A menagerie of approaches to ice sheet-ocean coupling,

with a slight emphasis on US Department of Energy models

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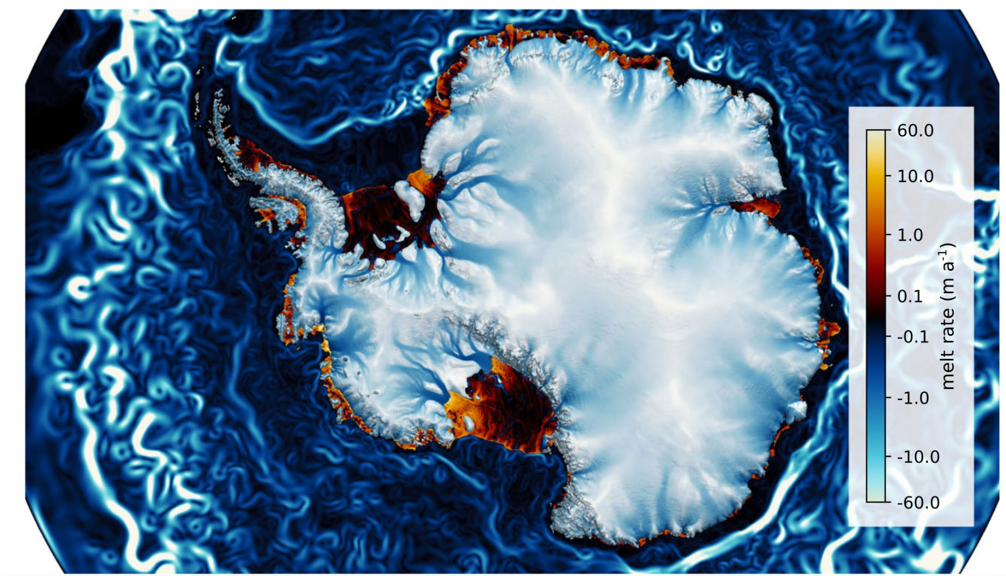
Outline

- Considerations for ice sheet-ocean coupling
  - Coupling
  - Ice-sheet component
  - Ocean component
- Initializing coupled models
- Comparing models (MISOMIP)
- US Department of Energy models:
  - POPSICLES
  - E3SM
- Effects of climate biases on ice-sheet forcing

Considerations in ice sheet-ocean coupling

- Coupling:
  - "Offline" coupling (with restart files)
  - "Online" coupling
  - ESM couplers
  - Dynamic component masking
  - Melting in grounded vs. floating cells

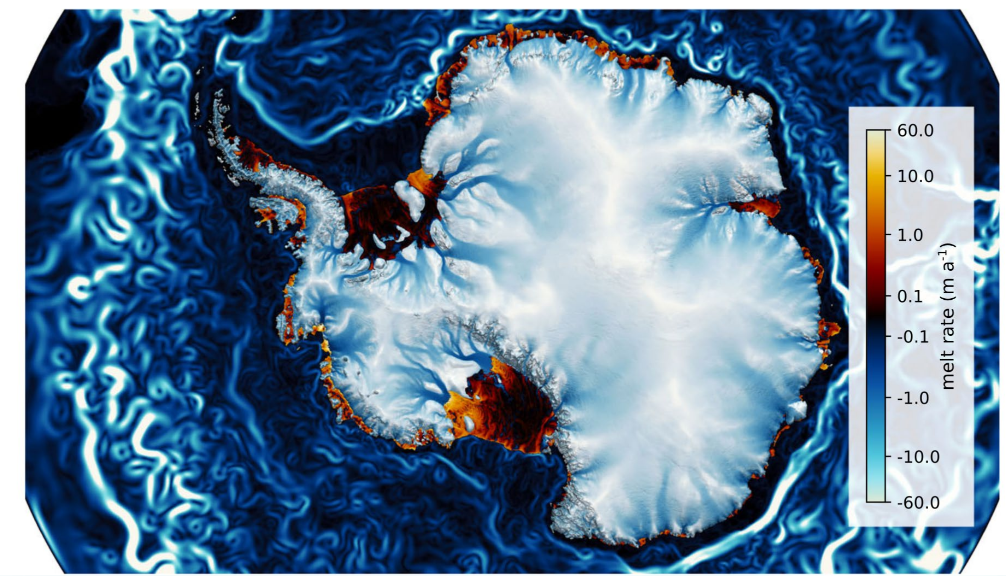


A snapshot from a coupled, circum-Antarctic simulation from POPSICLES (Asay-Davis et al. 2017).

Considerations in ice sheet-ocean coupling

- Coupling:
  - "Offline" coupling (with restart files)
  - "Online" coupling
  - ESM couplers
  - Dynamic component masking
  - Melting in grounded vs. floating cells

- In the ocean component:
  - Moving boundaries
    - Grounding lines
    - Calving fronts
    - Ice shelf thinning/thickening
  - Connectivity in the ocean
  - Pressure-gradient errors
  - The ice-ocean boundary layer



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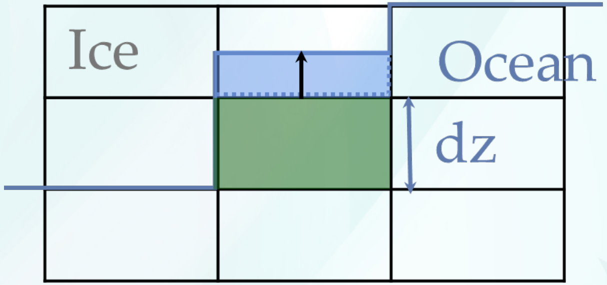
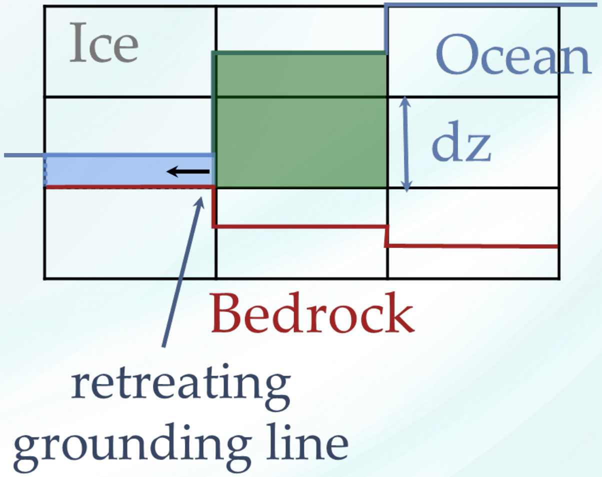
Coupling

"Offline" vs. "online" coupling

Offline

- Modify restart files
- Reinitialize ocean geometry at each coupling interval
- Pros:
  - ✓ Typically easier to implement
  - ✓ Simple solution to "wetting-and-drying" problem: **extrapolation**
  - ✓ Can use existing (offline) infrastructure for ocean model initialization
- Cons:
  - × Typically not conservative (or conservation is a hack)
  - × Unphysical extrapolation procedure
  - × Clumsy starting and stopping on HPC

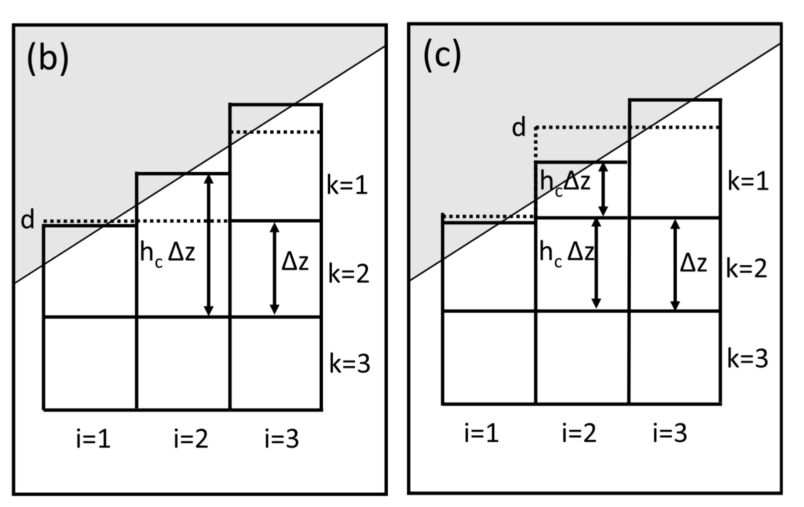




“Offline” vs. “online” coupling

Online

- “Coupler” communicates fields between components
- Ocean updates ice-shelf geometry every time step or coupling interval
- Pros:
  - ✓ Conservation
  - ✓ Fluid is pushed out or sucked in as boundary moves, consistent with physics
  - ✓ ESM coupling infrastructure can be used
- Cons:
  - × Moving boundaries, wetting-and-drying are hard to implement



Remeshing as part of online (“synchronous”) coupling in the MITgcm ice sheet-ocean model (Jordan et al. 2018)

Coupled ice sheet-ocean models (partial list)

Model	Citation/Notes
Offline-coupled	
Goldberg et al. model	Goldberg et al. (2012)
POPSICLES (POP-BISICLES)	
MITgcm-Úa	De Rydt and Gudmundsson (2017)
ISSM-MITgcm	Seroussi et al. (2017)
BISICLES-NEMO	In UKESM1
FESOM/Rimbay	Timmermann and Goeller (2017)
Elmer/Ice-NEMO	
Online-coupled	
MOM6-CISM	
Elmer/Ice-ROMS	
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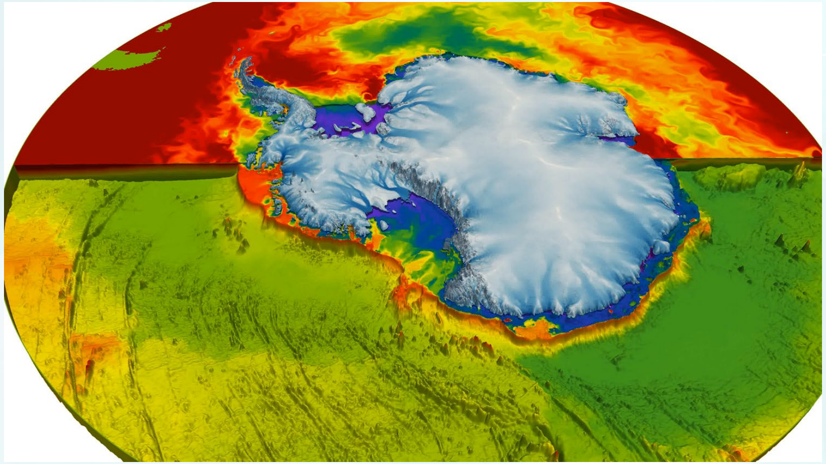
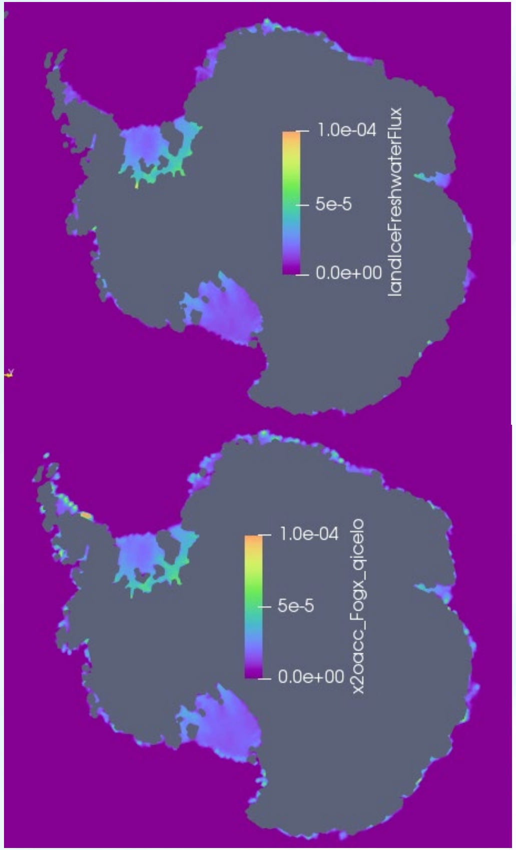
MPAS-O/MALI	In progress for E3SM v3
ROMS-icepack	In progress



A snapshot of ocean temperature and ice velocity from a coupled, circum-Antarctic simulation from POPSICLES.

ESM couplers: CIME

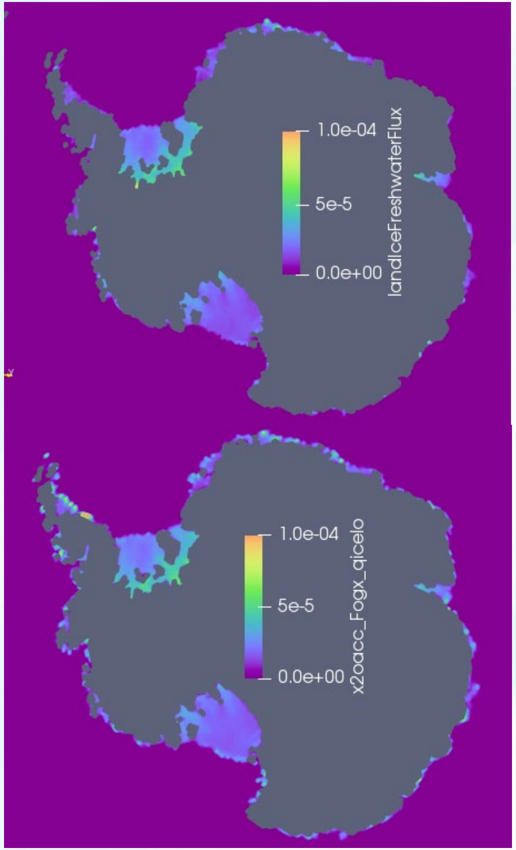
- Common Infrastructure for Modeling the Earth (CIME)
  - Used and jointly developed by Energy Exascale Earth System Model (E3SM) and the Community Earth System Model (CESM)



Melt rates computed within the E3SM ocean component (top) and from the CIME coupler (bottom)

ESM couplers: CIME

- Common Infrastructure for Modeling the Earth (CIME)
  - Used and jointly developed by Energy Exascale Earth System Model (E3SM) and the Community Earth System Model (CESM)
  - Boundary fluxes (melt rates, heat fluxes) appropriate for full coupling
  - These fluxes are computed
    - On ice-sheet grid (higher spatial res)
    - At ocean coupling frequency (higher temporal res)
  - Allows masking of melt rates based on flotation on ice-sheet grid
  - Coupling with dynamic geometry under development



