Variable-Resolution CESM (VR-CESM)

Annual CESM Tutorial, 2023

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NSF

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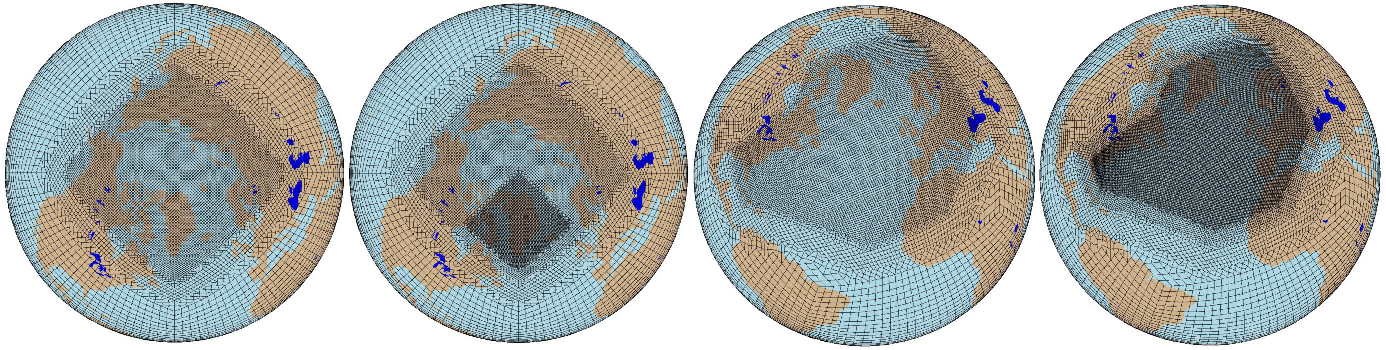
Part 1: What? Why? How?

What is VR-CESM?

Variable-resolution is CESM's label for static mesh refinement in CAM (sometimes also referred to as regional refinement)



There are various grid refinement approaches:

- Domain Nesting – high-resolution limited area model occupies a portion of a global model
- Static Mesh Refinement – refine a region of the global grid in the same model
- Adaptive Mesh Refinement – refine moving features in the same model

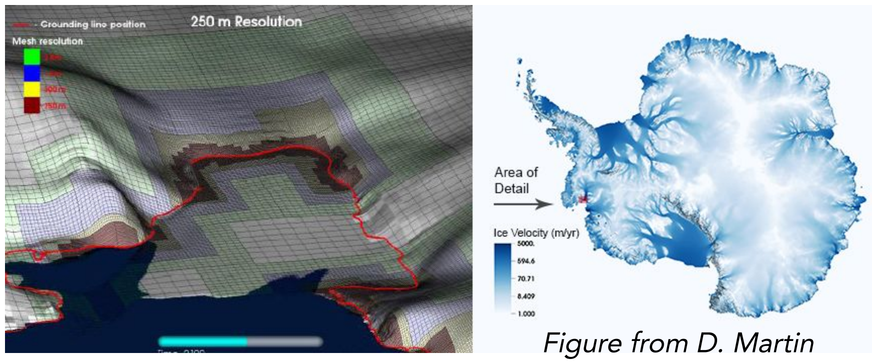


Figure from D. Martin

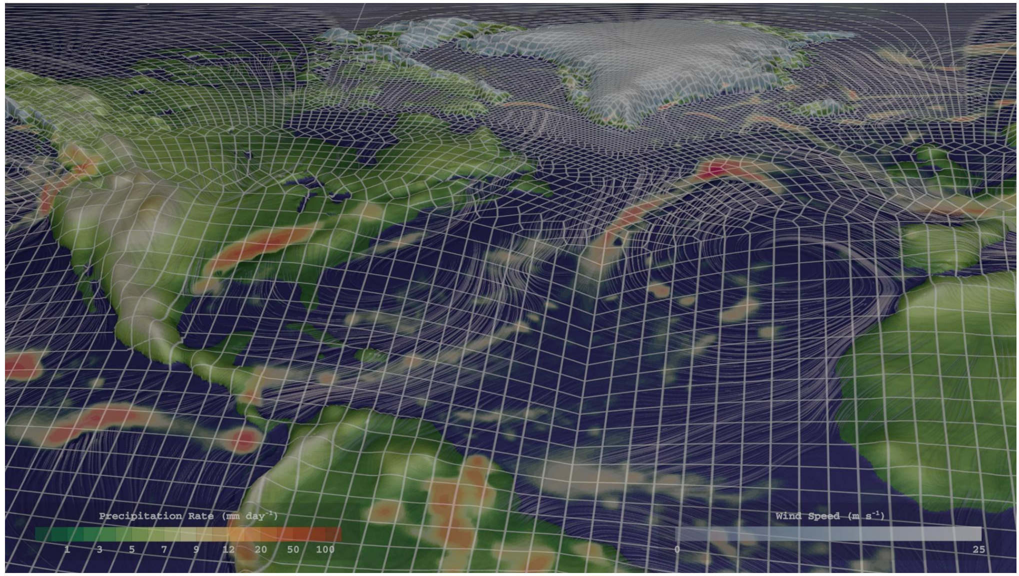
BISICLES-computed simulation of present-day Antarctic ice velocities. The image at the left illustrates adaptive placement of fine spatial resolution near grounding lines (red) for the Pine Island Glacier.

Visualizations:
https://youtu.be/3APH7vJnwR8
https://youtu.be/3We_Mz-yaB8
https://youtu.be/YwHgqDu75s8

Why VR-CESM?

The appeal of VR-CESM is the ability to simulate high-resolution in a global model at an affordable cost.

The steal a phrase - it makes the impossible, possible.



