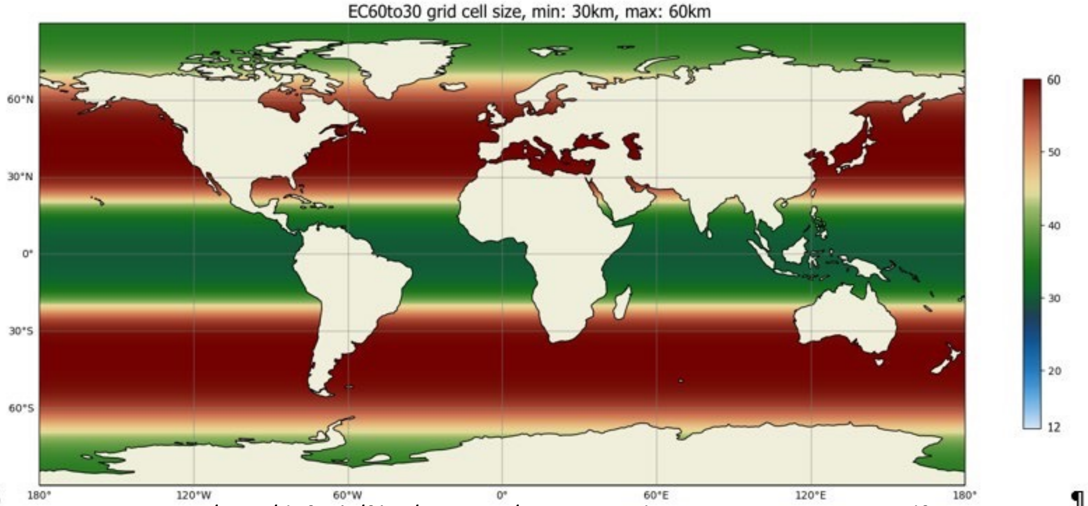
Ocean and sea ice grid cell size (km) for the Southern Ocean Regionally Refined Mesh (SORRM), down to 12 km

The standard-resolution mesh varies between 30- and 60-km grid cells globally

(a)



(b)

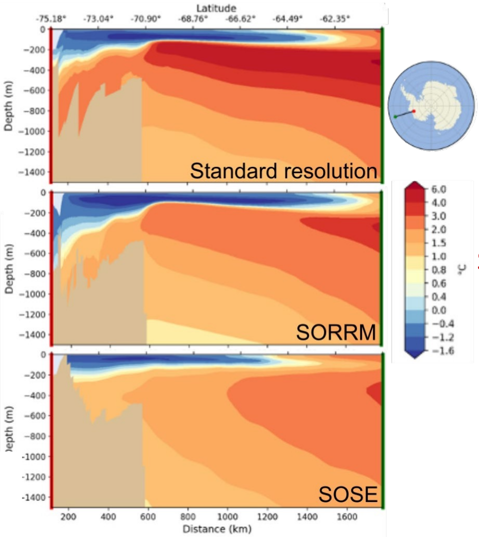


DOE/SC-CM-22-003: https://climatemodeling.science.energy.gov/sites/default/files/2022-07/FY2022_3rd_Quarter_Metrics3_0.pdf

Impacts of Regionally refined meshes

Modeled ocean temperatures along a transect in the Amundsen Sea region

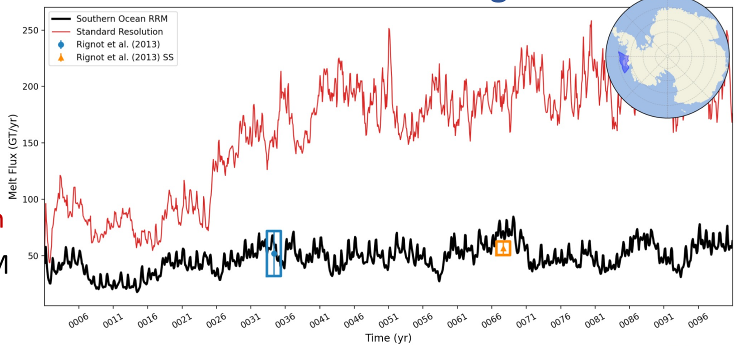
averaged over the last 30 years of 100-year simulations



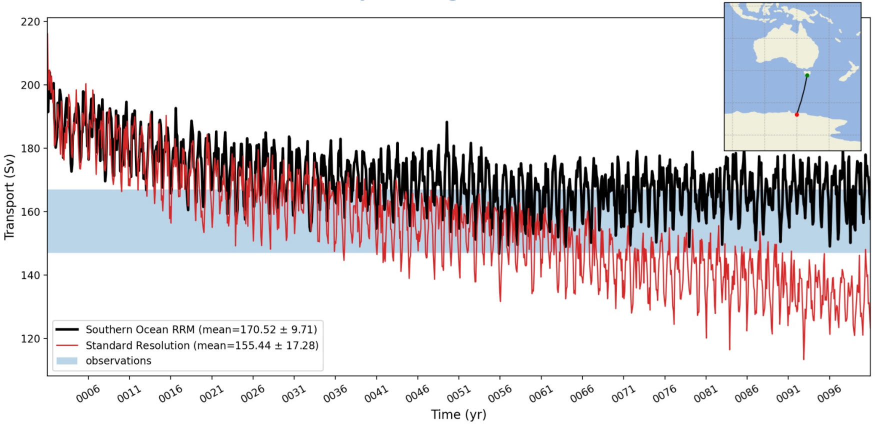
Standard resolution

SORRM

Area-integrated, sub-ice-shelf melt flux Abbot Ice Shelf region



Volumetric transport (Sv) Tasmania-Antarctic passage



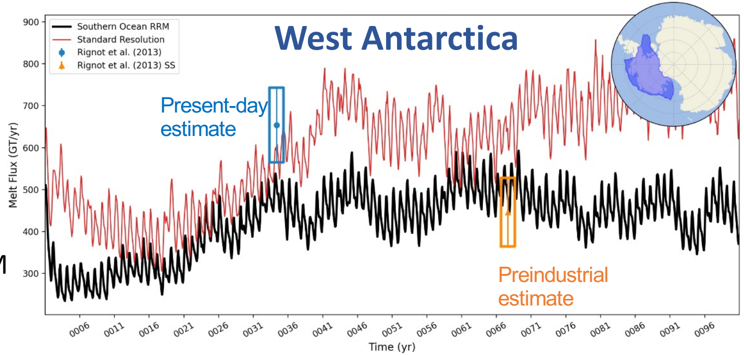
SORRM

Observations

Standard resolution

Standard resolution

SORRM



Box position along horizontal axis is arbitrary

S. Price and others

DOE/SC-CM-22-003: https://climatemodeling.science.energy.gov/sites/default/files/2022-07/FY2022_3rd_Quarter_Metrics3_0.pdf

Sea ice modeling

Lots of activity for both dynamics and column physics

Wave-ice interactions

Biogeochemistry

Snow physics and radiation

Rheologies

Landfast ice

C-grid discretizations

Computational efficiency

Macroporosity in ridges

Modeling needs

We are working toward meeting research and climate community needs

We have a long way to go to meet operational requests

Department of Energy / LANL efforts

Coastal, high resolution

Thank you

Elizabeth Hunke, eclare@lanl.gov