Variable-Resolution CESM (VR-CESM)

Annual CESM Tutorial, 2025

Adam R. Herrington

Project Scientist II

Climate and Global Dynamics Laboratory, National Center for Atmospheric Research

NCAR

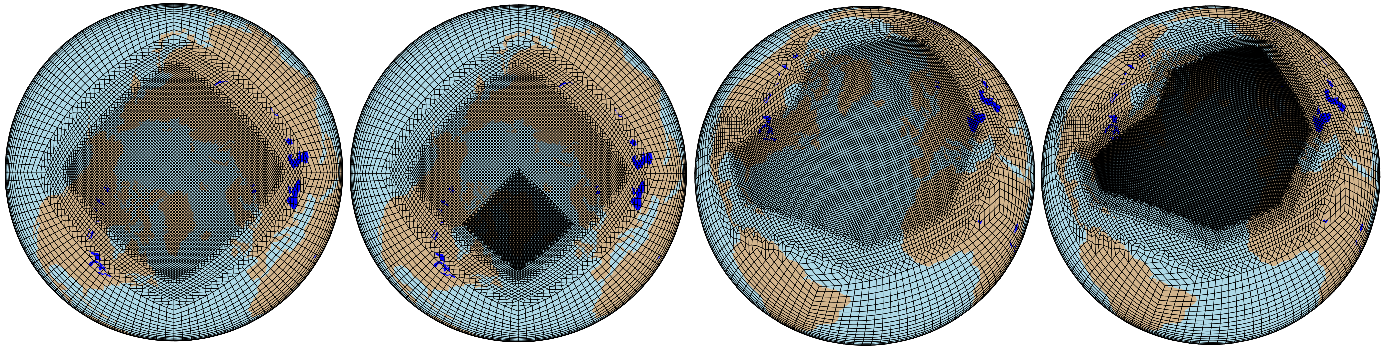
NSF

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Part 1: What is VR-CESM? Why use it? How to use it.

What is VR-CESM?

Variable-resolution is CESM's label for static mesh refinement in CAM (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

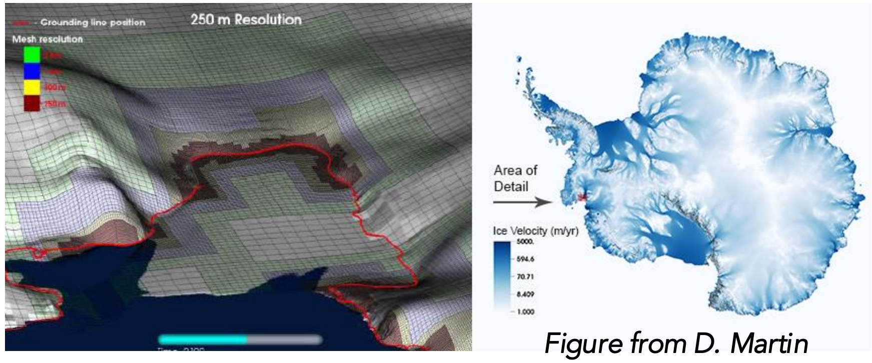


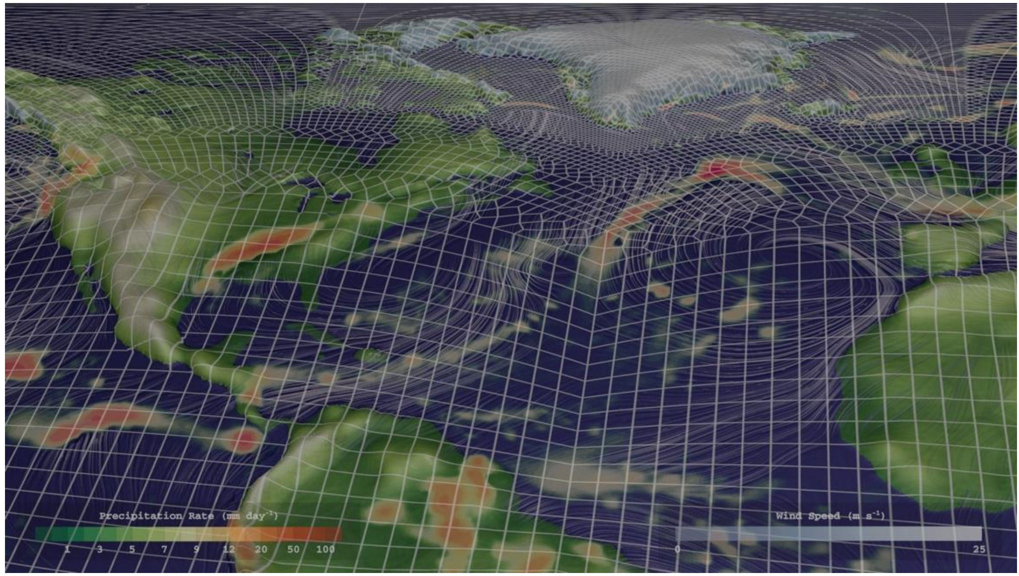
Figure from D. Martin

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://www.youtube.com/watch?v=zFEABDQILRs

Why VR-CESM?