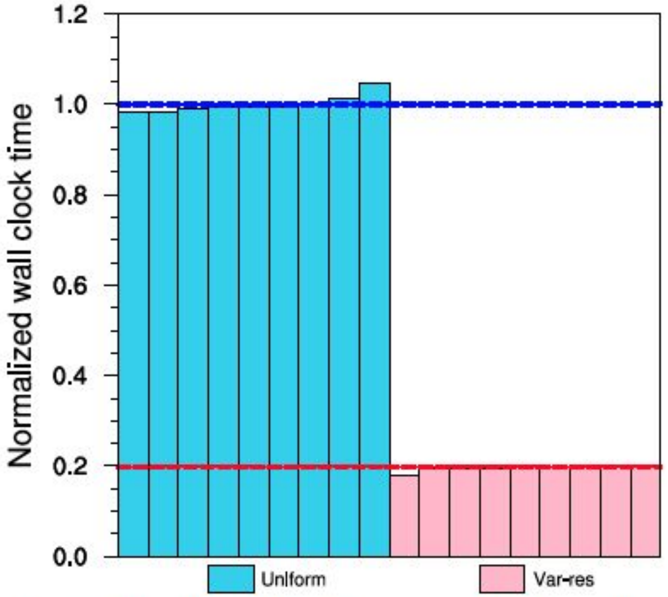
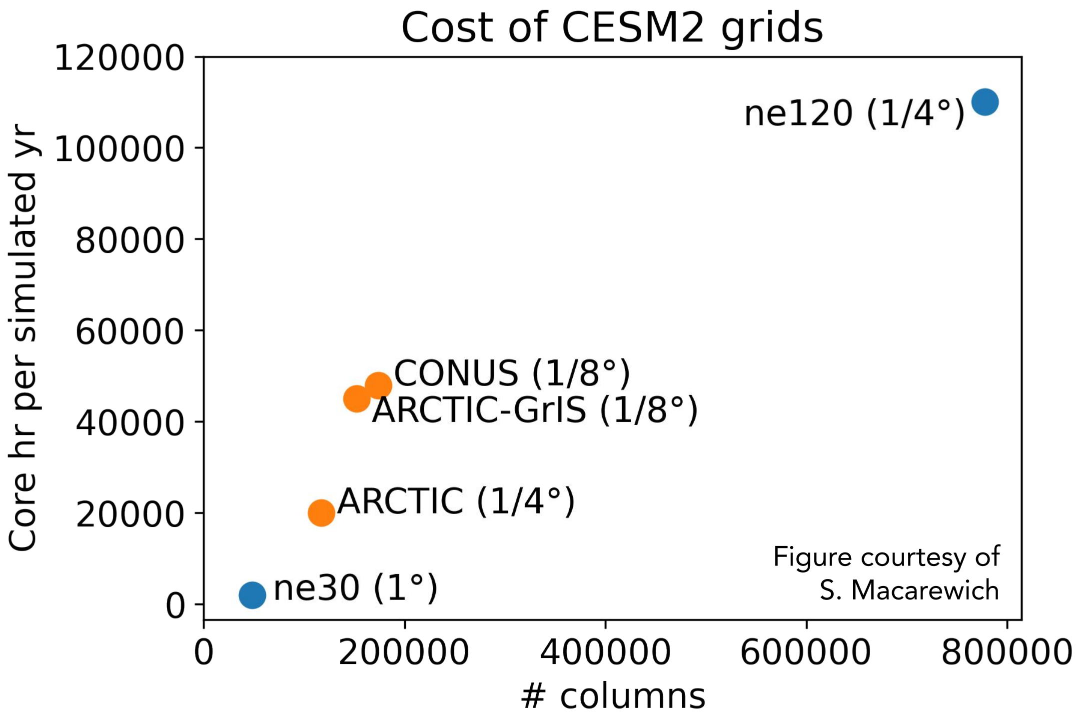


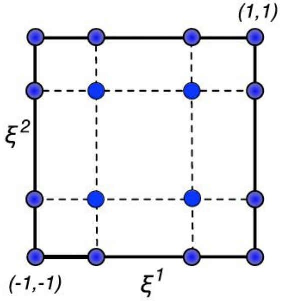
FIG. 10. Normalized wall clock time for idealized tropical cyclone simulations in the globally uniform mesh (light blue) and the variable-resolution grid (pink). The dashed lines indicate the theoretical scaling assuming model run time scales linearly with number of mesh elements.

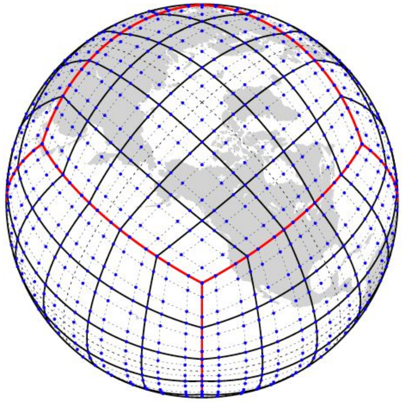
Zarzycki et al. 2014



MPAS
Model for Prediction Across Scales

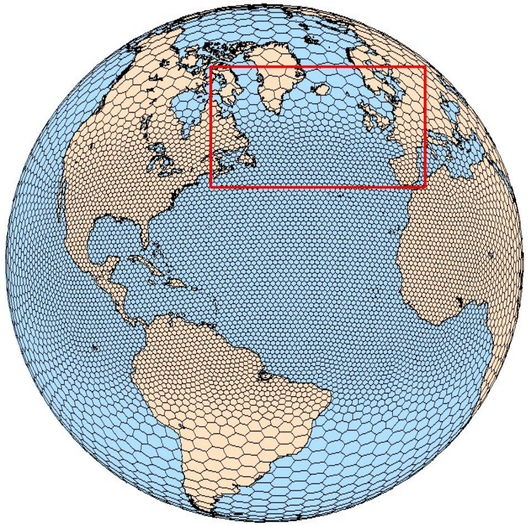
CAM support for VR-CESM

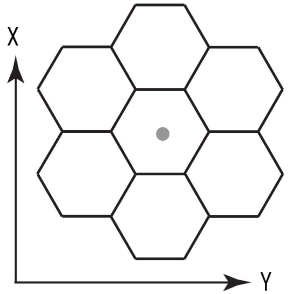


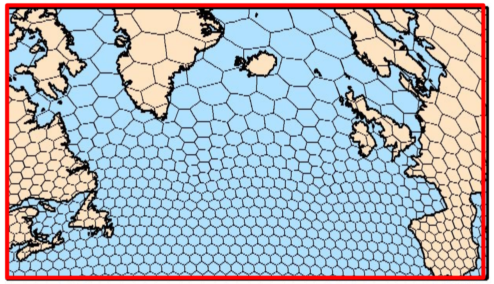


MPAS-A dynamical core

- Developed at MMM (c. 2013)
- Recently ported to CESM2.3+
- Centroidal Voronoi meshes
- Non-hydrostatic