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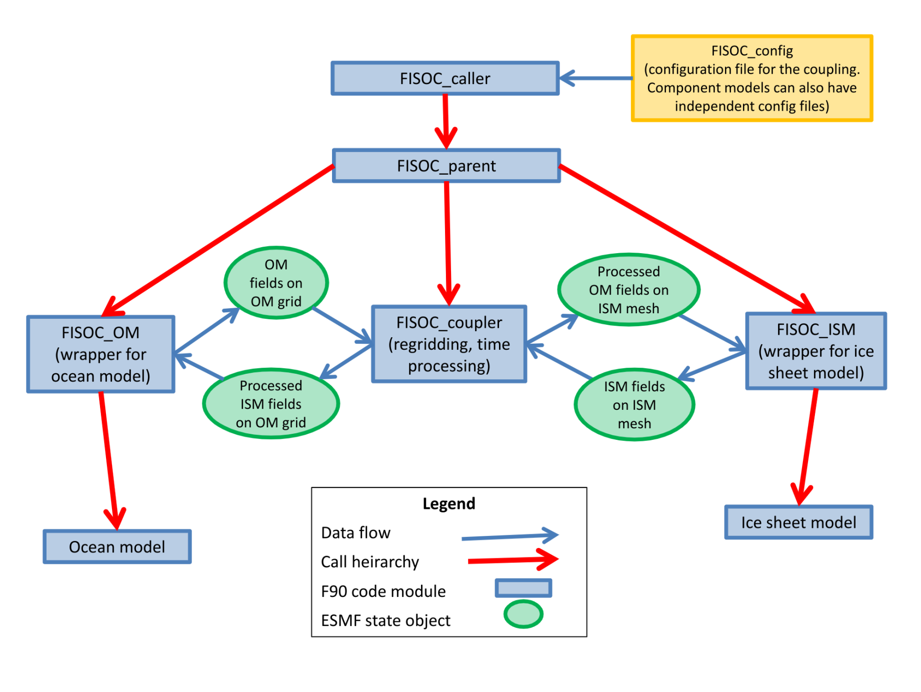
ESM couplers: FISOC and UKESM1

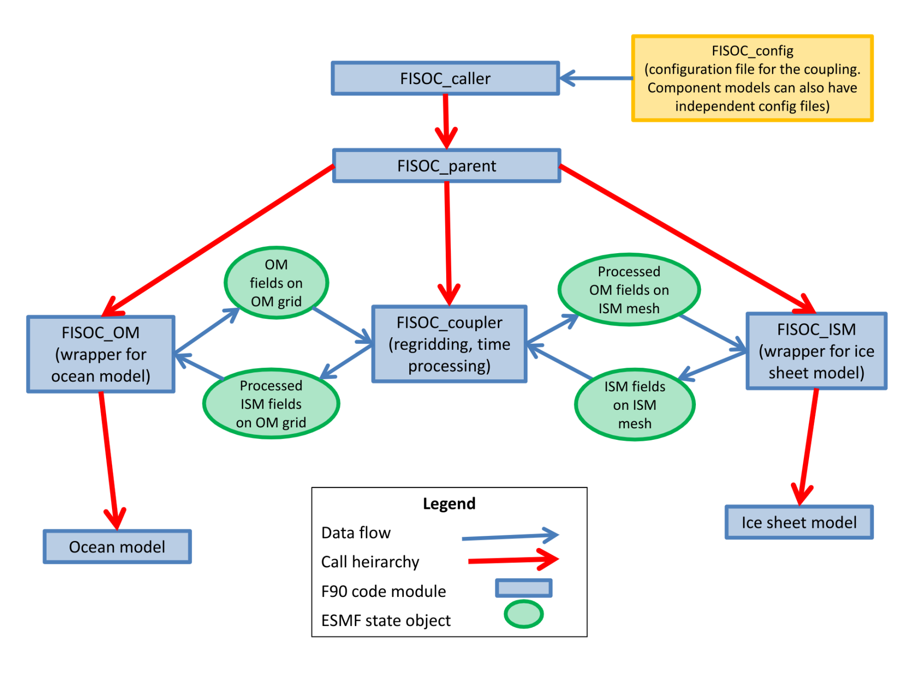
- FISOC: Framework for Ice Sheet – Ocean Coupling
  - Developed by Rupert Gladstone
  - Based on Earth System Modeling Framework (ESMF)
  - Used to couple ROMS to both Elmer/Ice and icepack



Flow chart of the FISOC coupler

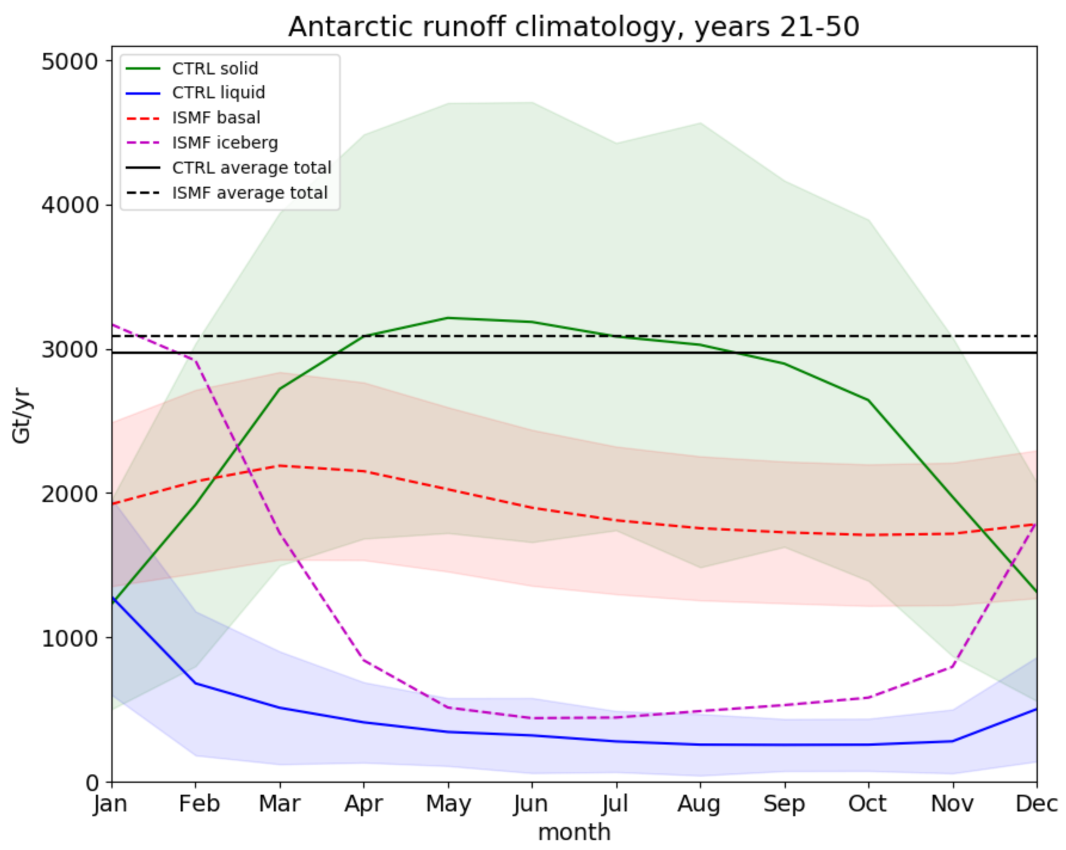
ESM couplers: FISOC and UKESM1

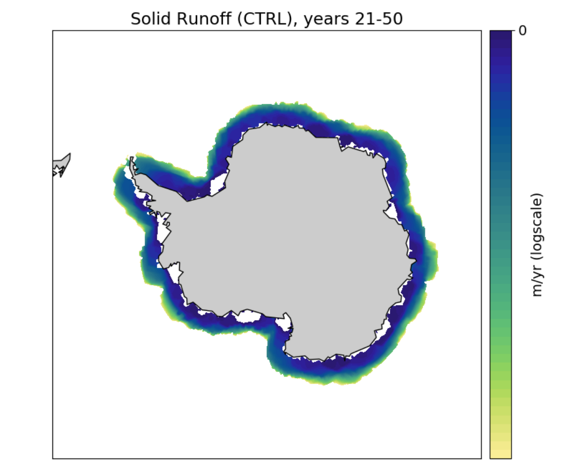
- FISOC: Framework for Ice Sheet – Ocean Coupling
  – Developed by Rupert Gladstone
  – Based on Earth System Modeling Framework (ESMF)
  – Used to couple ROMS to both Elmer/Ice and icepack
- UKESM1 (Seller et al. 2020)
  – BISICLES-NEMO coupling developed by Robin Smith
  – Offline coupling
  – NEMO geometry updated each "checkpoint" (every month or year)

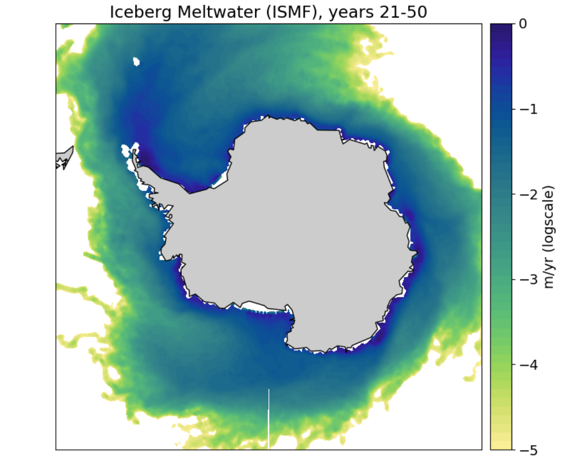


Flow chart of the FISOC coupler

Freshwater fluxes

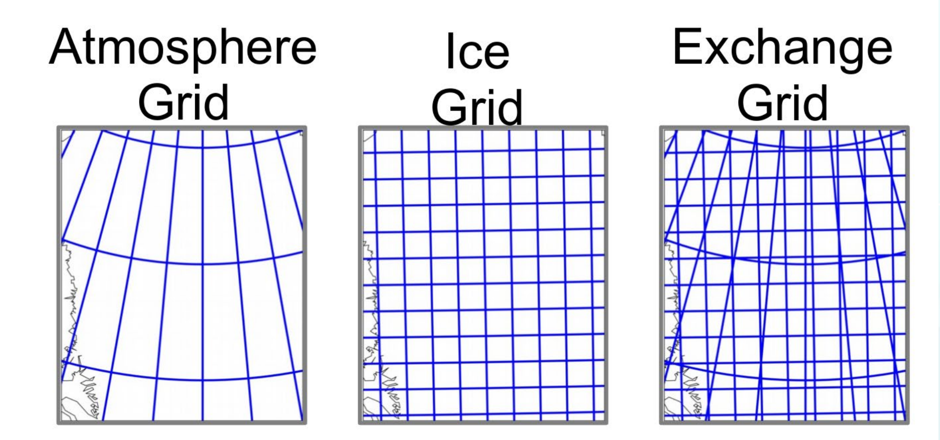




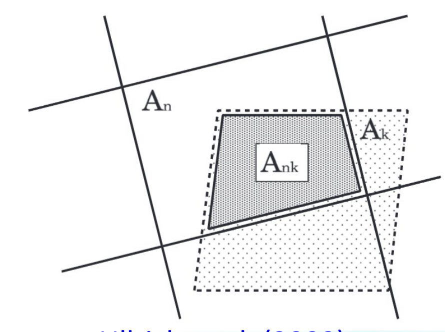


Dynamic masking between components

- Interpolation weights between ESM components are precomputed on overlap (“exchange”) grid
- Weights typically assume a fixed mask for exchange
- Moving calving fronts and grounding lines require dynamic masks
- Affects many component pairs:
  - Atmosphere-ice sheet
  - Atmosphere-ocean
  - Atmosphere-sea ice
  - Ice sheet-land
  - Ice sheet-ocean
  - Ocean-sea ice



Example of overlap (“exchange”) grid between ESM components [(Fischer et al. 2014)]

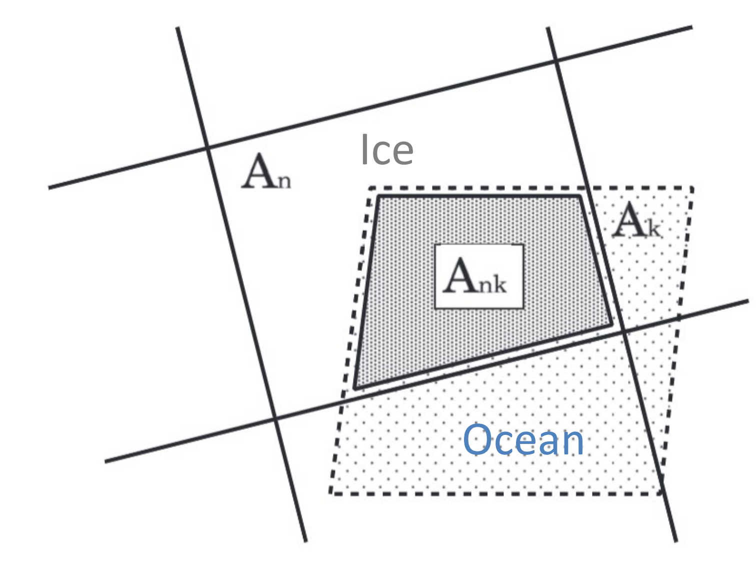


[Ullrich et al. (2009)]

Melting only in floating cells

- Typically, ocean model computes melting
- Melt rates remapped to ice-sheet mesh
- Remapping should account for floating vs. grounded ice-sheet cells
- No melting under grounded ice!