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



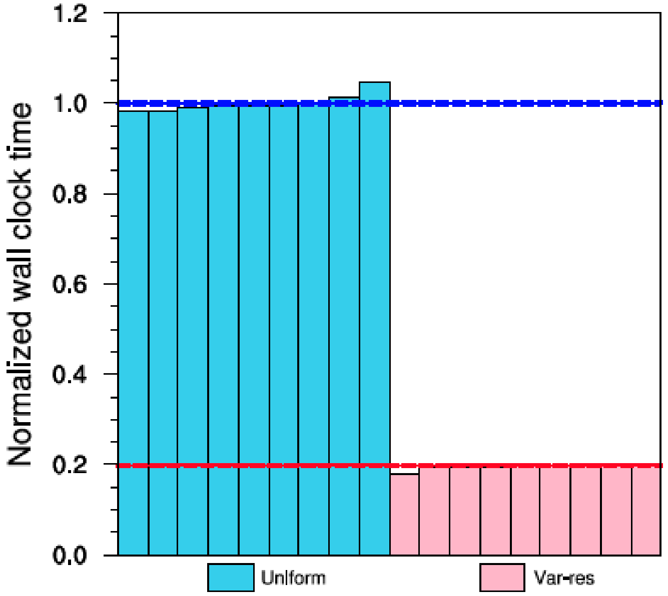
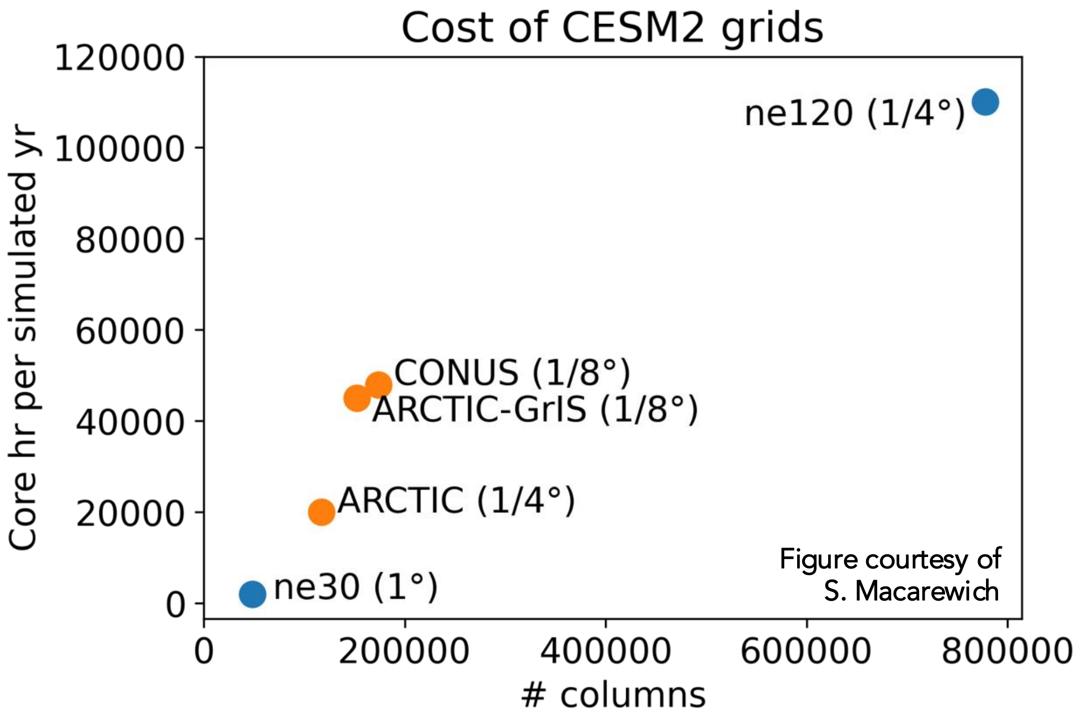
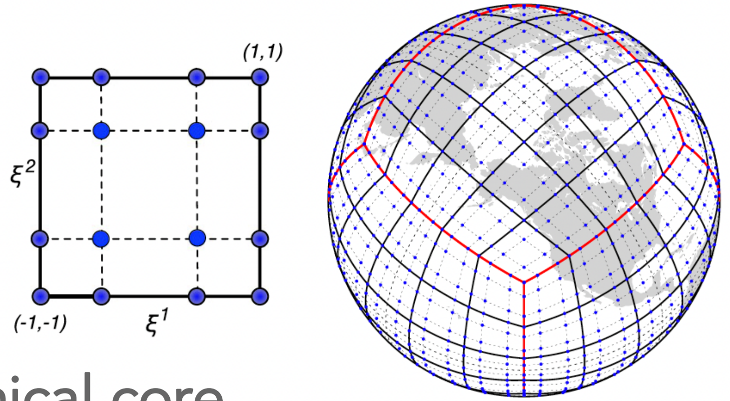


FIG. 10. Normalized wall clock time for idealized tropical cyclone simulations in the globally uniform mesh (light blue) and the variable-resolution grid (pink). The dashed lines indicate the theoretical scaling assuming model run time scales linearly with number of mesh elements.