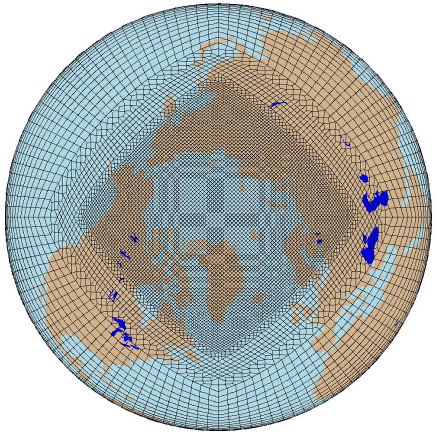




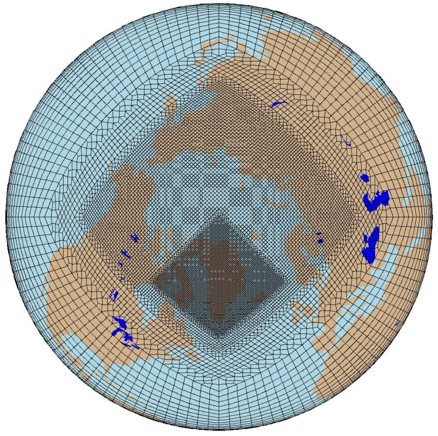
Spectral-element dynamical core

- Jointly developed by NCAR & DOE (HOMME)
- Hydrostatic version supported in CESM2.0
- Cubed-sphere mesh
- Three VR grids run out-of-the-box in CESM2.2+:

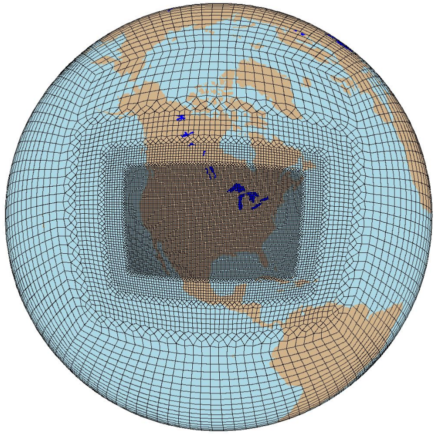
ARCTIC



ARCTICGRIS



CONUS



see cam6.3 users guide for instructions on running:

https://ncar.github.io/CAM/doc/build/html/CAM6.3_users_guide/atmospheric-configurations.html#cam-developmental-compsets

What needs to be changed when running VR-CESM?

REDACTED (TMI)

When increasing horizontal resolution in a global model, one needs to:

1. Reduce the strength of numerical filters
   - Less diffusion at higher-resolution
   - VR-CESM uses a scale-aware tensor hyper-viscosity
2. Reduce time-steps
   - Dynamical core time-step for stability
   - Physics time-step for physical realism
3. Increase the resolution of boundary conditions
   - Topography boundary conditions need ~2dx length-scales smoothed-out (i.e., rougher terrain at hi-res)
   - Resolve complex land surface type boundaries (coastlines, ice sheet margins, mountain glaciers)
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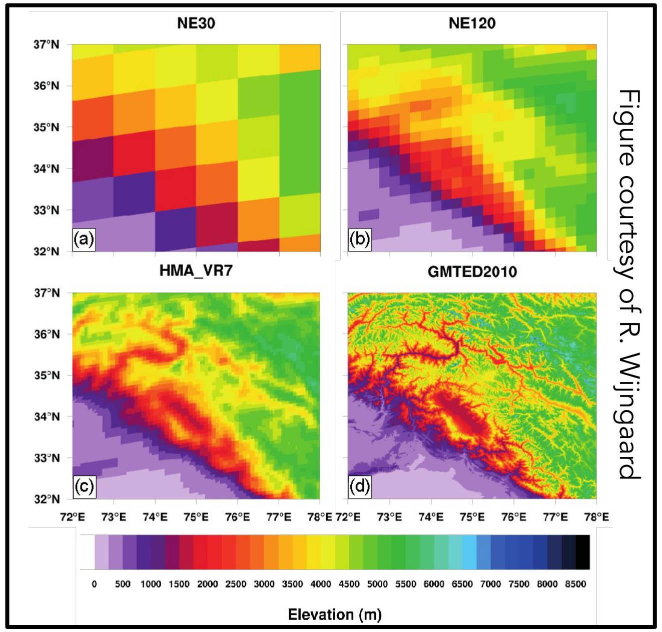
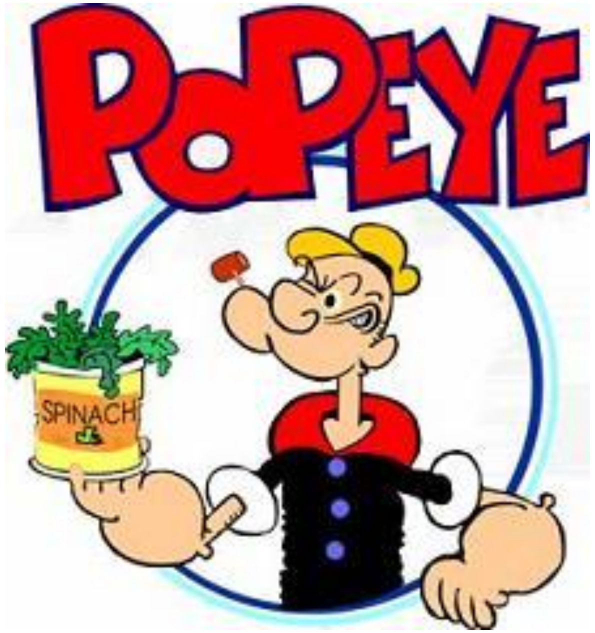


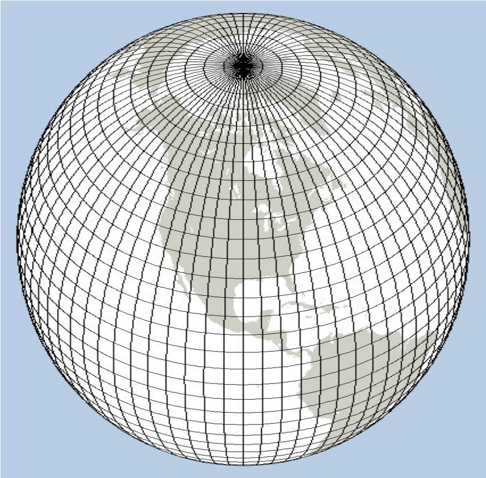
Figure courtesy of R. Wijngaard

You can run VR-CESM too! But you *must* know how to regrid to work with variable-resolution output…