- Considerations:
  - Likely easier to enforce if melt is computed on ice-sheet grid
  - Ice sheet mesh is often higher resolution



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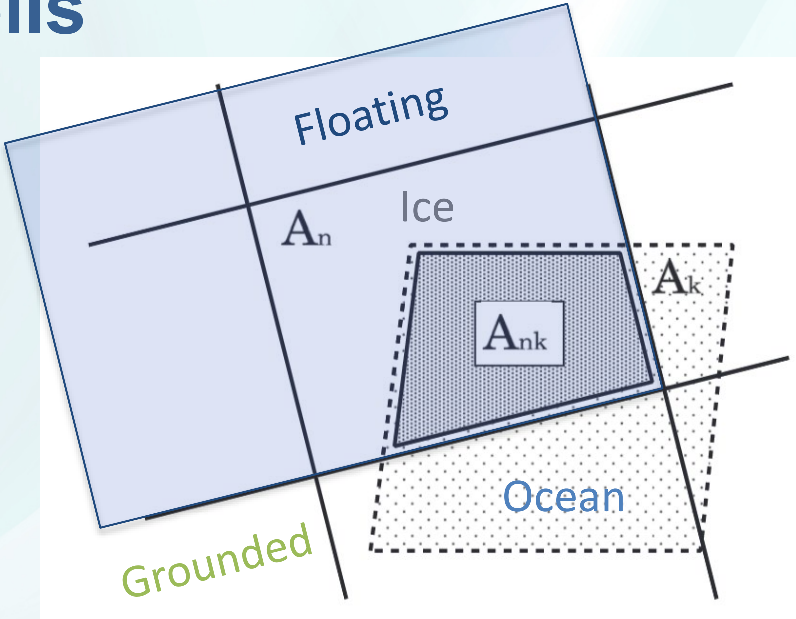

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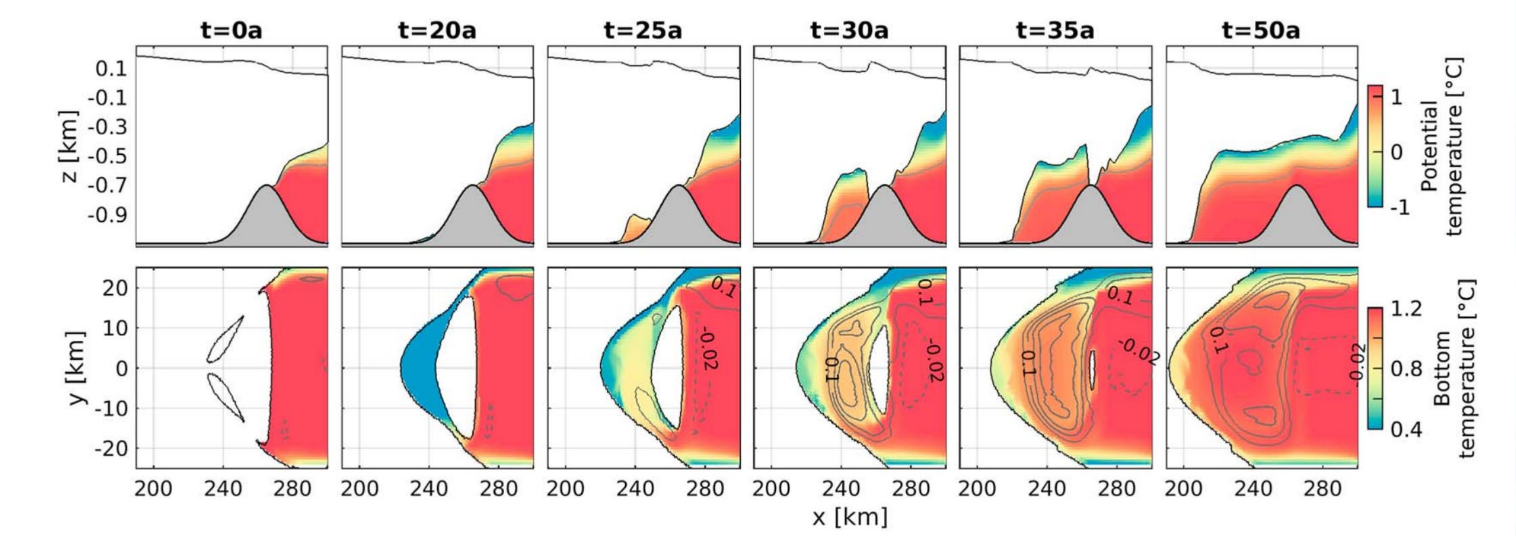
Considerations for the Ocean Component

Moving boundaries: thinning/thickening of the ice

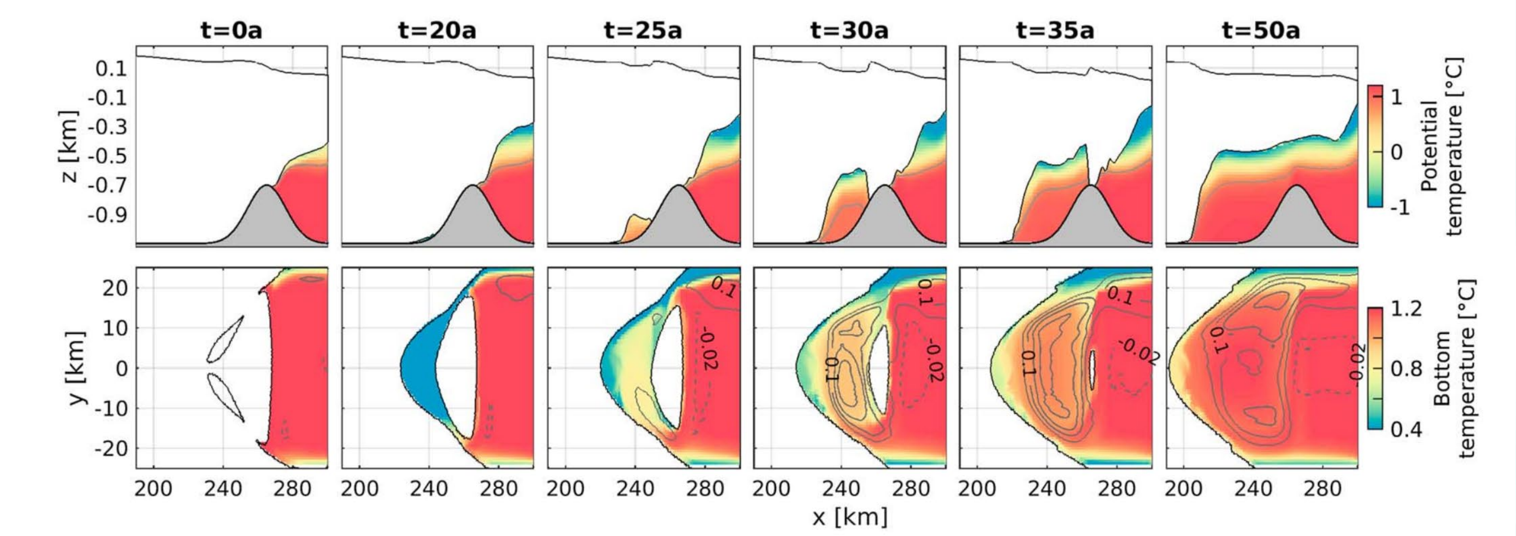
- Ocean models designed for small changes in water column (dynamic sea surface height)
- Not prepared for ice shelves over the ocean, or thickness changes



Coupled MITgcm-Úa evolution (De Rydt and Gudmundsson, 2017)

Moving boundaries: thinning/thickening of the ice

- Ocean models designed for small changes in water column (dynamic sea surface height)
- Not prepared for ice shelves over the ocean, or thickness changes
- Ice-shelf cavities must be added:
  - Top index in the model (z-level models)
  - Depress the sea surface (terrain following or layered models)
- Then, surface geometry must be allowed to change ("online" or "offline")



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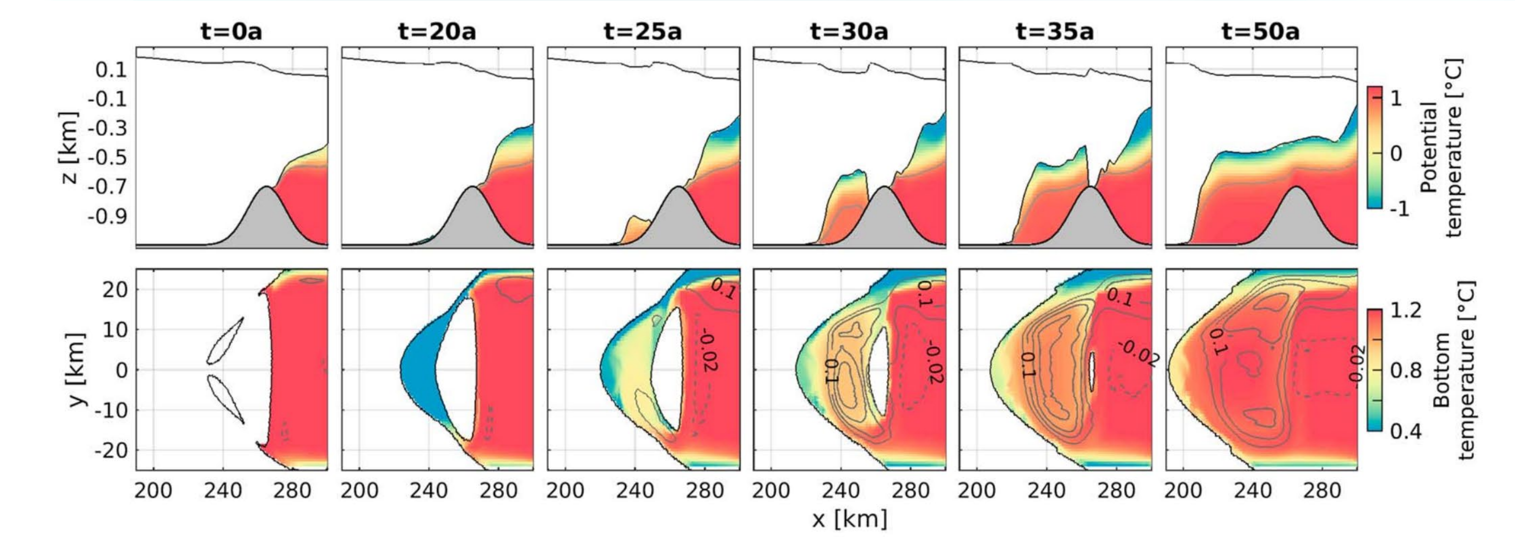
Moving boundaries: the grounding line

Approaches:

- Expand and contract the ocean domain as the GL moves (e.g. De Rydt and Gudmundsson, 2017)
- Extrapolate ocean properties



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Moving boundaries: the grounding line

Approaches:

- Expand and contract the ocean domain as the GL moves (e.g. De Rydt and Gudmundsson, 2017)
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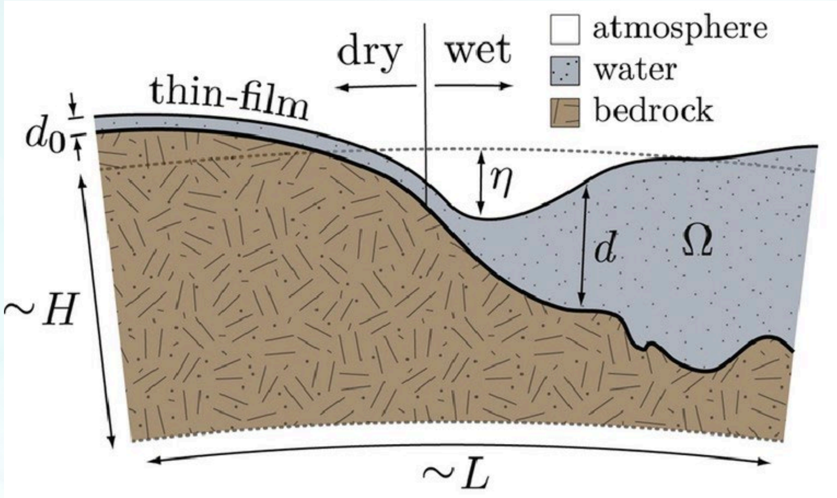
Or:

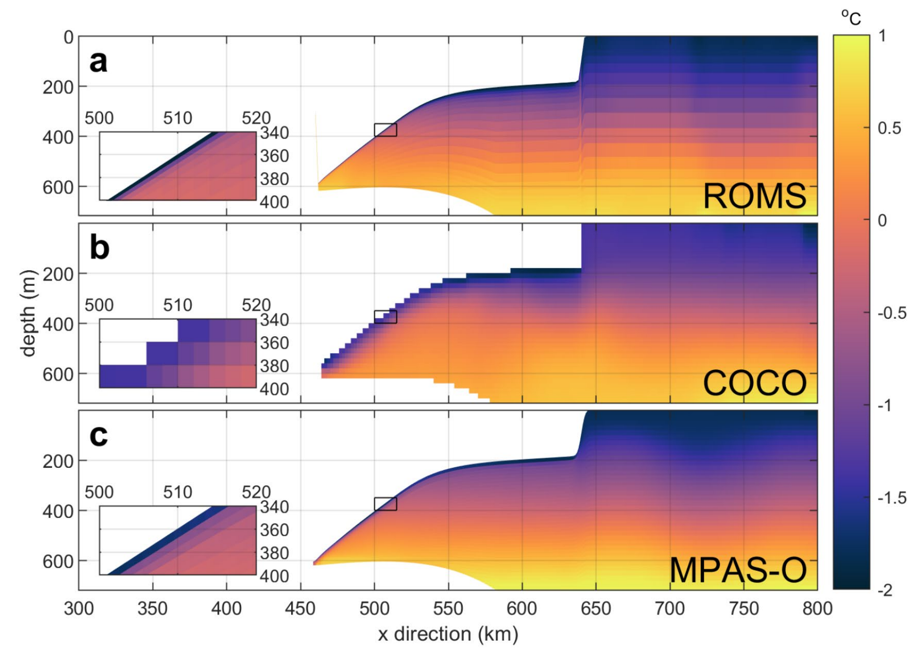
- Place a thin film of ocean under grounded ice that could unground (e.g. Goldberg et al. 2018)
- Like "wetting and drying" for tidal estuaries



Wetting and Drying with a thin film (Candy 2017)

Moving boundaries: the calving front

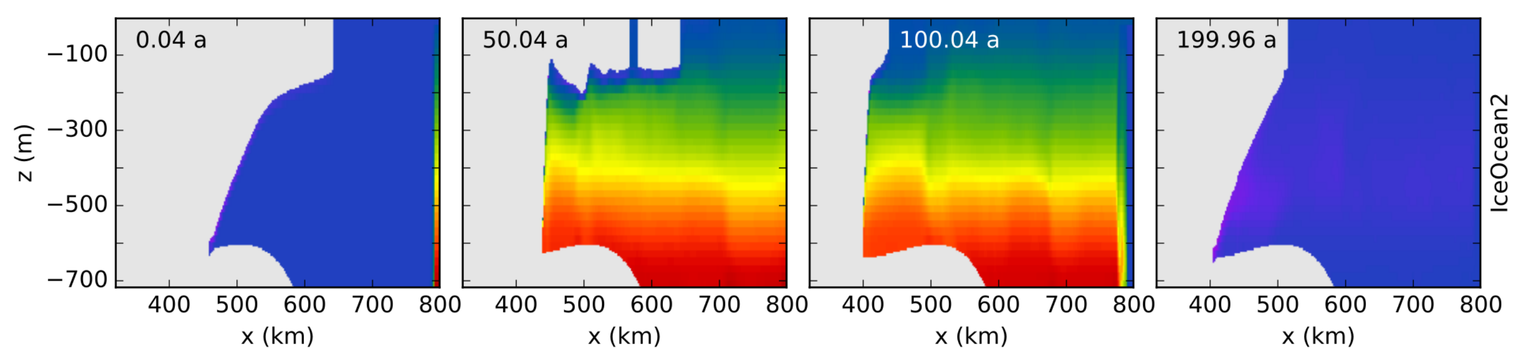
- Calving front can be:
  - A cliff (z-level models)
  - A smoothed slope (terrain following or layered models)



Ocean temperature and vertical coordinate in three ocean models (Gwyther et al., Ocean Modelling, accepted).