Zarzycki et al. 2014

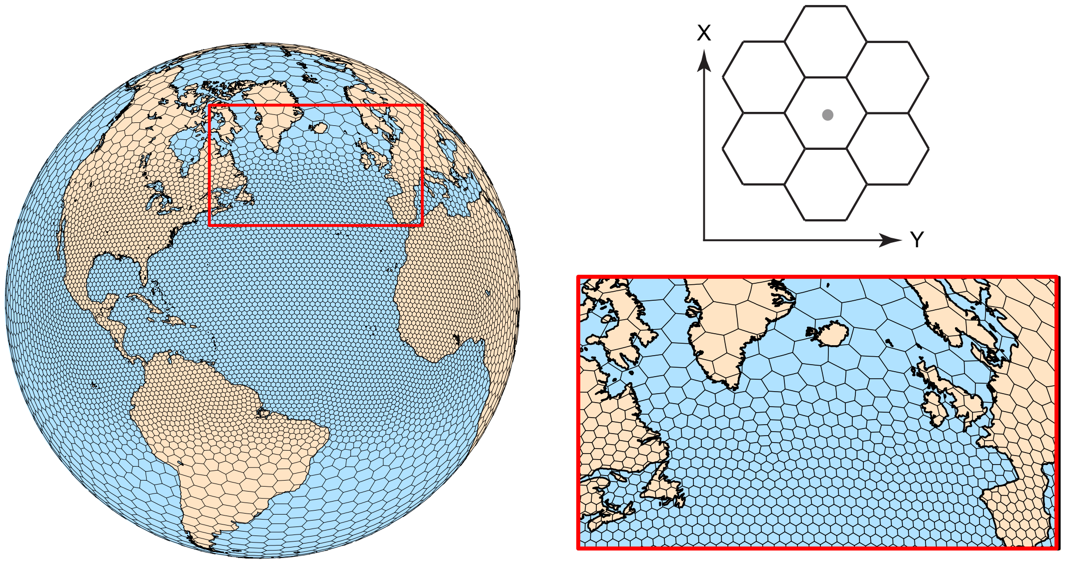


CAM support for VR-CESM



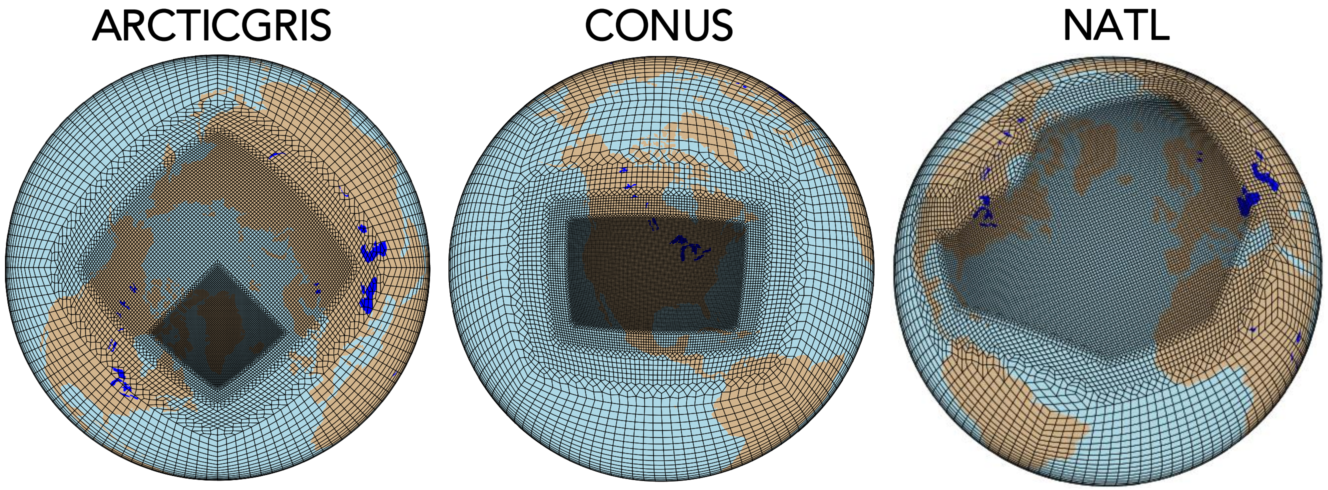
MPAS-A dynamical core

- Developed at MMM (c. 2013)
- Recently ported to CESM2.3
- Spherical Centroidal Voronoi Tesselation
- Fully-compressible non-hydrostatic



Spectral-element dynamical core

- Jointly developed by NCAR & DOE (HOMME)
- Hydrostatic (CESM2.0) non-hydrostatic (CESM3.1)
- Cubed-sphere mesh
- 5 VR grids run out-of-the-box in CESM3.0



see cam6.4 users guide for instructions on running:
https://ncar.github.io/CAM/doc/build/html/users_guide/atmospheric-configurations.html#cam-developmental-compsets

What needs to be changed when running VR-CESM?

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 & accuracy
   - Physics time-step for accuracy
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)
   - Emissions datasets for resolving point sources concentrated over urban centers

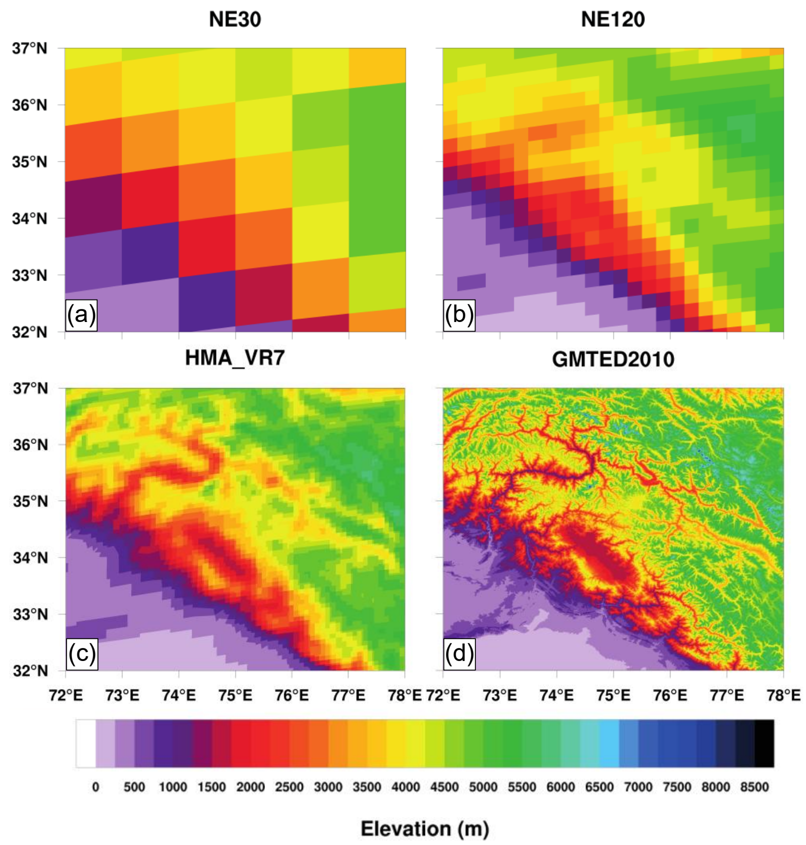
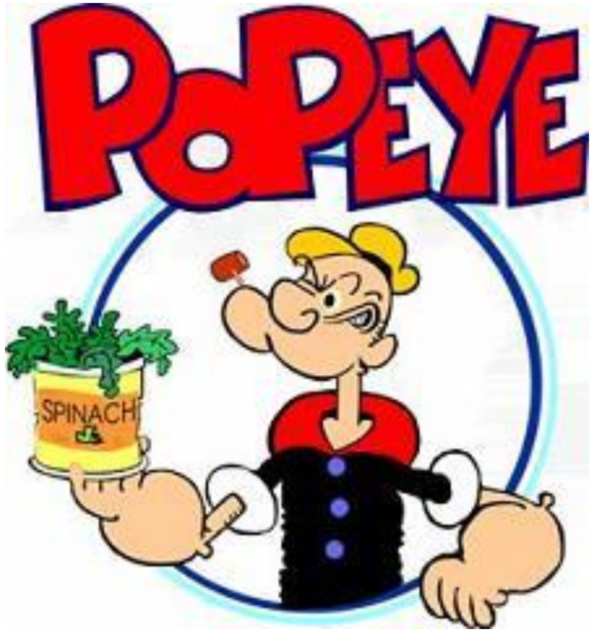