Part 2: Regridding

Structured vs. Unstructured grids

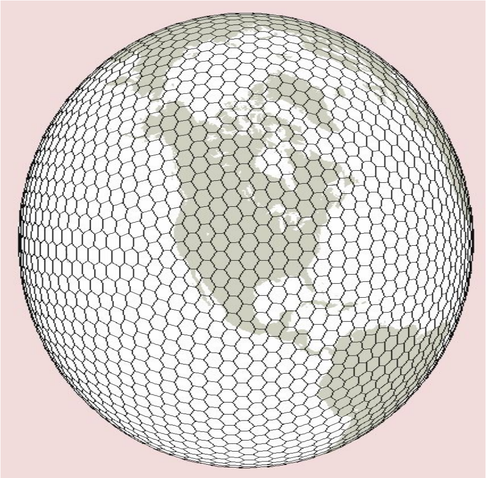


PS (time,lat,lon)

- 2D structured coordinate - lat-lon
- We are all familiar with this; we derive the equations of motion in this coordinate!

Zonal mean - average over lon

Stream function - $u = \frac{\partial \psi}{\partial y}, v = -\frac{\partial \psi}{\partial x}$



PS (time,ncol)

- 1D unstructured coordinate – ncol
- An index associated with each grid column
- Allows for flexible grid structures

Plotting - NCL, Python can create map plots from unstructured arrays

Zonal mean - remap to lat-lon grid

Stream function - remap to lat-lon grid

How to regrid?

"Proper" regridding in three steps:

1 Define destination grid

- What grid do you want to regrid to?
- Should be ~equal res. (or coarser) than the source grid.

2 Generate mapping weights file using source grid file and destination grid file

- Command line ESMF is the easiest to use (installed on cheyenne; ESMF_RegridWeightGen)
- Command line TempestRemap (https://github.com/ClimateGlobalChange/tempestremap)

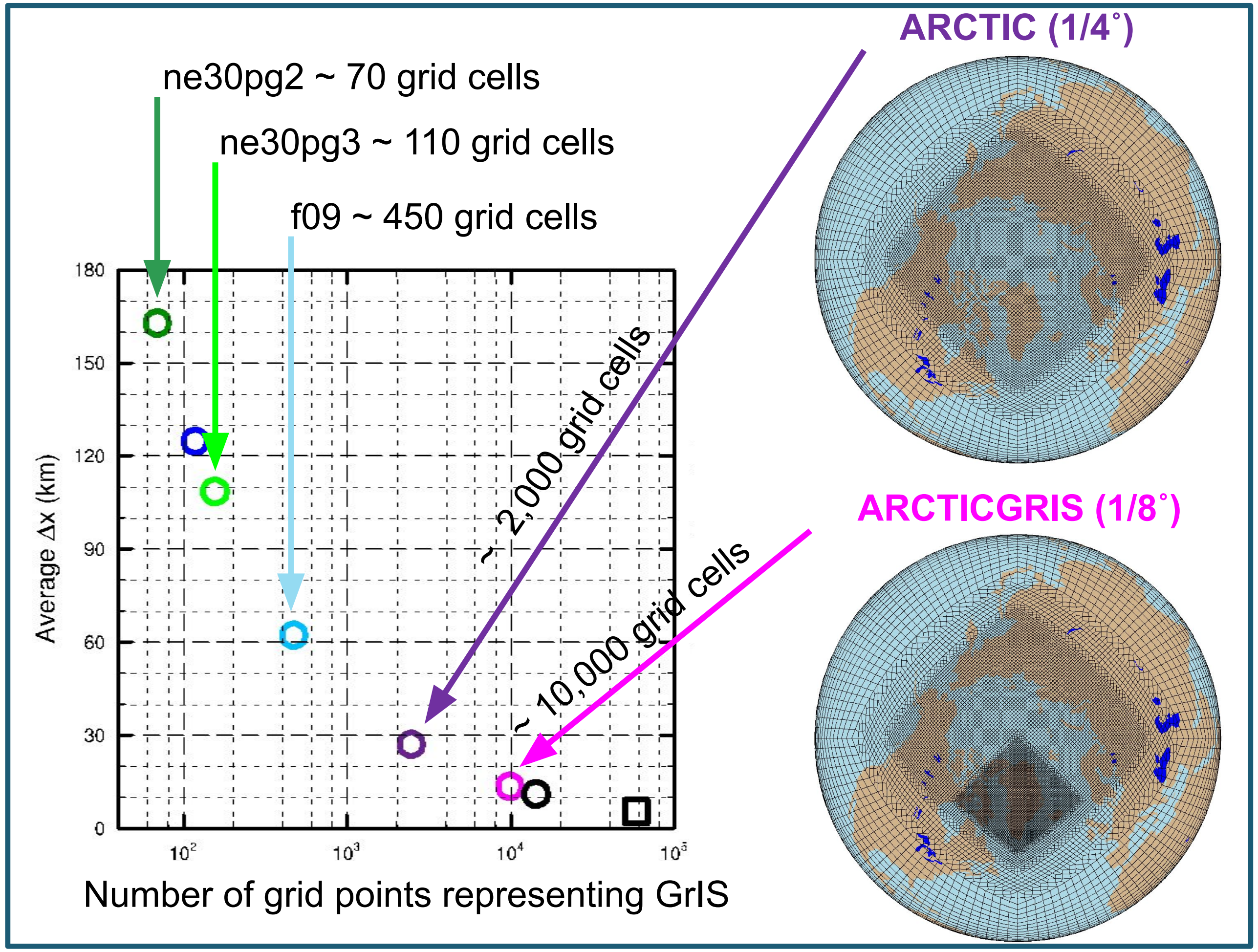
3 Regrid an array using the mapping weights file