Moving boundaries: the calving front

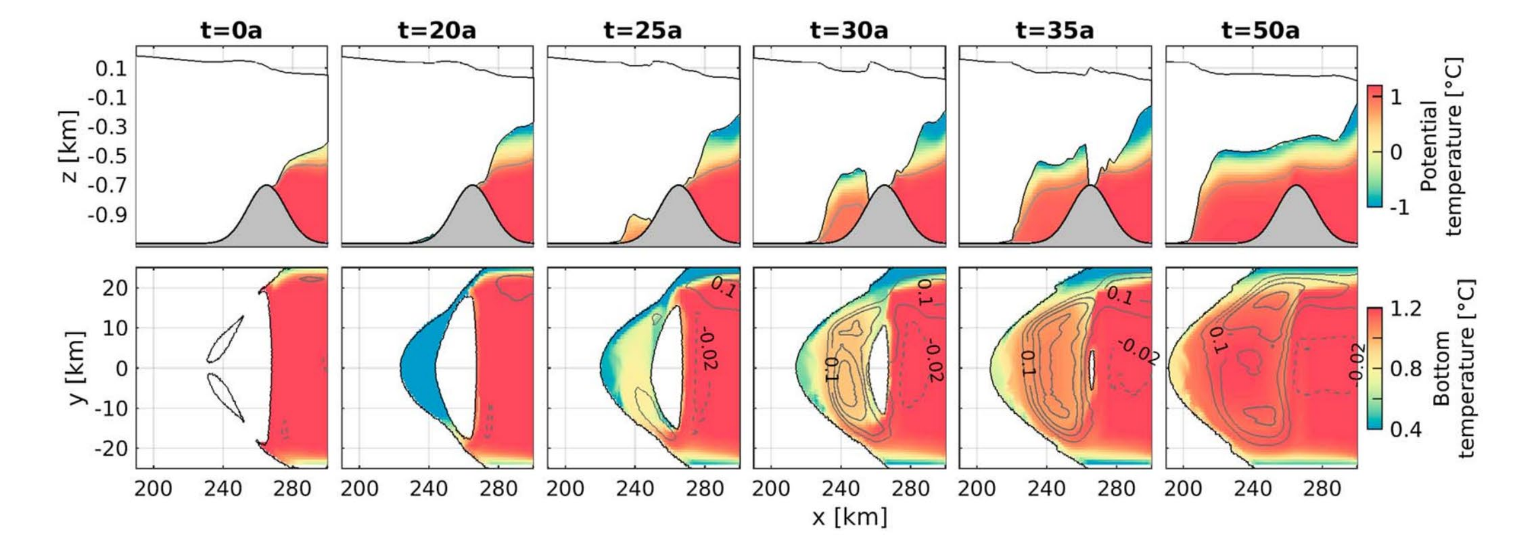
- Calving front can be:
  - A cliff (z-level models)
  - A smoothed slope (terrain following or layered models)
- Some models support abrupt calving
- Others support only continuous calving
- For smoothed calving fronts, typically calving treated as vertical thinning



POPSICLES simulation with dynamic calving (Asay-Davis et al. 2016).

Connectivity in the ocean

- Inclusion of disconnected lakes can cause:
  - Numerical errors
  - Unwanted melting
- Some models "Flood fill" to ensure connectivity
- GL retreat can connect subglacial lakes to the ocean (De Rydt and Gudmundsson, 2017)
- Potentially leads to rapid thinning and retreat



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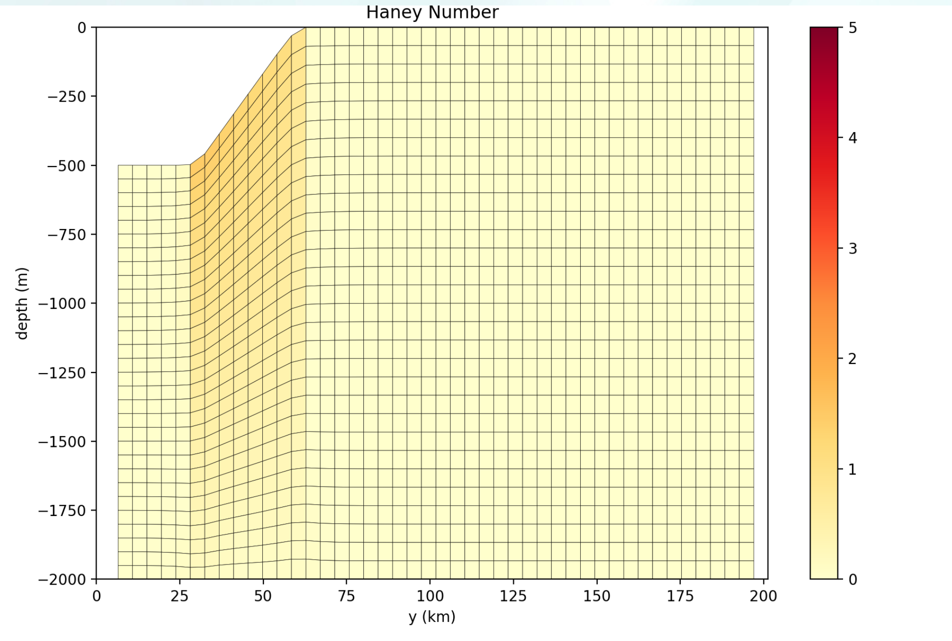
Pressure-gradient errors

- Terrain-following and some layered models prone to significant pressure-gradient errors
- Without special treatment, thin layers with steep slopes lead to spurious flow



The Haney number measures how thin and sloped adjacent cells are. Higher Haney number typically means bigger pressure gradient errors.

Pressure-gradient errors

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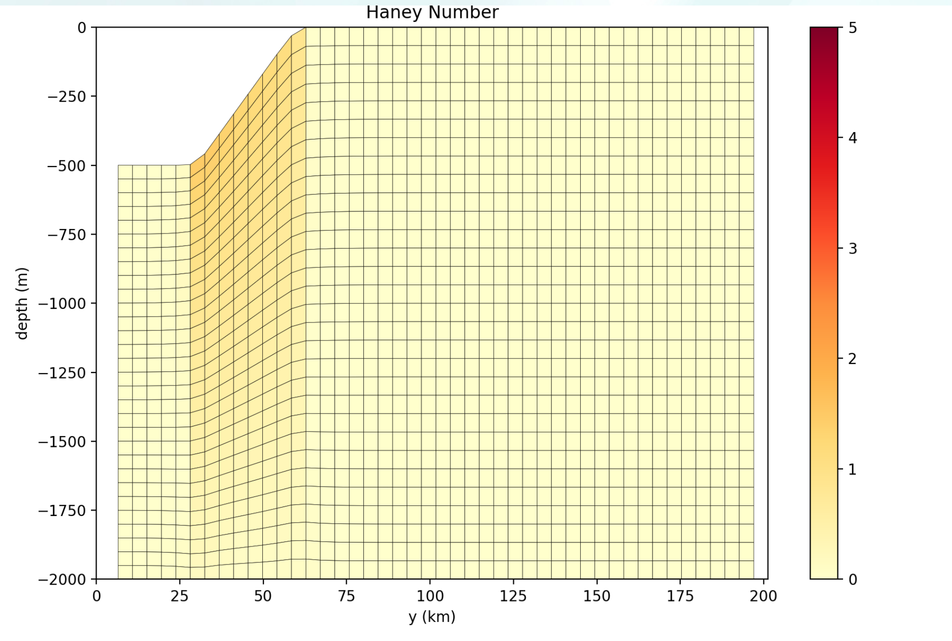

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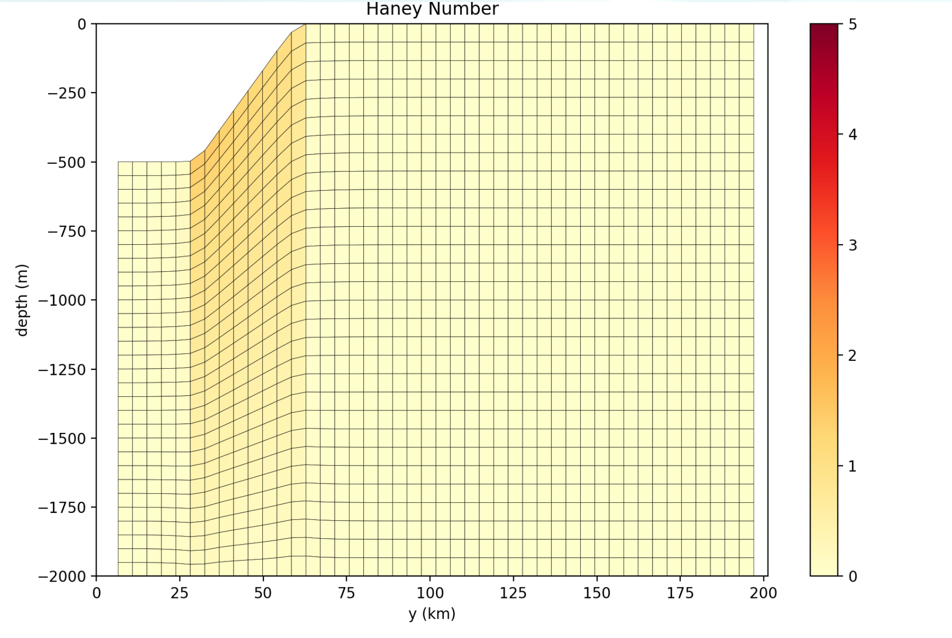

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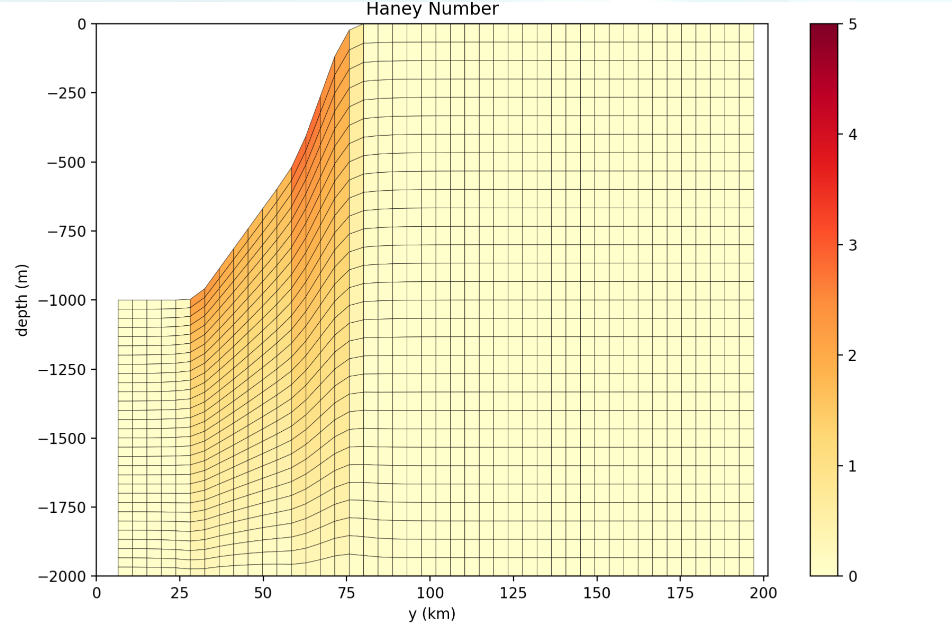

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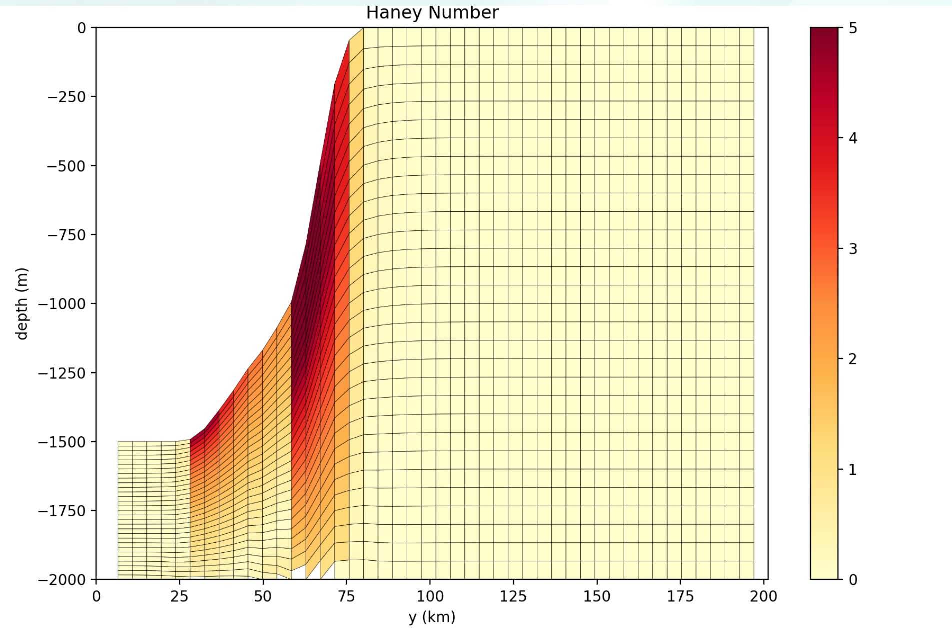