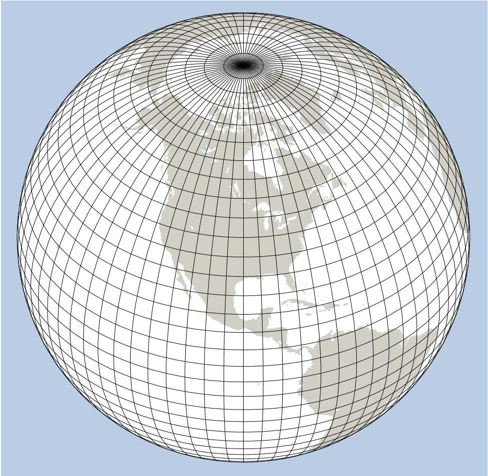
Figure courtesy of R. Wijngaard

You can run VR-CESM too! But you need to know how to regrid model output to analyze your simulations



Part 2: Regridding

Structured vs. Unstructured grids

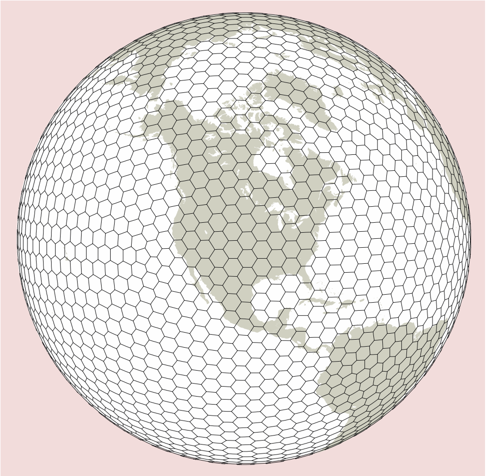


PS (time,lat,lon)

- 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 do we regrid?

Method 1: Regrid entire netCDF history files

- ❑ Quick and dirty -- takes up unnecessary storage space.
- ❑ Performed using command line packages (NCO, CDO).
- ❑ Usually requires a "mapping weights file" as input. For NCO,

```
ncremap -m <path-to-wgtfile> in.nc out.nc
```

Method 2: Regrid arrays on the fly in analysis scripts

- ❑ The more practical and sustainable approach.
- ❑ Invoke libraries/functions in your preferred analysis language (Python, NCL, MATLAB)
    - ❑ Internal regrid routines that don't require a mapping weights file (less accurate).
    - ❑ Internal regrid routines that require a mapping weights file (more accurate). For Python,

```
load xESMF library
…
read_weights(filename, n_in, n_out)
apply_weights(weights, indata, shape_in, shape_out)
```

How to generate a mapping weights file?

1 Define destination grid

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

2 Locate source and destination grid file. On Derecho,

- ❑ SCRIP grid files: /glade/campaign/cesm/cesmdata/inputdata/**share/scripgrids/**
- ❑ ESMF mesh files: /glade/campaign/cesm/cesmdata/inputdata/**share/meshes/**

3 Generate mapping weights file using source and destination grid files

- ❑ Command line TempestRemap (https://github.com/ClimateGlobalChange/tempestremap)
- ❑ Command line ESMF. On Casper,

```
module load mpi-serial
module load esmf
...
ESMF_RegridWeightGen -s <src-gridfile> -d <dst-gridfile> -m <method> -w <wgts-filename>
```