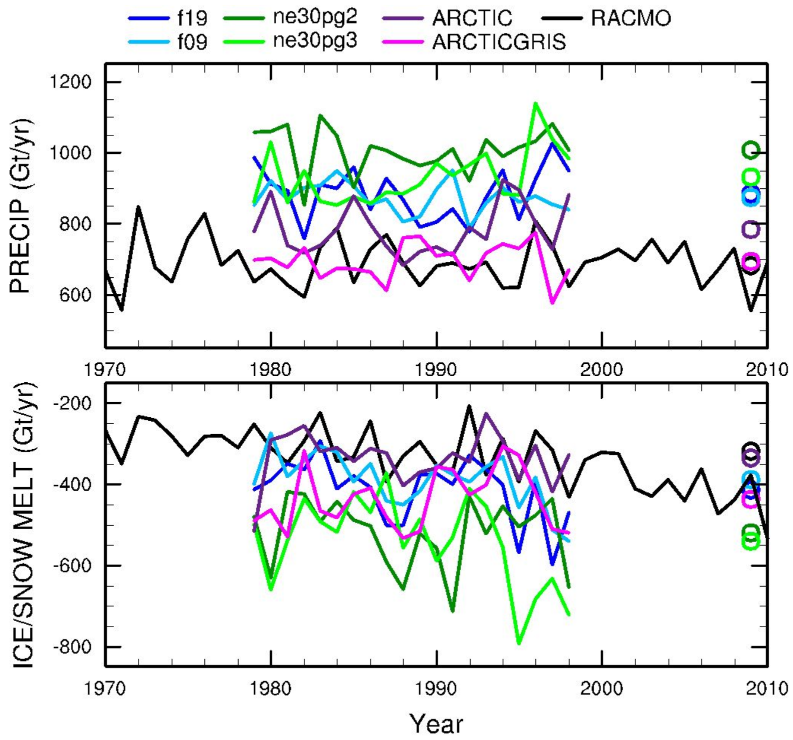
- NCL
  - load "$NCARG_ROOT/lib/ncarg/nclscripts/esmf/ESMF_regridding.ncl"
  - PS_regrid = ESMF_regrid_with_weights(PS,wgtpath,False)
- Python
  - load xESMF library
  - read_weights(filename, n_in, n_out); apply_weights(weights, indata, shape_in, shape_out)

Part 3: Case study of Greenland

Greenland Surface Mass Balance: AMIP Experiments

The Greenland Ice Sheet (GrIS) is an important component of the Earth System, but it is challenging to resolve at 1°

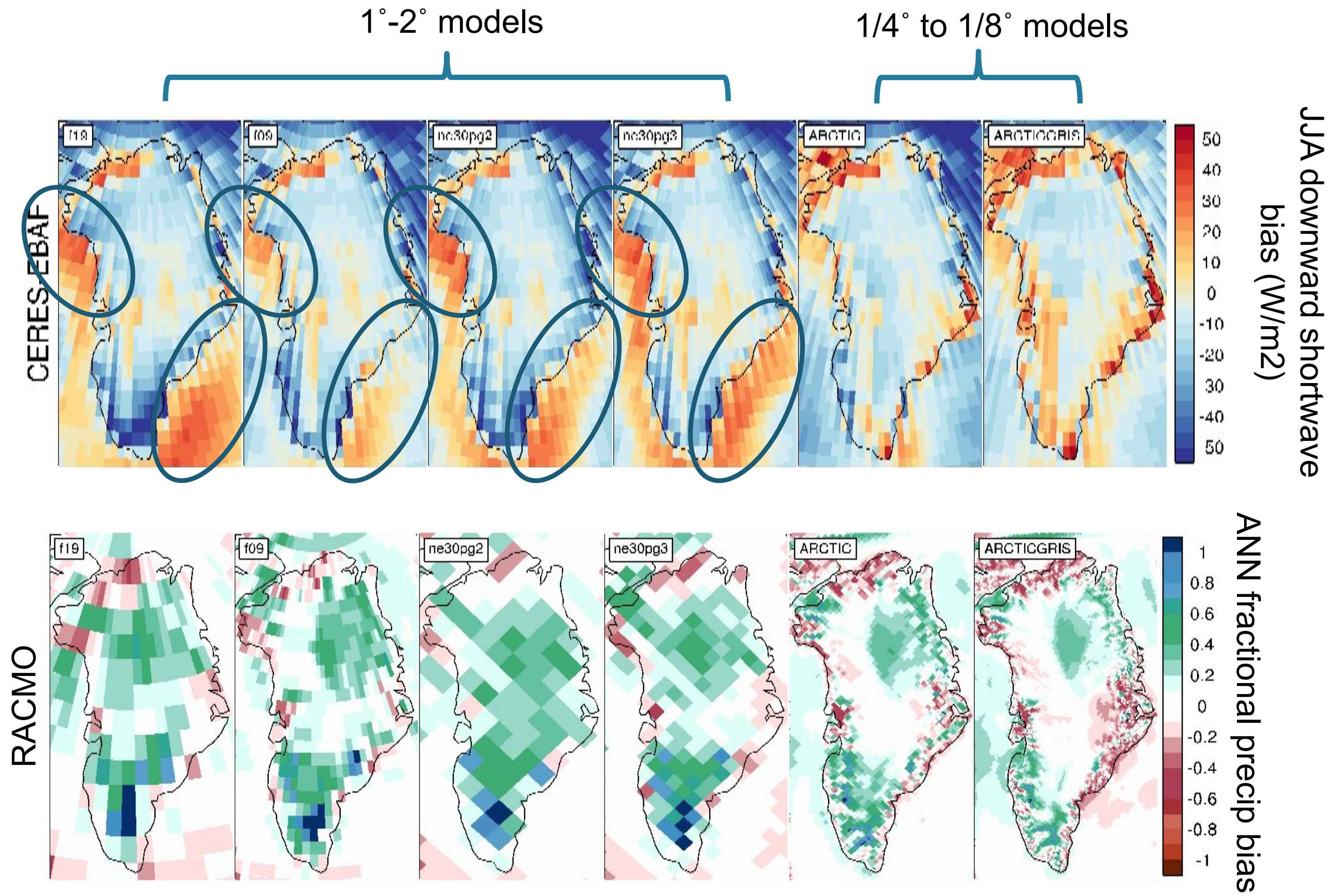




- GrIS Surface Mass Balance (SMB) is the integrated precipitation minus runoff+evap+subl
- Precipitation and melting processes are ~continuously improved from 2° and 1/8° and you can do a pretty good job with 1/4°