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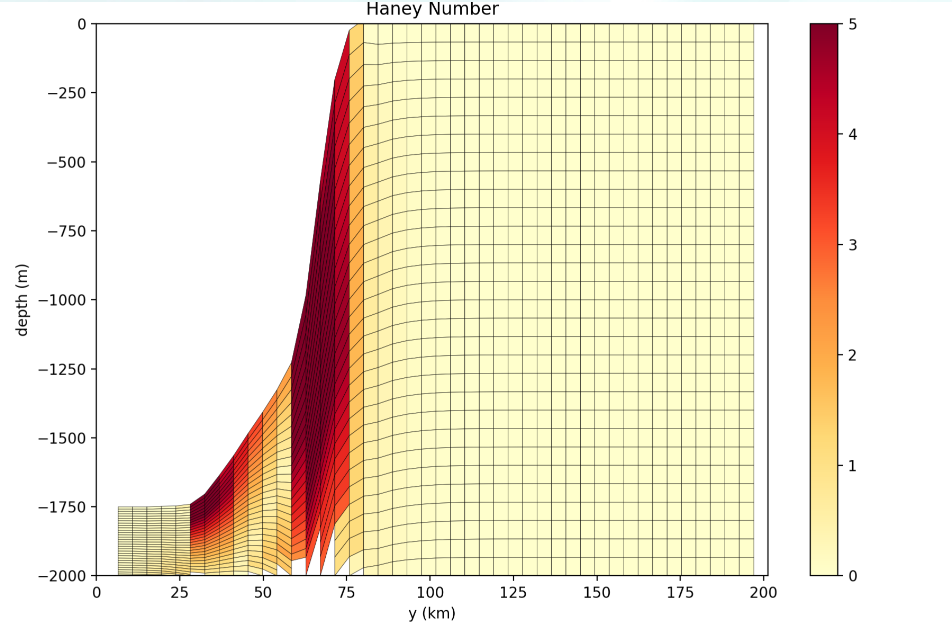

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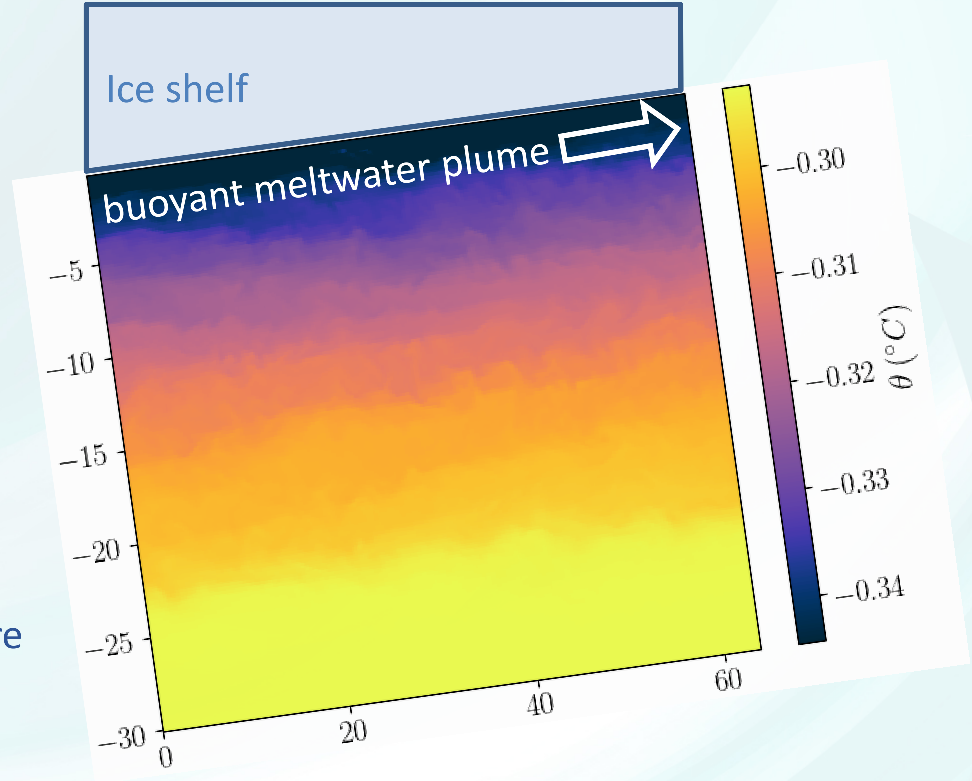
Ice-ocean boundary layer physics

- “3 equation” approach (originally developed for sea ice) generally used for coupling of heat and freshwater flux in ice/ocean BL
- Can we improve on this? Are our ocean model simulations good enough to warrant the effort? Are there adequate & appropriate observations?



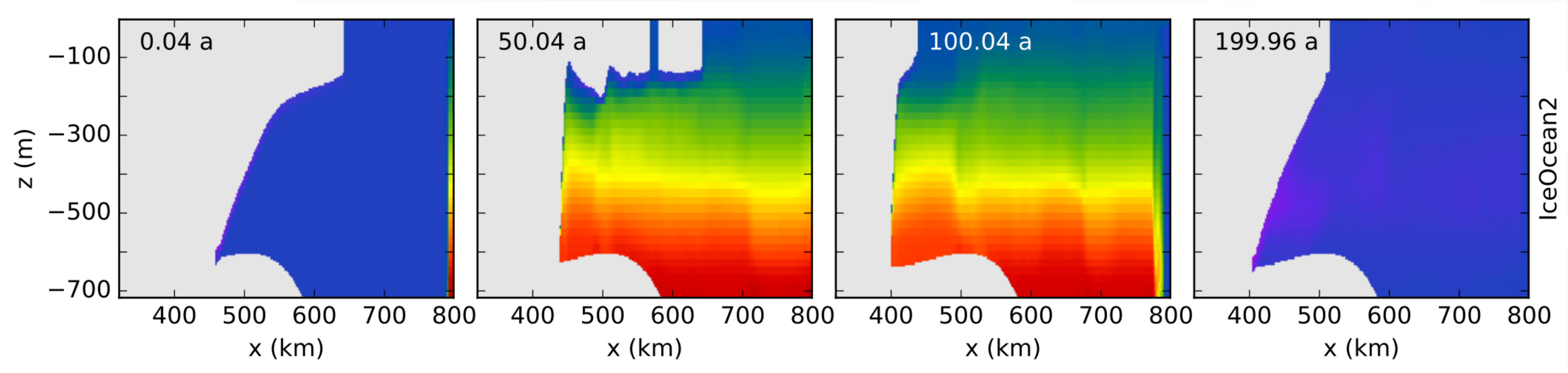
Right: Cross-section of ocean potential temperature from a large-eddy simulation below a dynamically melting ice shelf with a slope of 0.1 degrees in the horizontal-direction (C.B. Begeman, LANL).

Initializing coupled ice-ocean models

Idealized: typically start from no melt

- Examples:
  - Goldberg et al. (2012)
  - MISOMIP1
- Ice sheet can spin up to steady state (10^3 to 10^4 years)

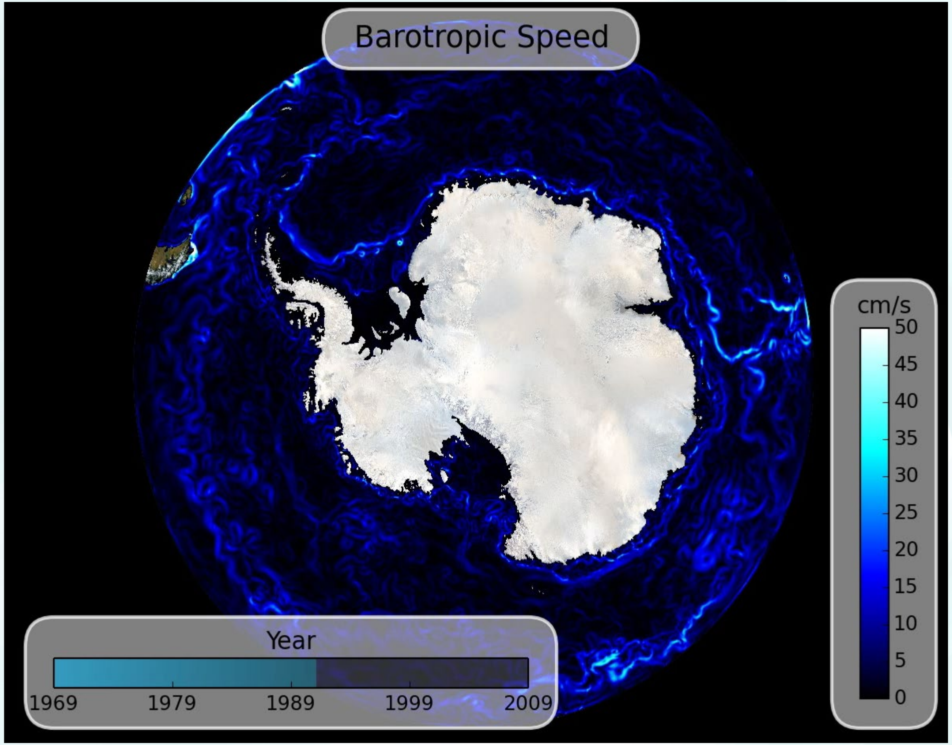
- Ocean
  - Starts from rest
  - "Cold" I.C. → low melt, weak "shock"
  - "Warm" I.C. → rapid melt increase, strong "shock"



POPSICLES simulation starting from dynamic calving (Asay-Davis et al. 2016).

Realistic: Spin up ocean component

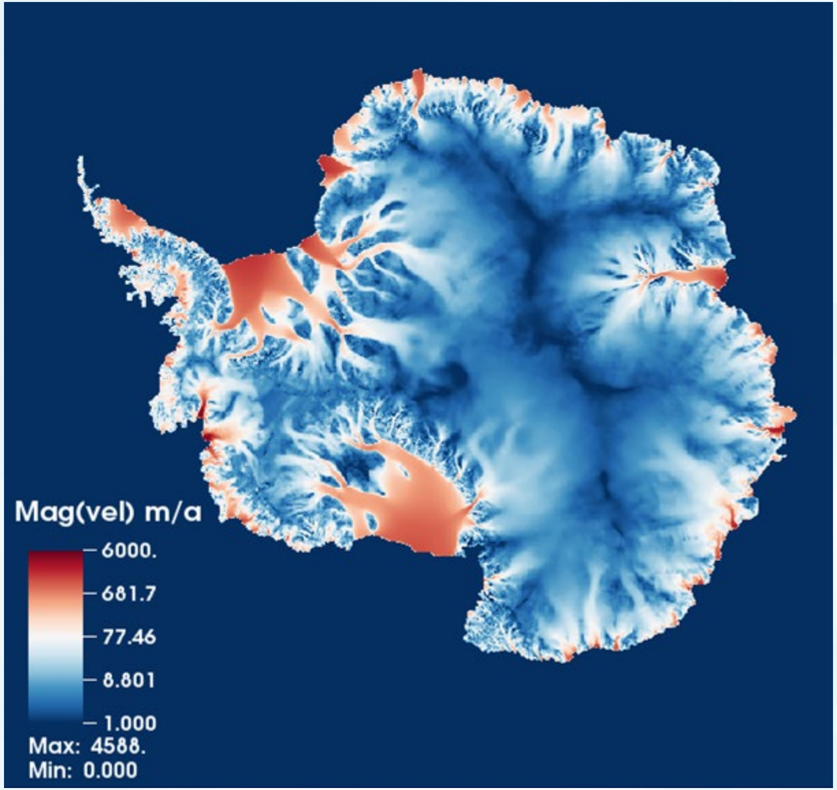
- Constant geometry from
  - Observations (e.g. BedMachine) or
  - Ice sheet initial condition (maybe also BedMachine)
- Start at rest
- Temperature and salinity from climatology
- Extrapolated (somehow) under ice shelves
- Run for ~5-30 years (depending on what you can afford)
- Tuning to improve melt rates?



The vertically averaged ocean speed in a POPSICLES simulation

Realistic: ice-sheet initialization

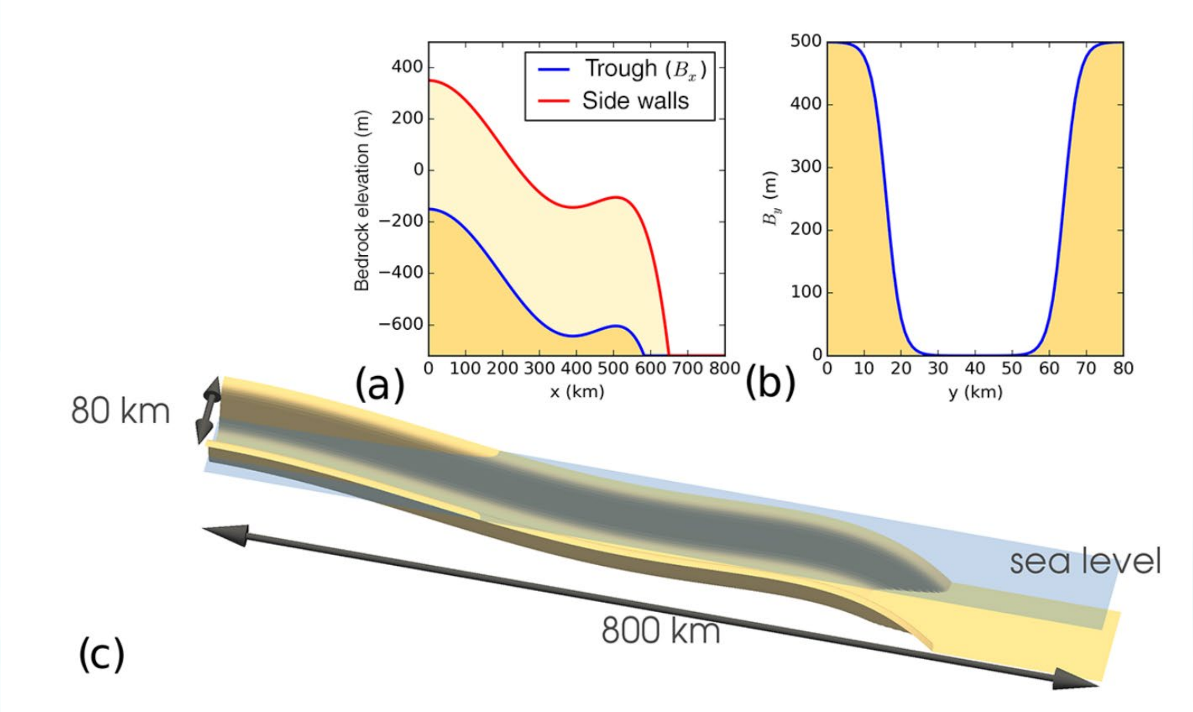
- Spin-up
- Data assimilation
- (What we've discussed in the workshop so far)
- …
- Constant (or variable) melt rates from
  - Ocean spin-up
  - Observations
- Upon coupling, potential shocks:
  - If ocean geometry abruptly changes
  - If melt rate abruptly changes