Part 3: Applications

Response of N. Atlantic storms to SST anomalies

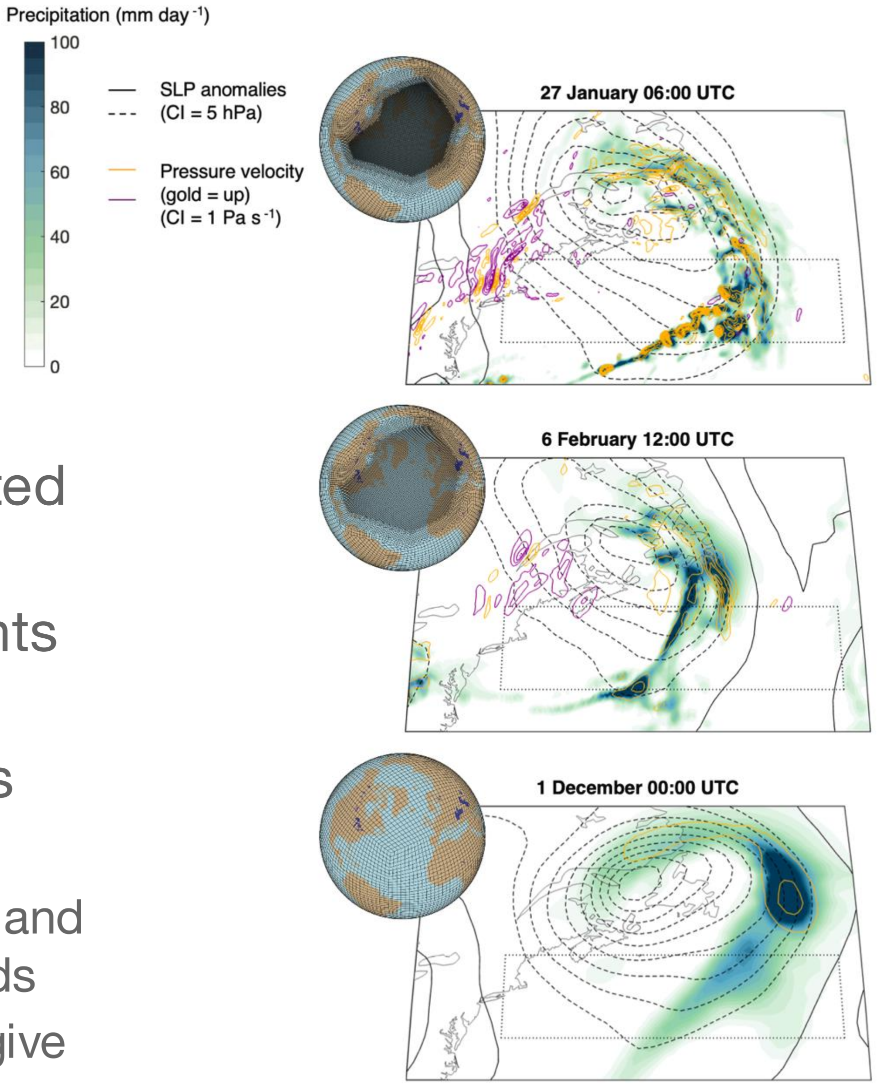
JAMES | Journal of Advances in Modeling Earth Systems®

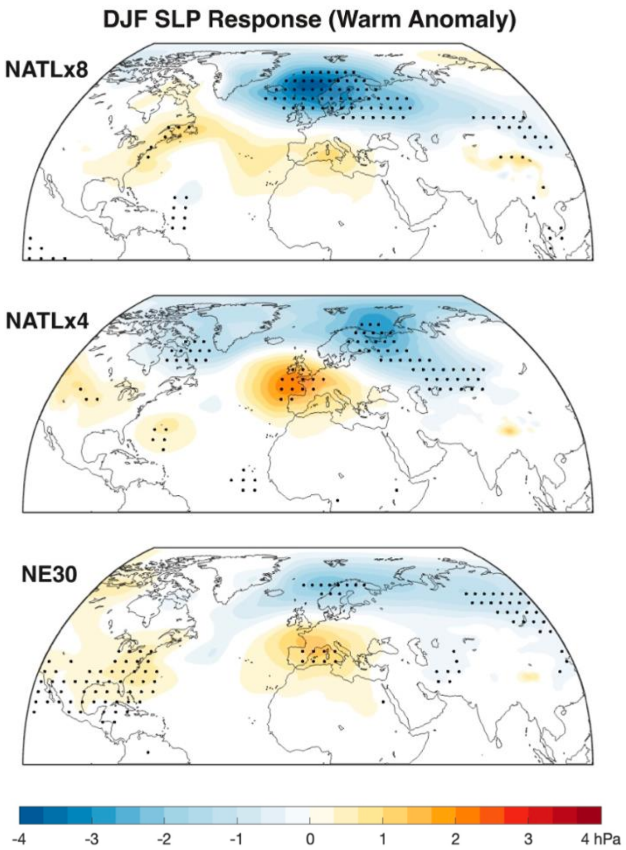
Research Article | Open Access

Resolving Weather Fronts Increases the Large-Scale Circulation Response to Gulf Stream SST Anomalies in Variable-Resolution CESM2 Simulations