Herrington et al. (2022), *JAMES*

Greenland Clouds & Precipitation

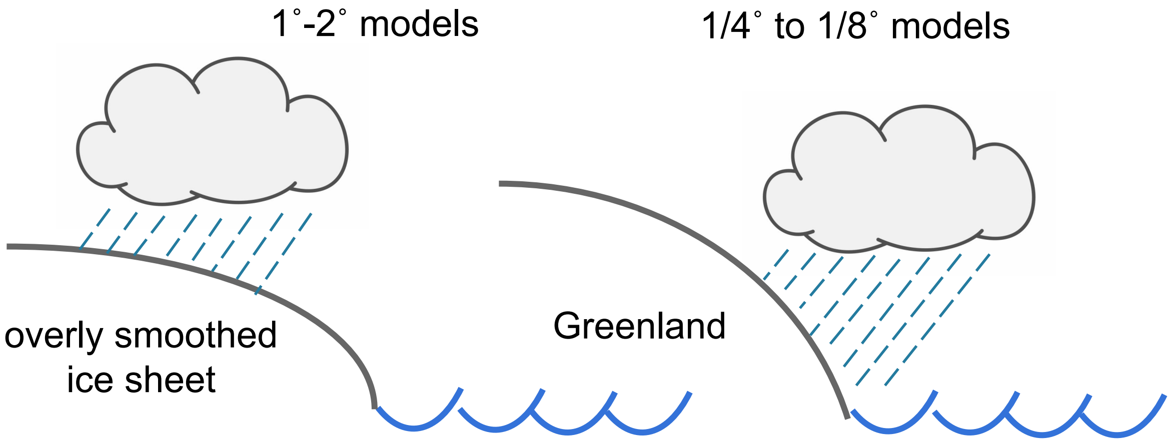


1-2° models are missing clouds around the coastlines, and the interior is too cloudy

Herrington et al. (2022), *JAMES*

Model Topography and Flat Ice Sheets

- Model topography is smoothed as to not excite grid scale (2dx) modes
- Results in a flat ice sheet in 1-2° models, with storms penetrating far too deep into the ice sheet interior (Pollard 2000, CD)



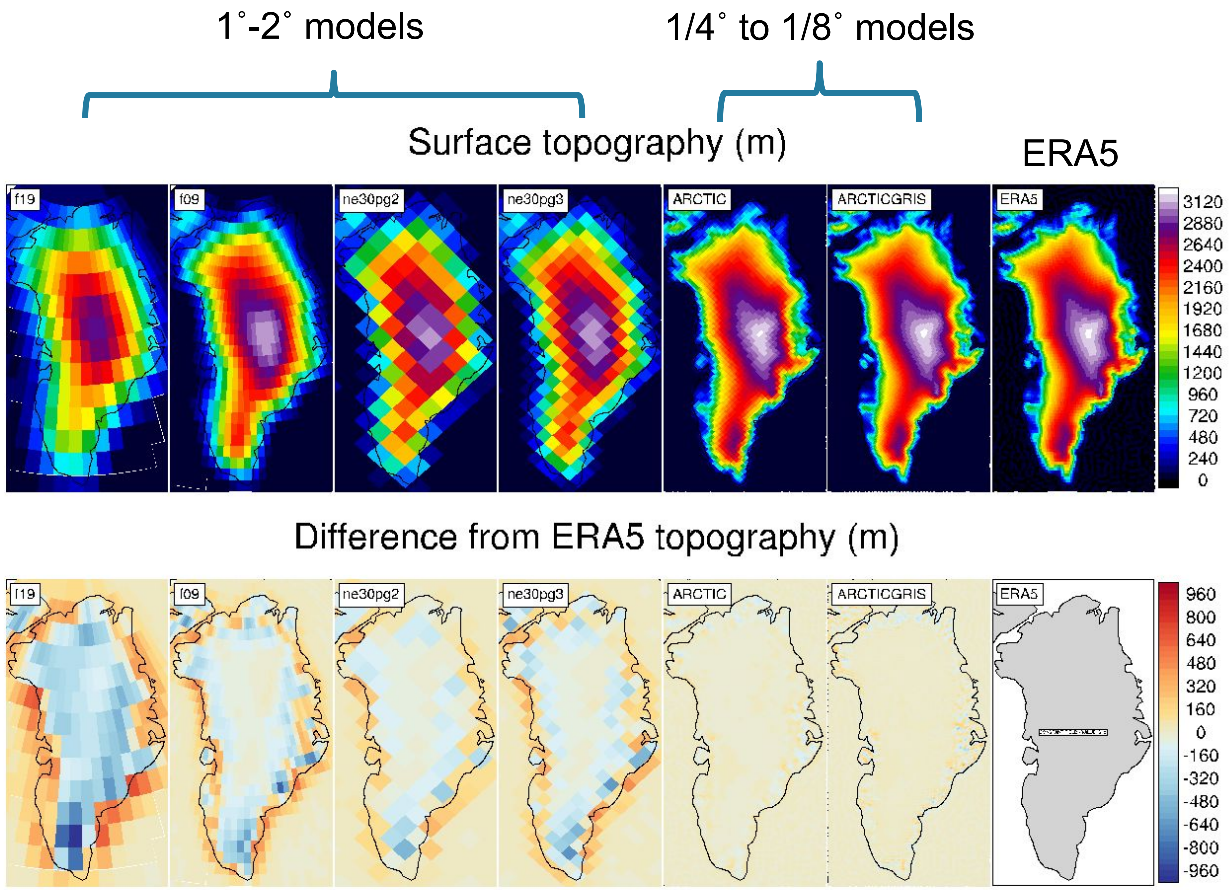


Figure from Waling et al., in prep. The topography generation software (https://github.com/NCAR/Topo) is described in Lauritzen et al. 2015, GMD.