The ice speed in a POPSICLES simulation

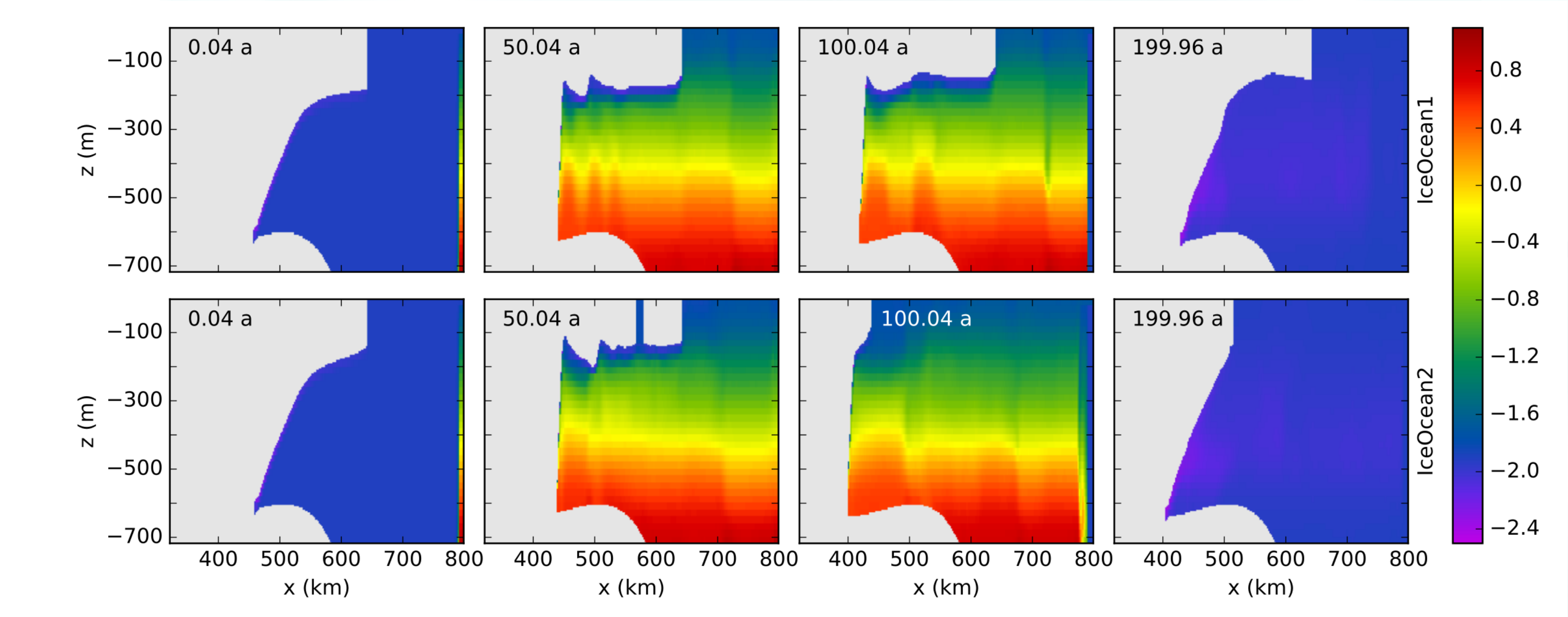
Comparing models: Marine Ice Sheet-Ocean Model Intercomparison Project (MISOMIP)

MISOMIP1 experiments



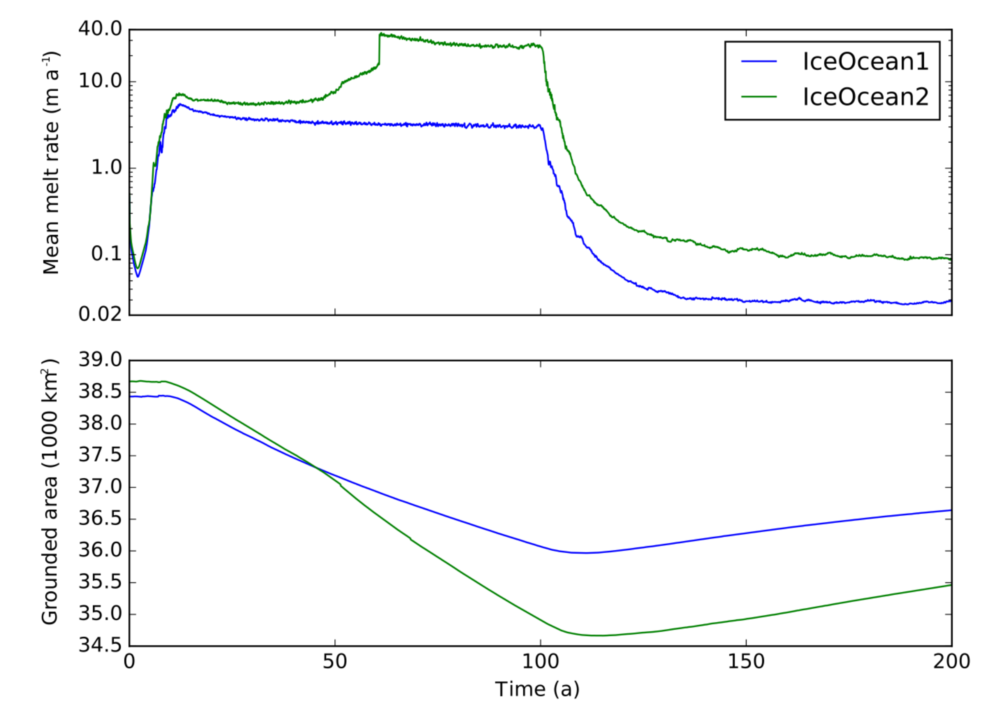
Bedrock topography for the MISOMIP1 experiments (also MISMIP+ and ISOMIP+), with steep a trough and a region of "reverse-sloped" bed (Asay-Davis et al. 2016)

MISOMIP1 experiments



Ocean temperature from POPSICLES MISOMIP1 simulations without calving (top) and with calving (bottom) at 0, 50, 100 and 200 years (Asay-Davis et al. 2016).

MISOMIP1 experiments



Mean melt rates and grounded area vs. time from POPSICLES MISOMIP1 simulations (Asay-Davis et al. 2016) without calving (blue) and with calving (green).

Models participating in MISOMIP1

Model	Citation/Notes
Offline-coupled	
Goldberg et al. model	Goldberg et al. (2012)
POPSICLES (POP-BISICLES)	
MITgcm-Úa	De Rydt and Gudmundsson (2017)
ISSM-MITgcm	Seroussi et al. (2017)
BISICLES-NEMO	In UKESM1
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Elmer/Ice-NEMO	
Online-coupled	
MOM6-CISM	
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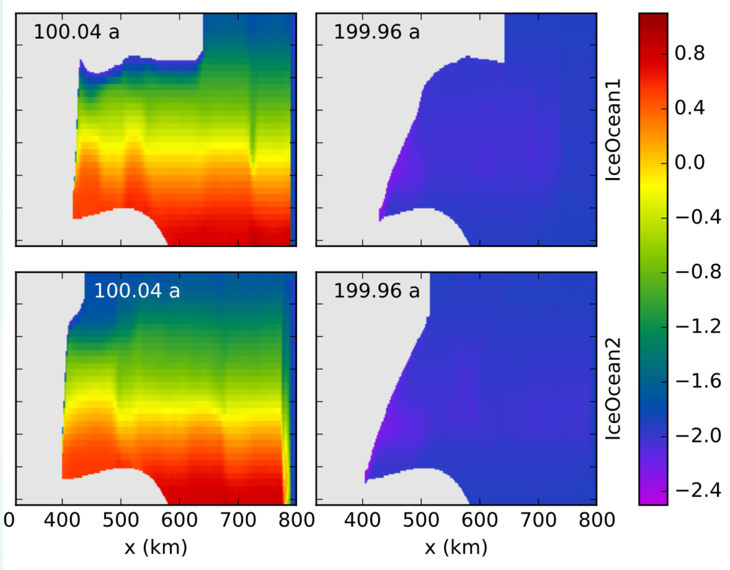
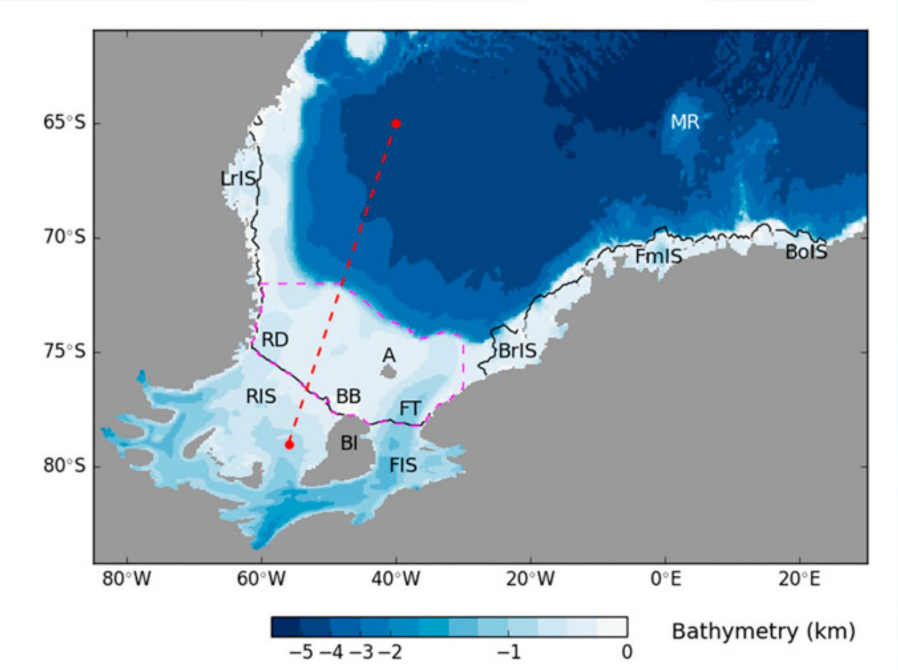
MITgcm (ocean and ice sheet)	Goldberg et al. (2018), Jordan et al. (2018)
MPAS-O/MALI	In progress for E3SM v3
ROMS-icepack	In progress



Ocean temperature from POPSICLES MISOMIP1 simulations without calving (top) and with calving (bottom) at 100 and 200 years (Asay-Davis et al. 2016).

Plans for MISOMIP2

- Realistic forcing and model geometries
- Regional Foci:
  - Amundsen Sea
  - Weddell Sea
- Simulations:
  - Standalone ocean
  - Standalone ice sheet
  - Coupled ice sheet-ocean
- Simulation time frame:
  - 1990-2020
- Topography and Forcing:
  - "Come as you are"



Weddell Sea regional domain [(Naughten et al. 2019)]

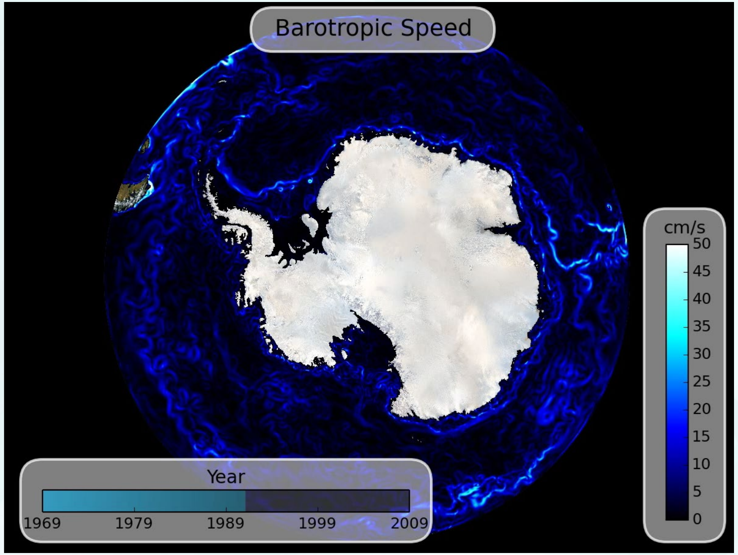
US Department of Energy (DOE) models

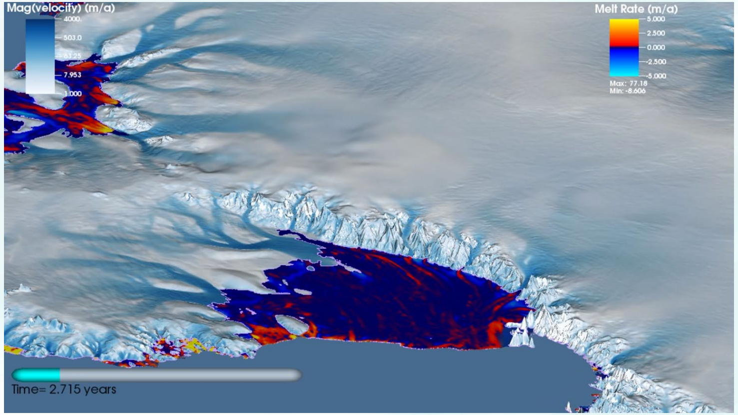
POPSICLES

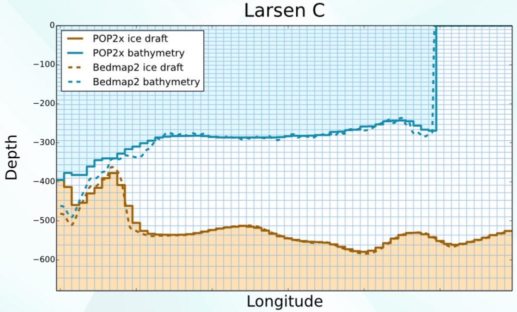
Pan-Antarctic coupled ice sheet-ocean model

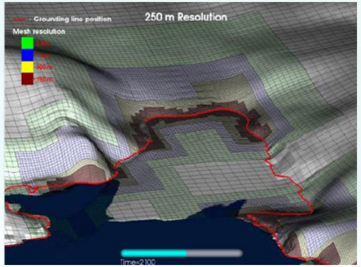
Components:

- Parallel Ocean Program (POP)
- BISICLES Ice-Sheet Model
- Offline coupling
- High resolution to resolve largest ocean eddies and grounding-line dynamics
  - ocean: 0.1º (~5-10 km)
  - ice-sheet: 500 m (adaptive)