Robert C. J. Wills, Adam R. Herrington, Isla R. Simpson, David S. Battisti

First published: 15 July 2024 | https://doi.org/10.1029/2023MS004123

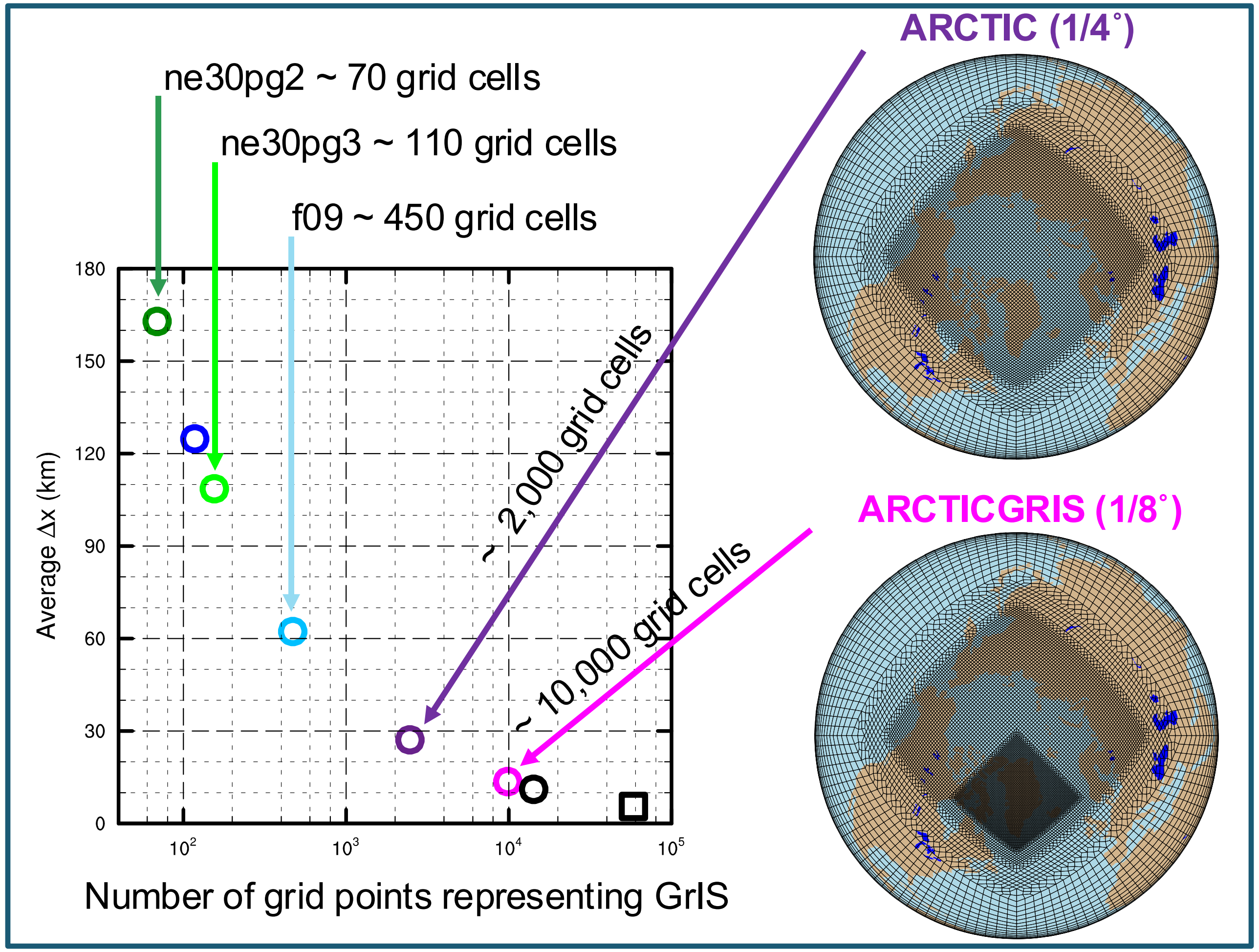


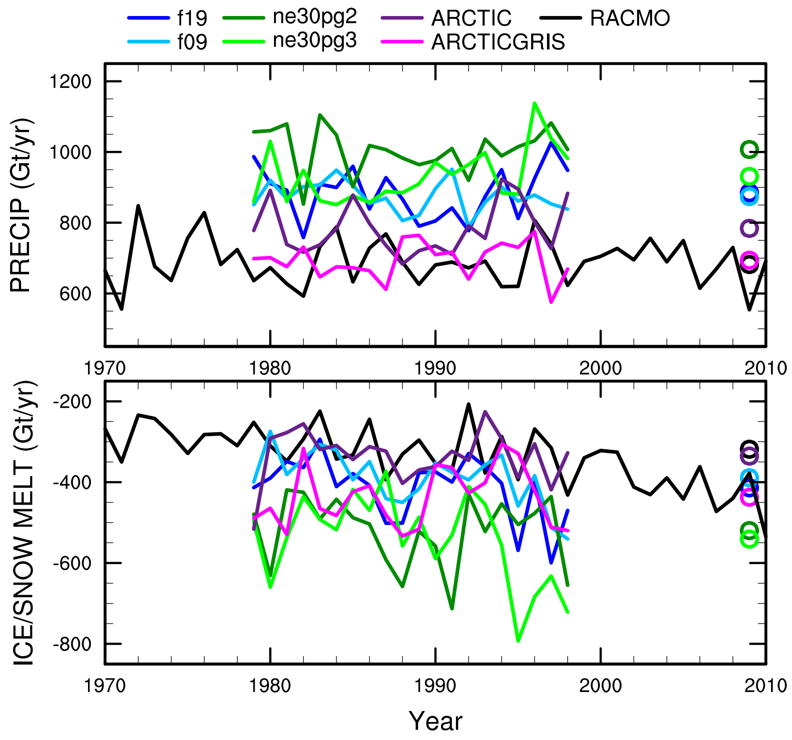


- 1° - synoptic fronts are represented as a single feature
- 1/4° - multiple convective elements form the cold front
- 1/8° - lots of convective elements form the cold and warm fronts
  - Deeper circulations transport heat and momentum upwards and polewards
  - Feeds back on the large-scale to give an NAO-like response

Greenland Surface Mass Balance: AMIP Experiments

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

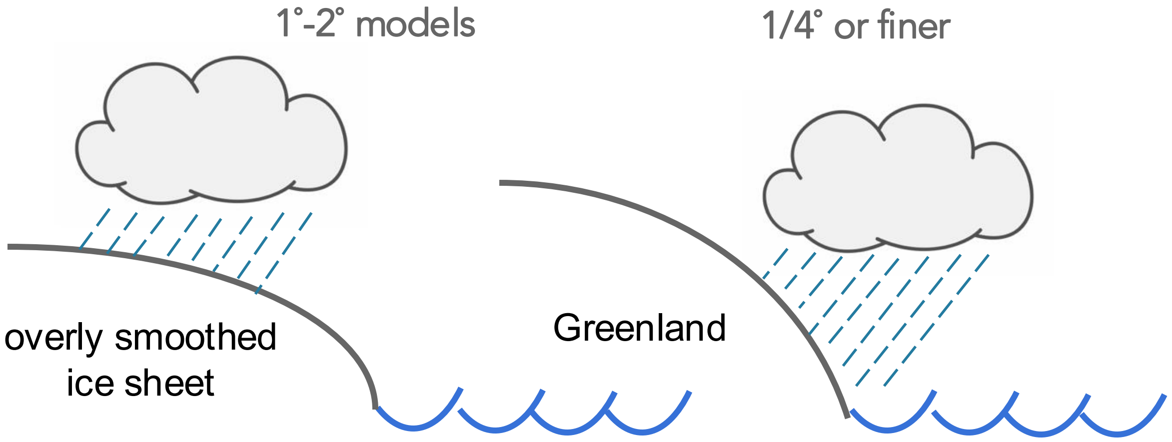




- GrIS Surface Mass Balance (SMB) is the integrated precipitation minus runoff+evap+subl
- Precipitation and melting processes are ~continuously improved from 2° and 1/8° and you can do a pretty good job with 1/4°