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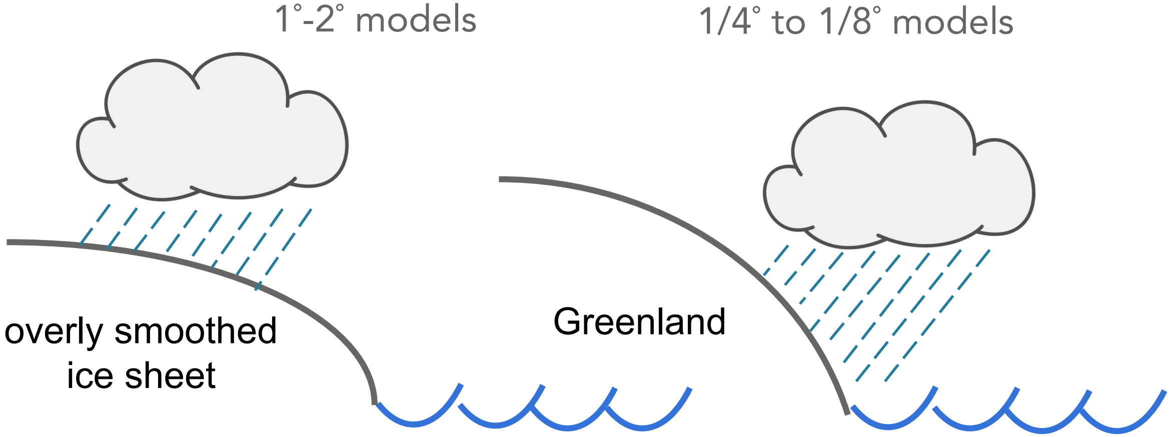

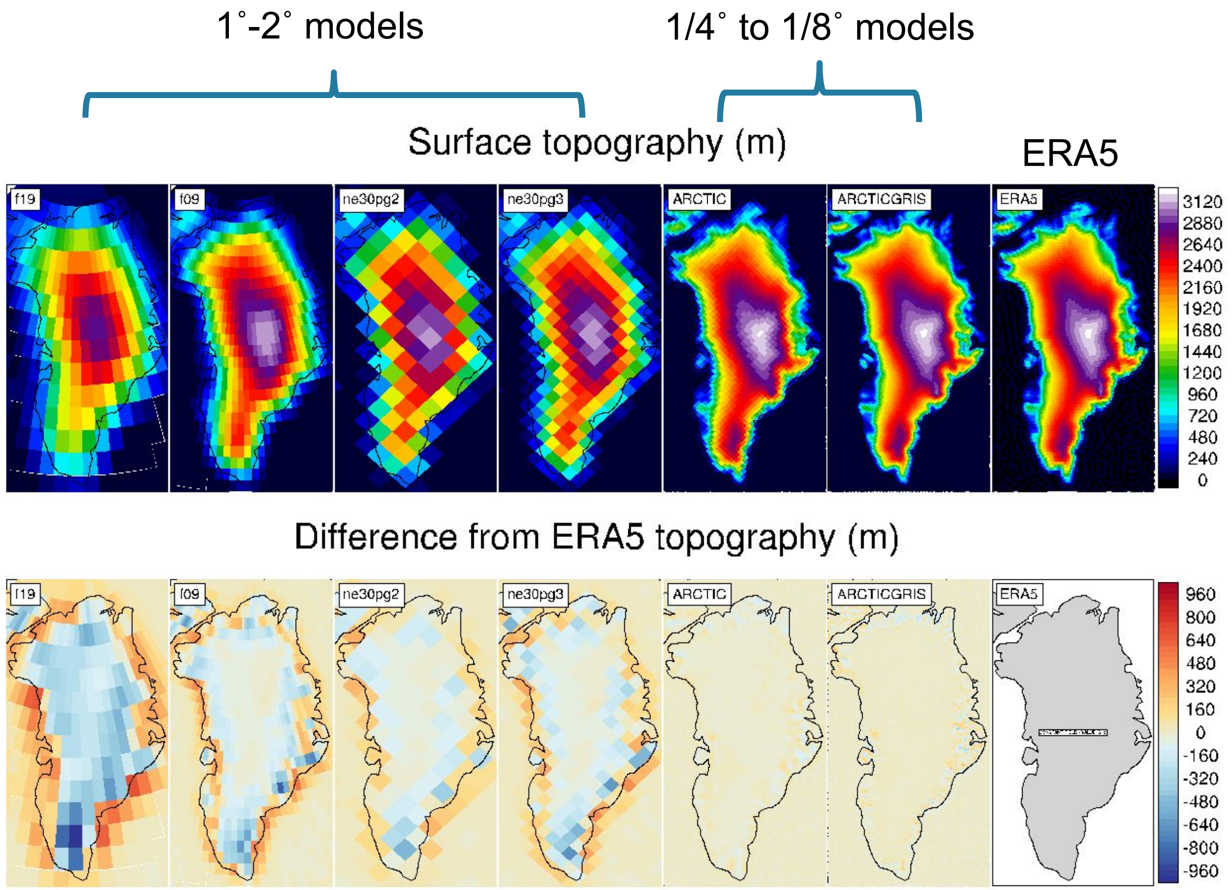

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Any Questions?

Extra Slides

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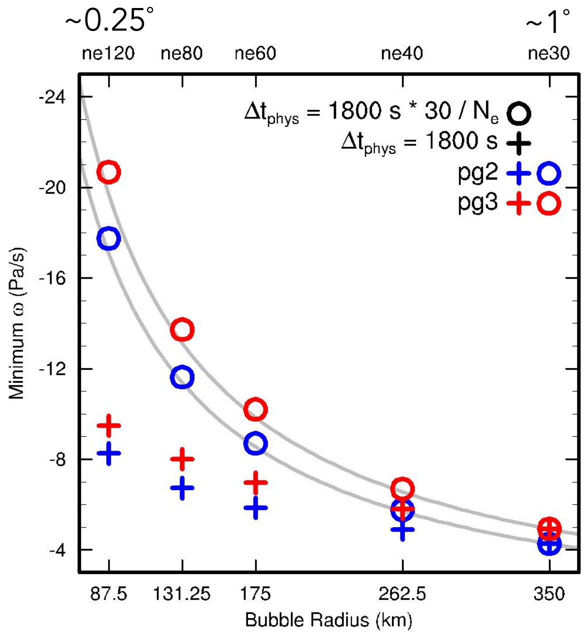