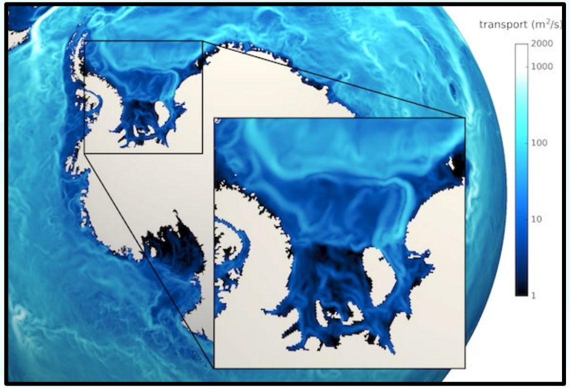


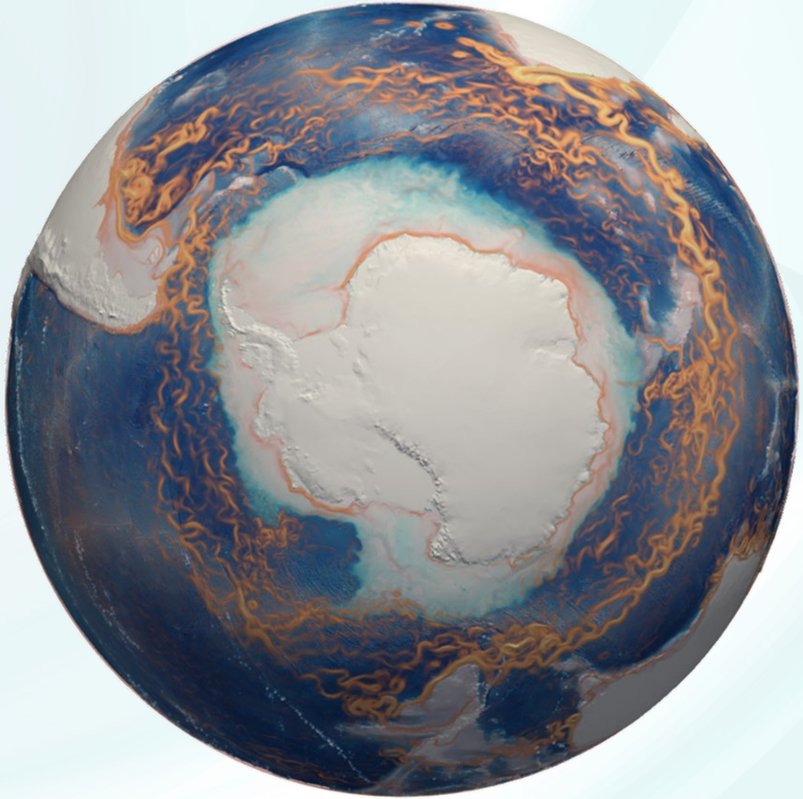




Energy Exascale Earth System Model (E3SM)

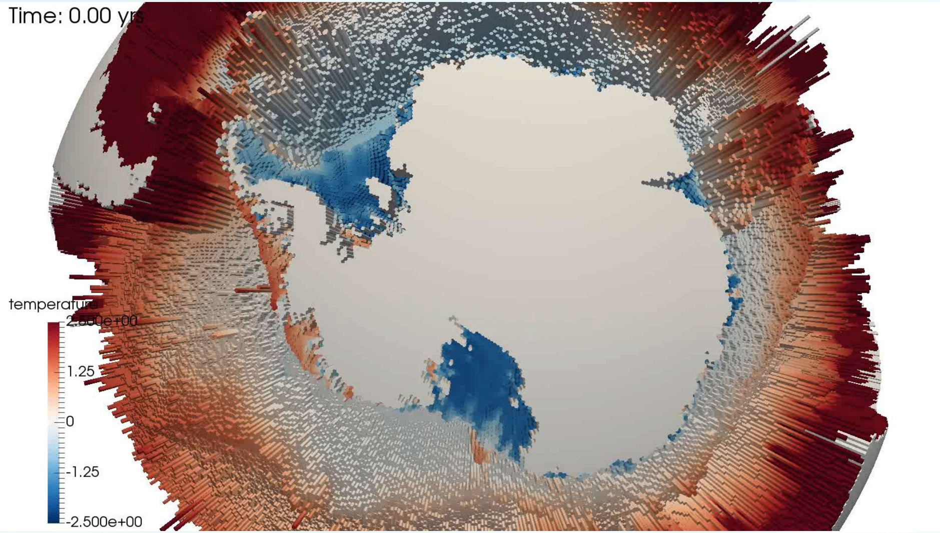
- Variable-resolution components (atmosphere, land, ocean, sea-ice, and ice-sheet)
- Focused on interactions between the climate system and the energy sectors
- Cryosphere science focus: projections of Antarctic sea-level change

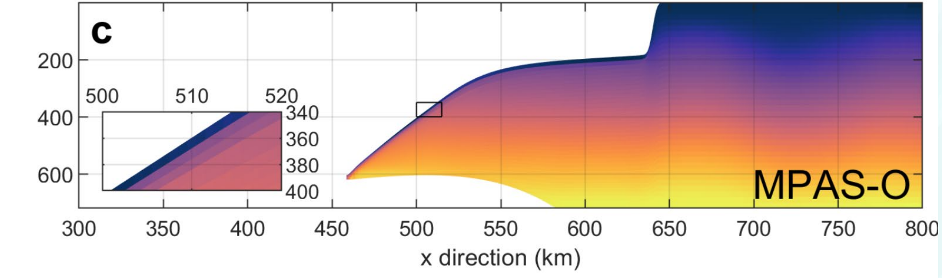




Model for Prediction Across Scales – Ocean (MPAS-O)

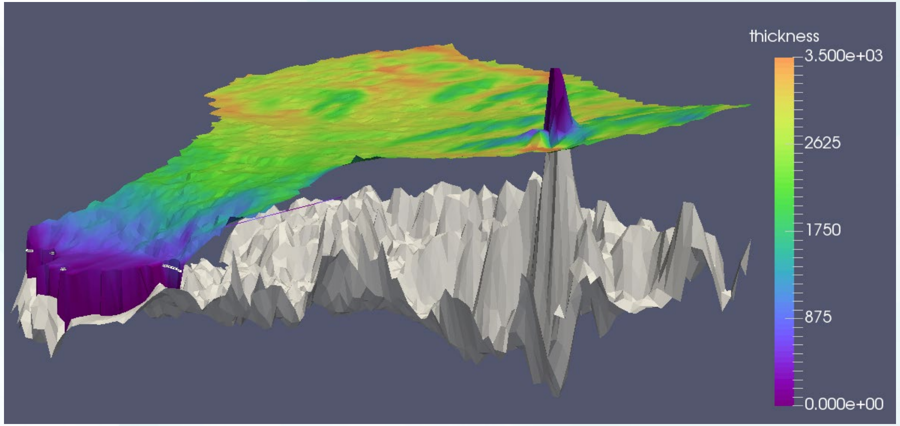
- Unstructured horizontal grid
- Voronoi cells
- Finite volume
- Ice-shelf cavities:
  - Terrain-following top coordinate
  - Smoothed calving front
- Cryosphere Configuration:
  - Static ice-shelf cavities (Bedmap2)
  - Two horizontal resolutions in Southern Ocean and Antarctic continental shelf:
    - ~30 km (“low res.”)
    - ~10 km (“mid res.”)
    - Plans for ~5-6 km (“high res.”) focused on Antarctic



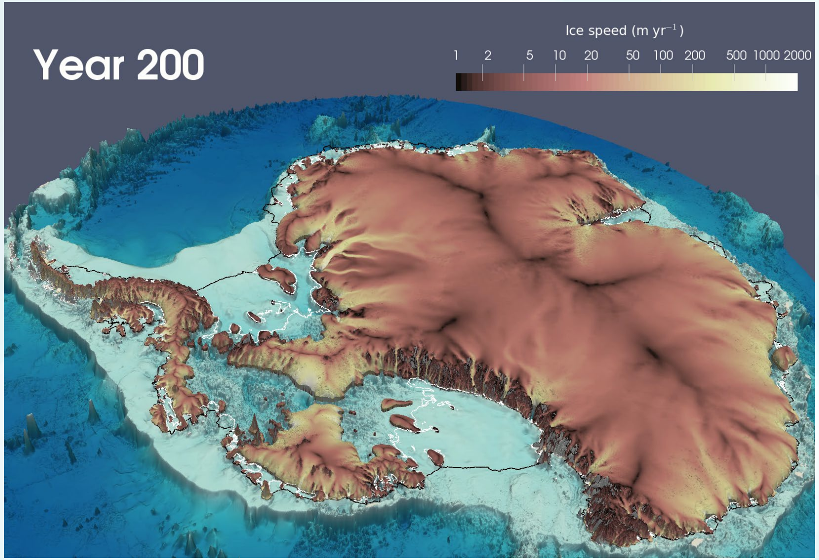


MPAS-Albany Land Ice (MALI) model

- Discussed by Steve, Mauro and Irina
- Unstructured
- Finite element velocity solver
- Finite volume thickness/temperature evolution



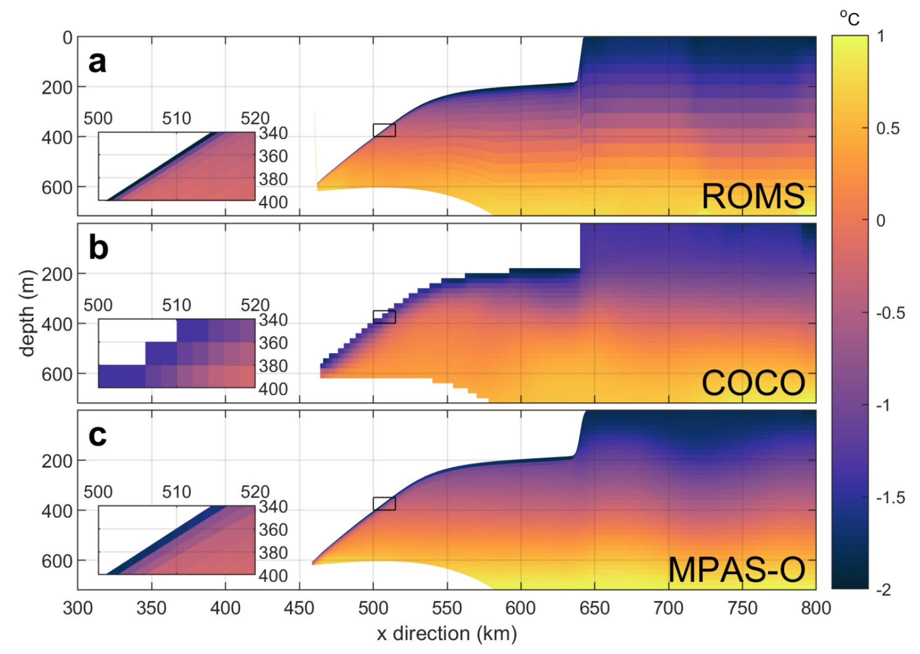
Thwaites regional domain (Hoffman et al. 2019)



ABUMIP simulations

Ice sheet-ocean boundary fluxes

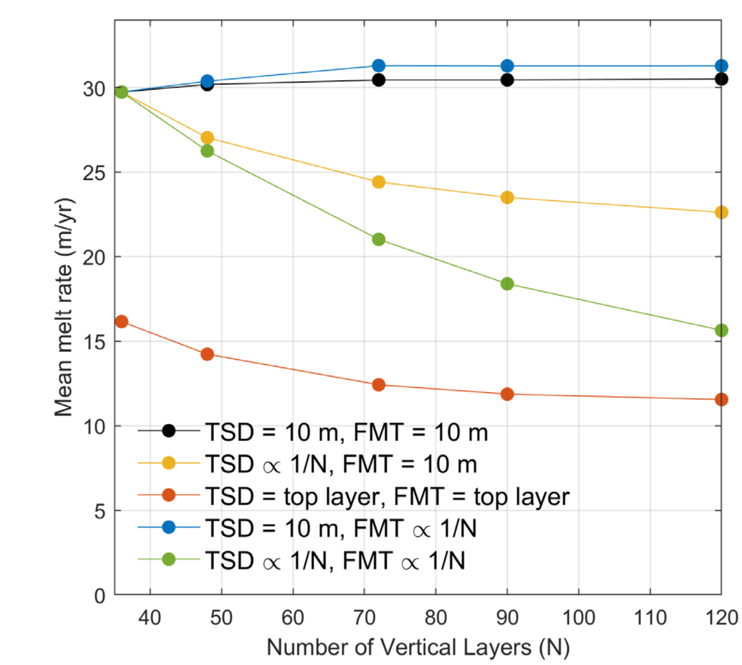
- Heat and melt fluxes are computed in the coupler
- From the ice sheet:
  - Bottom-layer temperature and thickness
- From the ocean (all vary horizontally):
  - Boundary-layer temperature and salinity (averaged over top 10 m)
  - Heat- and salt-transfer coefficients
  - Effective ocean density for flotation
- "Three-equation" boundary conditions
  - Melt rate (freshwater flux)
  - Heat flux
  - Interface temperature and salinity



Ocean temperature and vertical coordinate in three ocean models (Gwyther et al., Ocean Modelling, accepted). Simulations are based on ISOMIP+ experiments under the MISOMIP project.

Ice sheet-ocean boundary fluxes

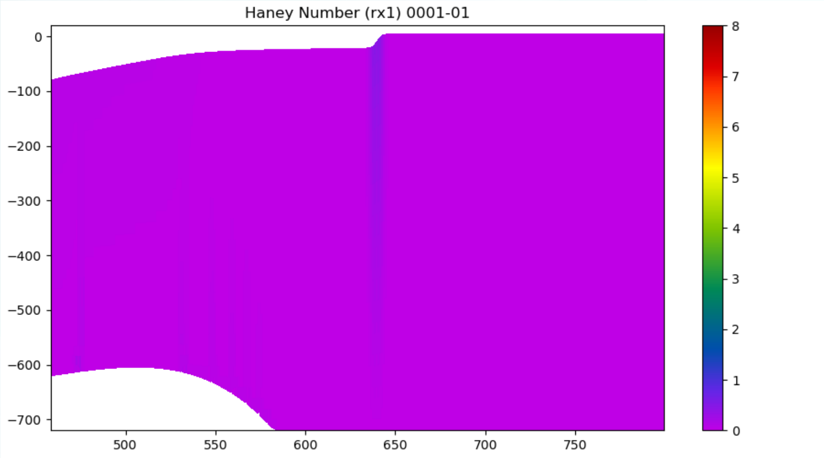
- Boundary-layer (BL) temperature and salinity averaged over top 10 m
- Heat and freshwater fluxes distributed with a 10-m length scale
- Leads to nearly resolution-independent results
- But(!!) 10 m is completely arbitrary
  - Better understanding of transition from unresolved to resolved BL turbulence needed
  - DNS, LES, lab experiments underway, but more is needed
  - Look for review by Malyarenko et al. (under review in Ocean Modelling)



Mean melt rate vs. model resolution in MPAS-O (Gwyther et al., Ocean Modelling, accepted).