Model Topography and Flat Ice Sheets

- Model topography is smoothed –smooth out grid scale features so we don't generate 2dx modes (dx=grid spacing)
- Results in a flat ice sheet in 1-2° models, with storms penetrating far too deep into the ice sheet interior (Pollard 2000, CD)



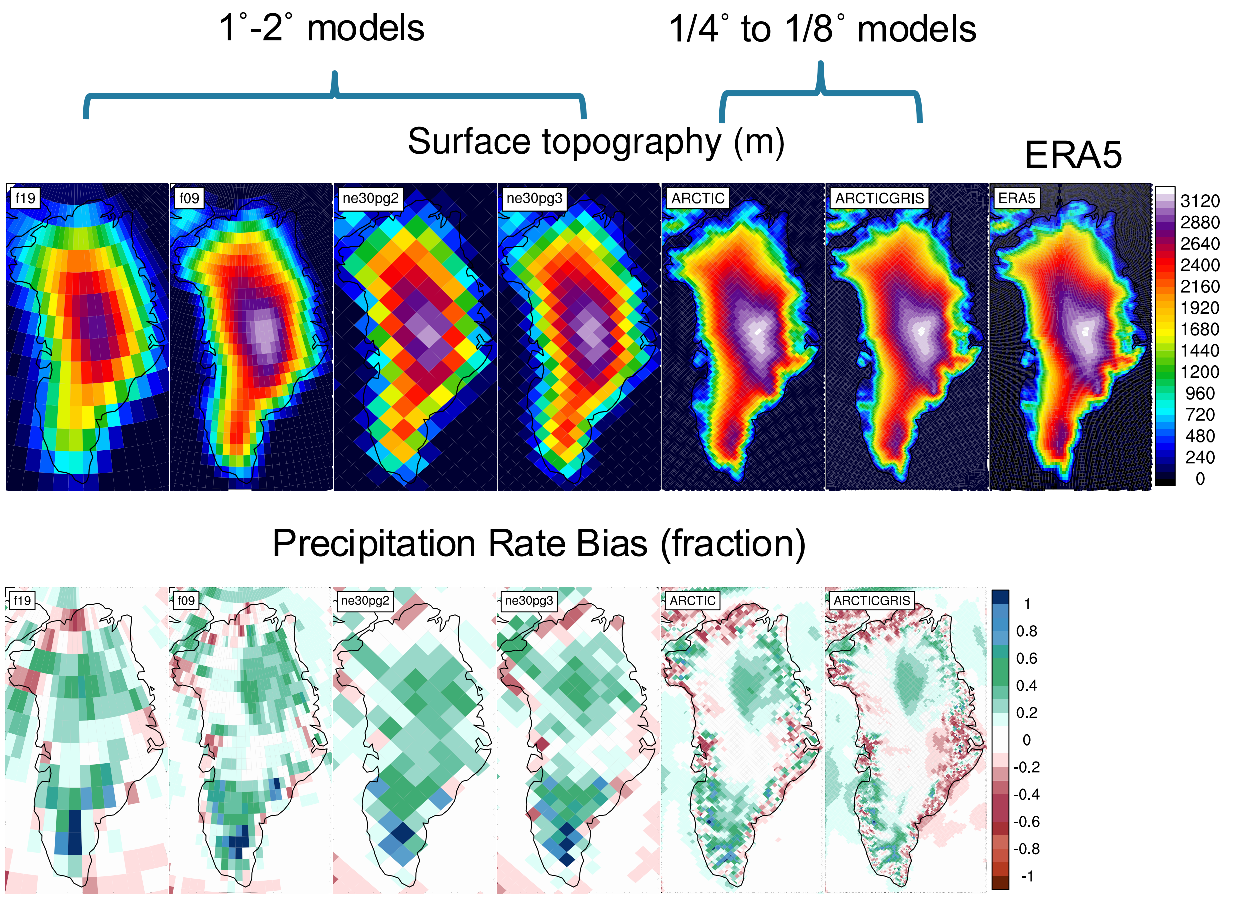


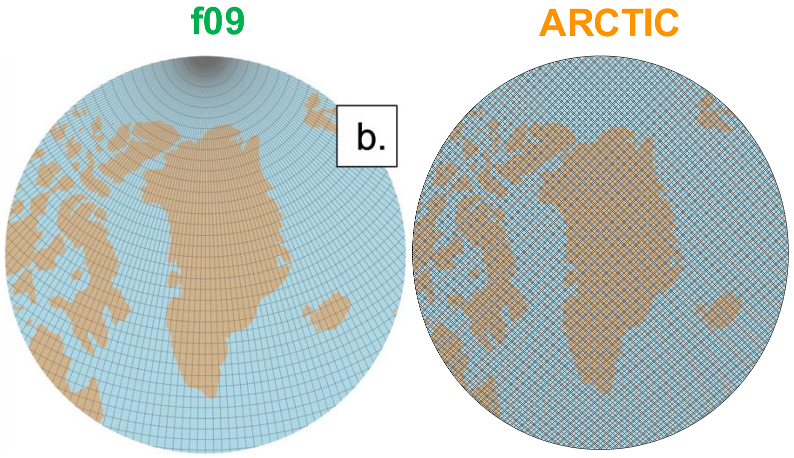
Figure from Waling et al. 2024. The topography generation software (https://github.com/NCAR/Topo) is described in Lauritzen et al. 2015, GMD.