Herrington et al. (2019), JAMES

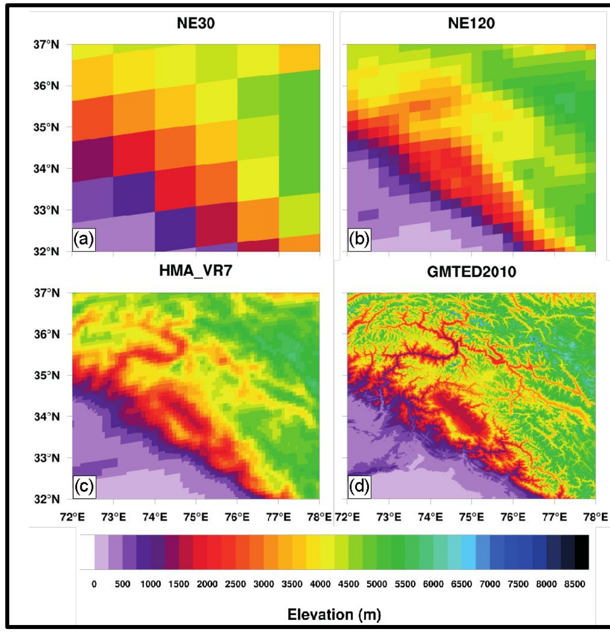


Figure courtesy of R. Wijngaard

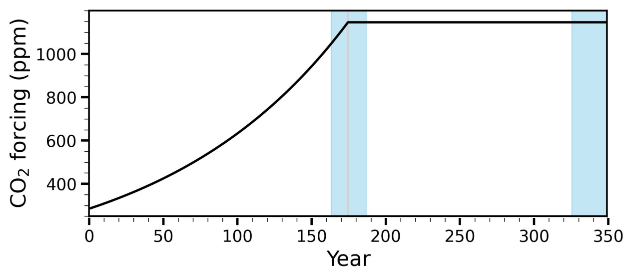
ARCTIC ¼° VR grid: Idealized Warming Experiment

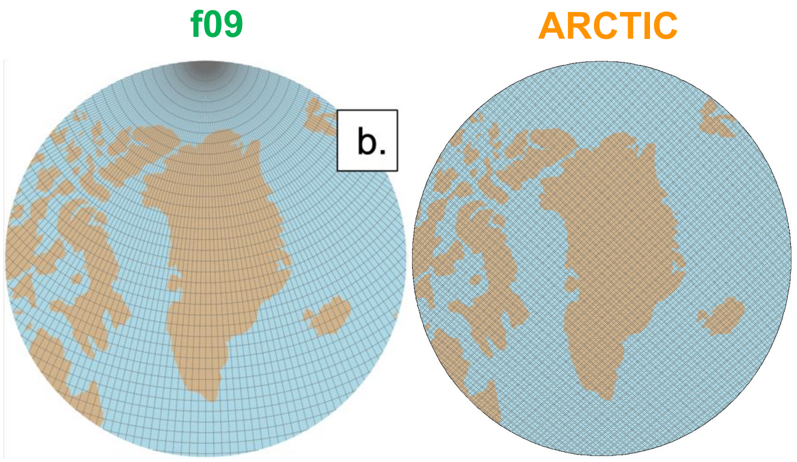
Here, we couple the ARCTIC grid to POP2/CISM2, re-tune the model and test:

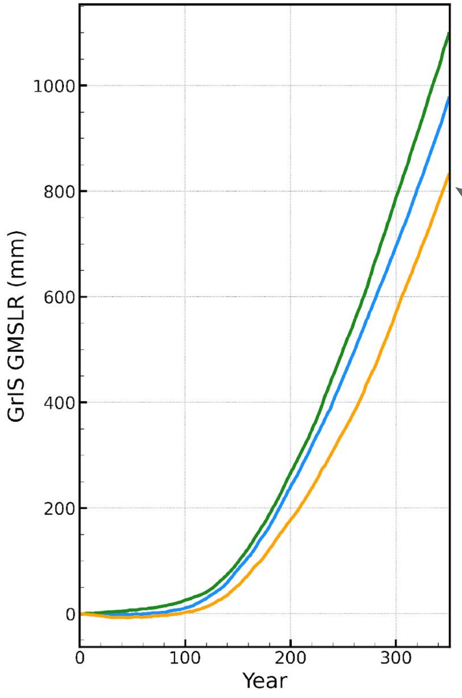
Is the GrIS *response* different between 1° (f09) and 1/4° (ARCTIC)?

- f09 – CESM2.1-CMIP6*
- f09 – CESM2.1-no hacks**
- ARCTIC – CESM2.2

1%CO2/yr; hold fixed at 4XCO2

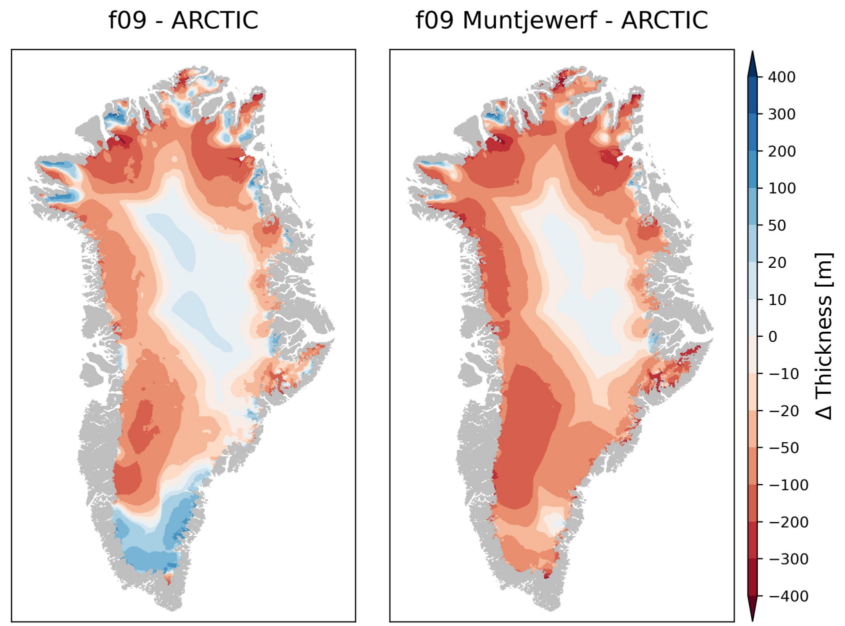






GrIS sea level contribution in the experiments

ARCTIC exhibits a smaller increase in melting, which primarily explains its lower mass loss and sea level rise.



Errors (i.e., 1° minus ¼°) in ice thickness change after 350 years. The 1° model melts too much at the ice margins, and this thickness change propagates into the interior via changes in ice flow.

* Muntjewerf et al. 2020

** removes the hacks in CMIP6 runs that reduce GrIS precip biases in f09