Coupling MPAS-O and MALI within E3SM (underway)

- Adding higher-order horizontal pressure gradient to MPAS-O (Adcroft et al. 2008)
- Adapting wetting-and-drying scheme already in use for coastal modeling
- Thin film approach (everywhere with grounded marine ice)
- Melt rates computed in coupler (as previously discussed)
- Prescribed dynamic ice-shelf geometry already supported



MPAS-O simulation with prescribed ice-shelf geometry

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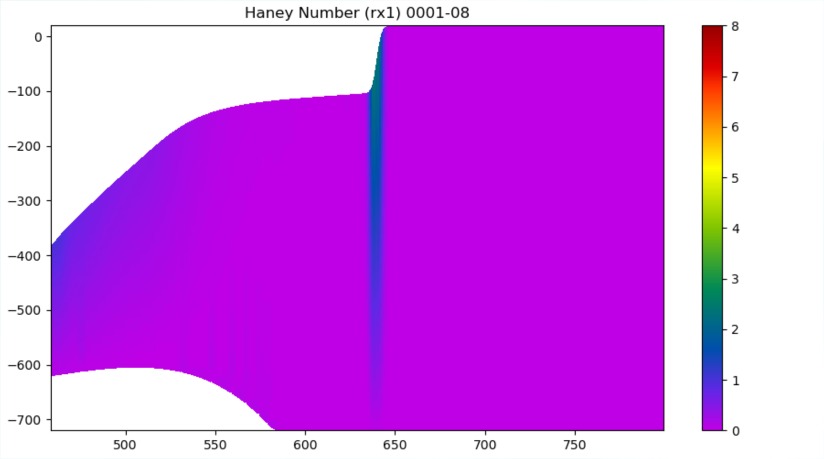

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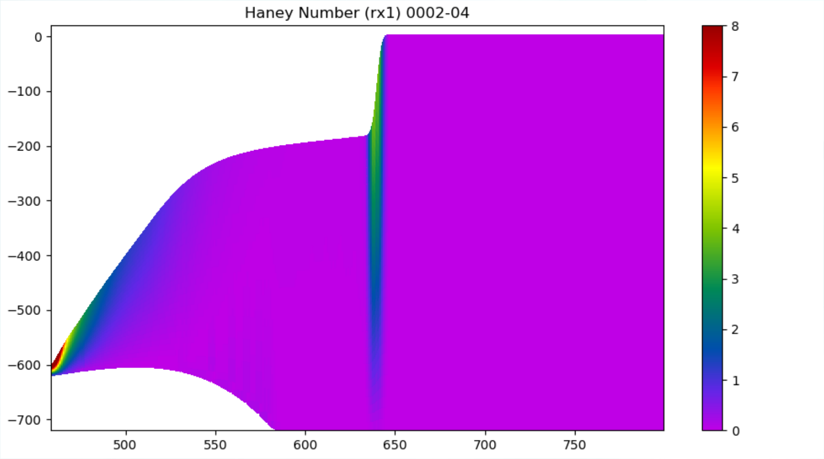

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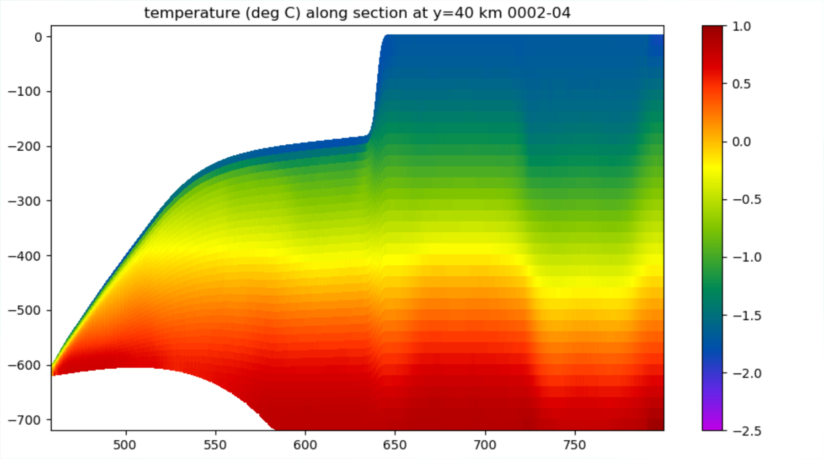
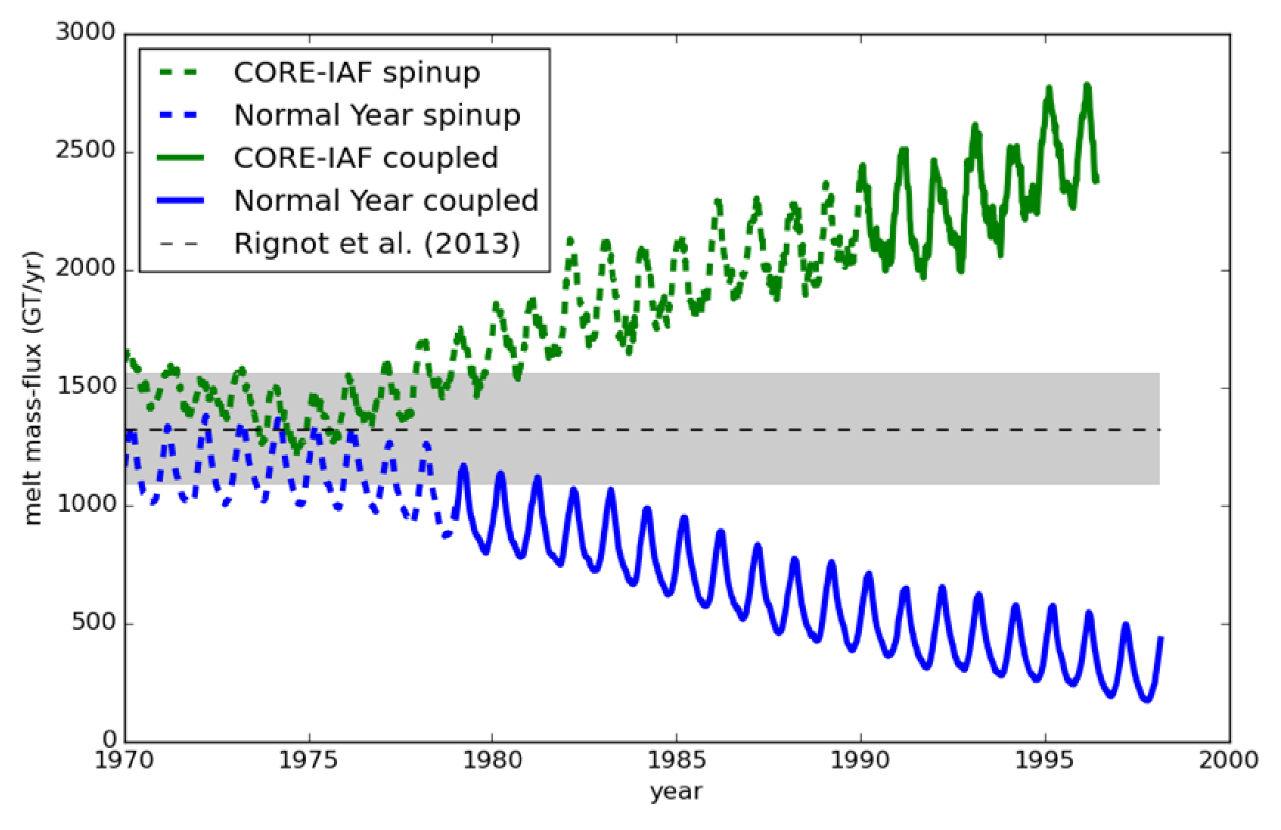


MPAS-O simulation with prescribed ice-shelf geometry

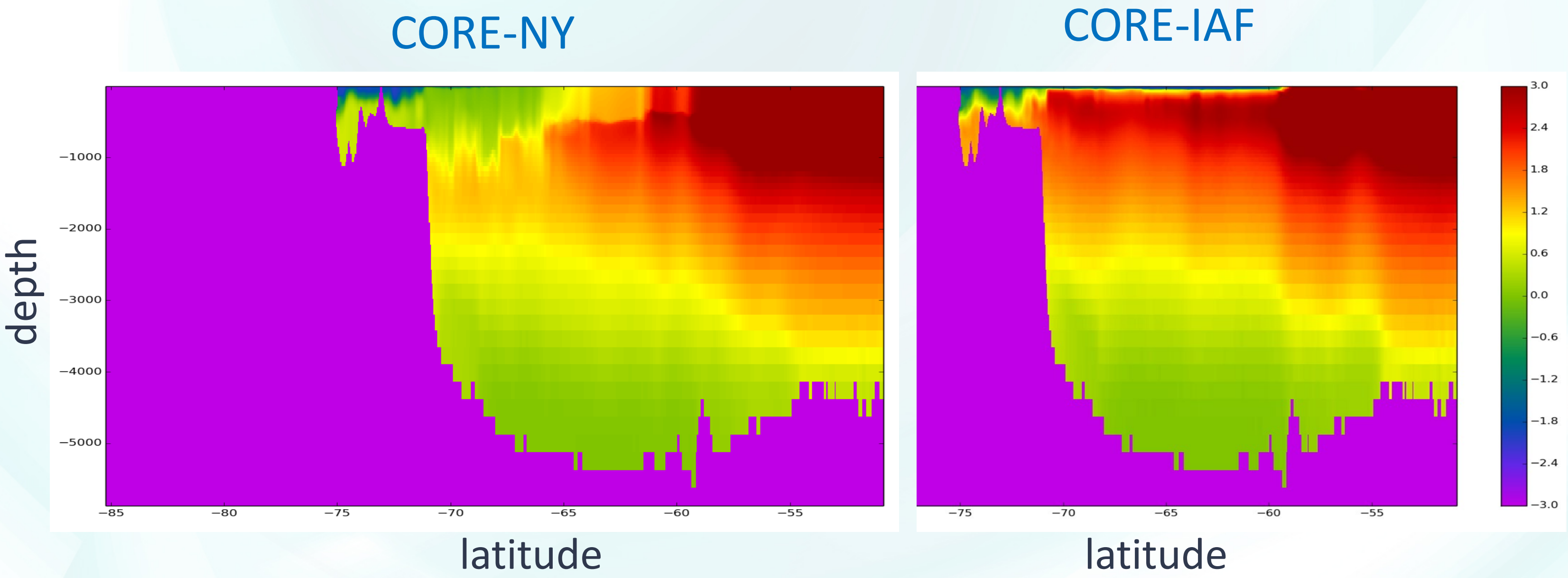
Effects of climate biases on ice-sheet forcing

POPSICLES Simulations

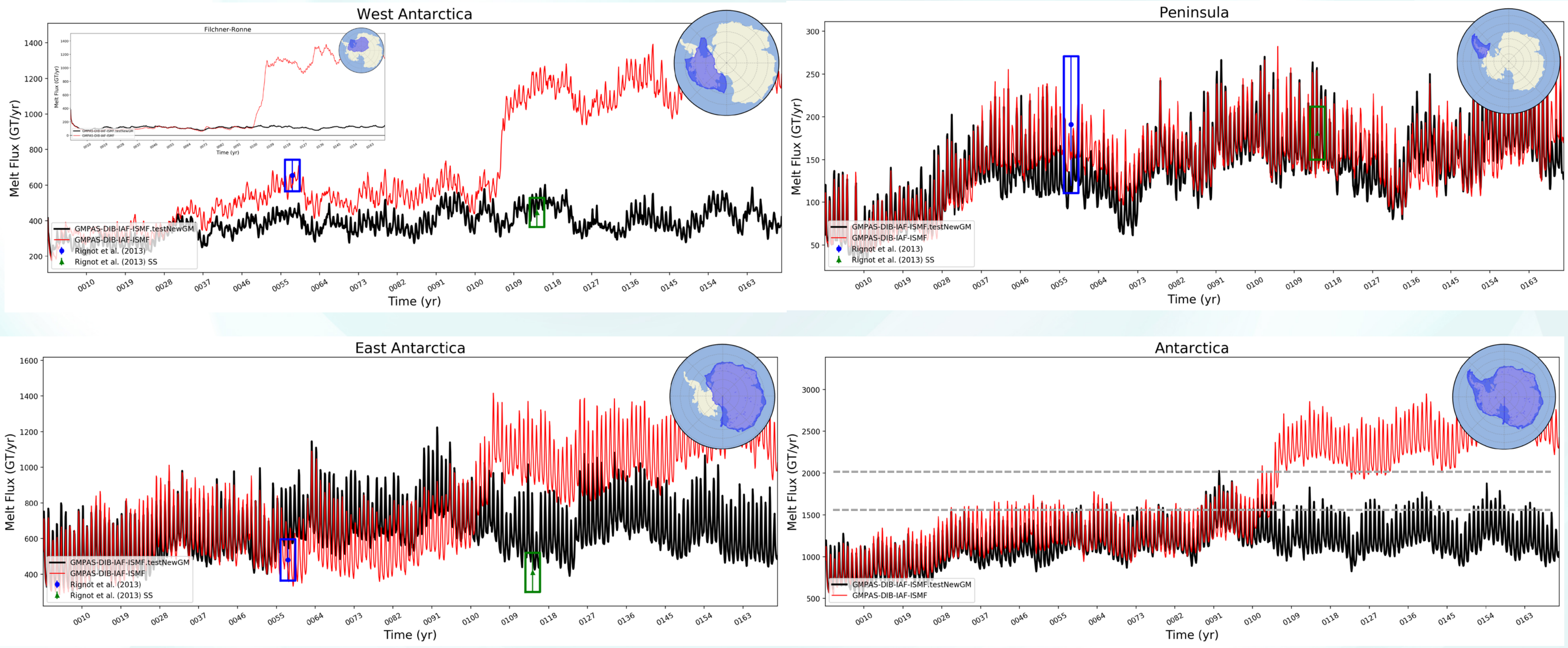


POPSICLES Simulations

Cross-section of **potential temperature** through the **Amundsen Sea Embayment** (105^{o}W)



E3SM Simulations



(blue and green boxes are estimates from Rignot et al., 2011)

Thank you!