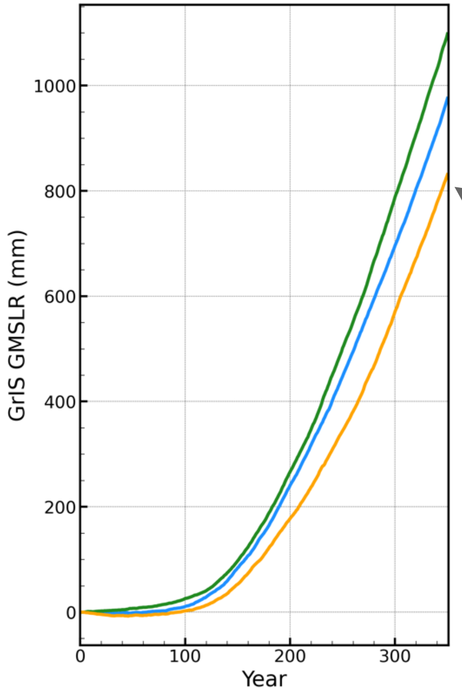
ARCTIC ¼° VR grid: Idealized Warming Experiment

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)?

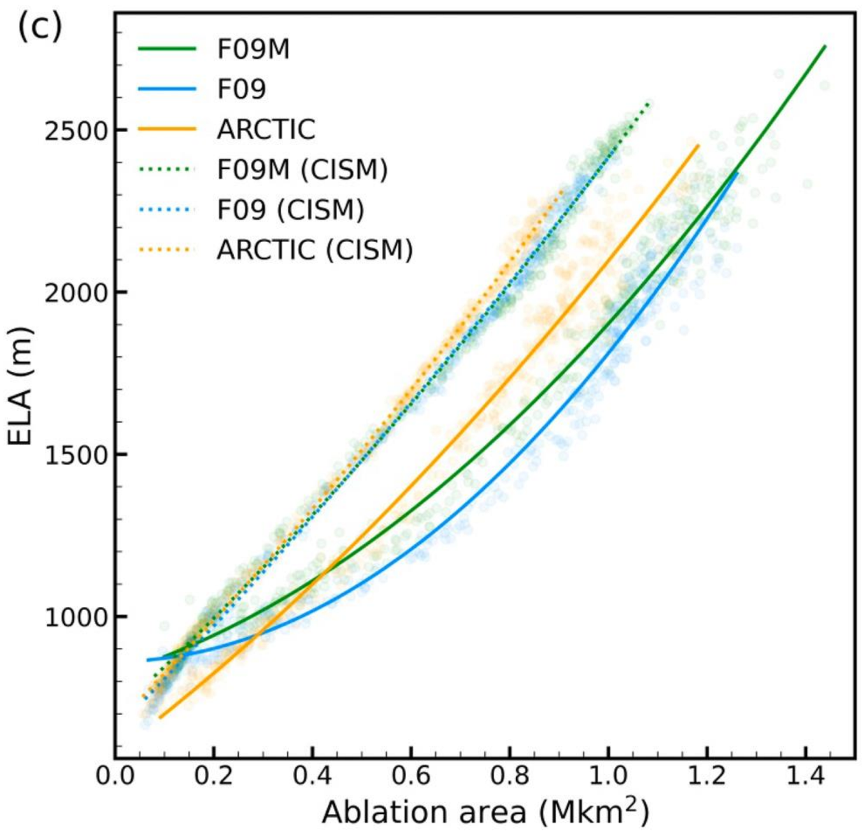
- f09 – CESM2.1-CMIP6*
- f09 – CESM2.1-no hacks
- ARCTIC – CESM2.2





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.

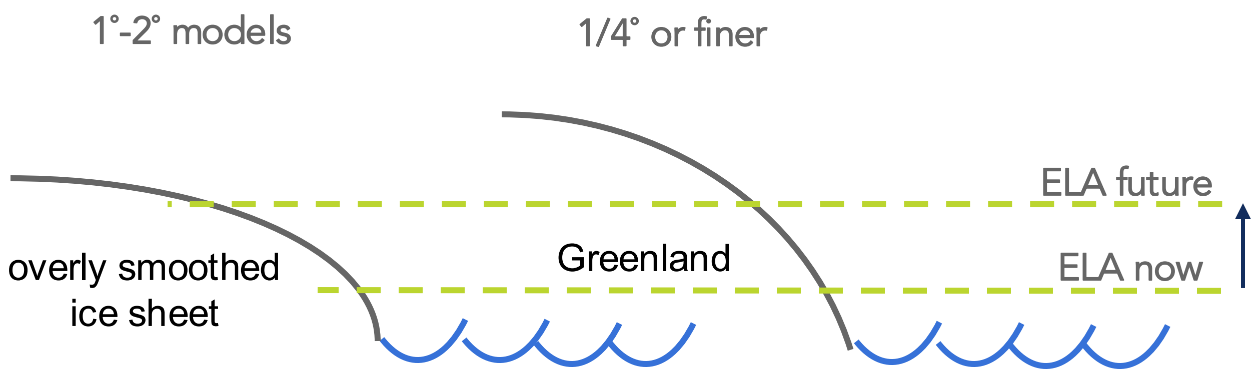


ARCTIC ablation area increases less when the ELA rises. This is because the margins of the ice sheet are steeper, and more realistic at ¼°.

ELA = Equilibrium Line Altitude

Yin et al., 2024
*Muntjewerf et al. 2020

Coarser models overestimate ablation zone expansion



Any Questions?