Impact of grids and dynamical cores in CESM2.2 on the meteorology and climate of the Arctic

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Abstract
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Plain Language Summary

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1 Introduction

General Circulation Models (GCMs) are powerful tools for understanding the meteorology and climate of the high-latitudes, which are among the most sensitive regions on Earth to global and environmental change. Despite their importance, the numerical treatment of polar regions is handled in vastly-different ways due to the so-called *pole-problem* (?, ?). The pole-problem refers to instability arising from the convergence of meridians at the polar points on latitude-longitude grids (e.g., Figure 1a). Depending on the numerical design, methods exist to stabilize the pole problem, and latitude-longitude grids may be advantageous for polar processes as structures can be represented with more degrees of freedom than elsewhere in the computational domain. With the recent trend towards globally uniform unstructured grids, any potential benefits of latitude-longitude grids on polar regions may become a relic of the past. In this study, a spectrum of grids and dynamical cores (hereafter referred to as *dycores*) available in the Community Earth System Model, version 2.2 (CESM; `http://www.cesm.ucar.edu/models/cesm2/`), from conventional latitude-longitude grids to unstructured grids with globally uniform grid spacing to unstructured grids with regional refinement over the Arctic, are evaluated to understand the impacts of grids and dycores on the simulated characteristics of the Arctic, with a special focus on the Greenland Ice Sheet.

In the 1970's the pole problem was largely defeated through wide-spread adoption of efficient spectral transform methods in GCMs. These methods transform grid point fields into a global, isotropic representation in wave space, where linear operators in the equation set can be solved for exactly. While spectral transform methods were still commonly used into the 21st century, more recently, local numerical methods have become more desirable for their ability to run efficiently on massively parallel systems. The pole-problem has thus re-emerged in contemporary climate models using latitude-longitude grids, and some combination of reduced grids and polar filters are necessary to ameliorate this instability (?, ?). Polar filters are akin to a band-aid; they subdue the growth of unstable modes by introducing additional damping to the solution over polar regions. One might expect that this additional damping reduces the effective resolution such that the resolved scales are similar across the entire domain, but this is unlikely to occur in practice.

An alternative approach is to use unstructured grids. Unstructured grids allow for more flexible grid structures than latitude-longitude grids, permitting quasi-uniform grid spacing globally that eliminates the pole-problem entirely (e.g., Figure 1c). This grid flexibility also allows for variable-resolution or regional grid refinement. Grids can be developed with refinement over polar regions that could in principle make up for any loss in polar resolution in transitioning away from latitude-longitude grids (e.g., Figure 2), although this comes at the cost of a smaller CFL-limiting time-step in the refined region. But unstructured grids scale more efficiently on parallel systems than latitude-longitude grids, resulting in latitude-longitude grids becoming less common, and unstructured grids more common as computing power continued to increase over time.

The meteorology and climate of the Arctic is characterized by a range of processes and scales that are difficult to represent in GCMs (?, ?, ?, ?). Synoptic scale storms are well represented at typical GCM resolutions, but mesoscale Polar Lows are not. These

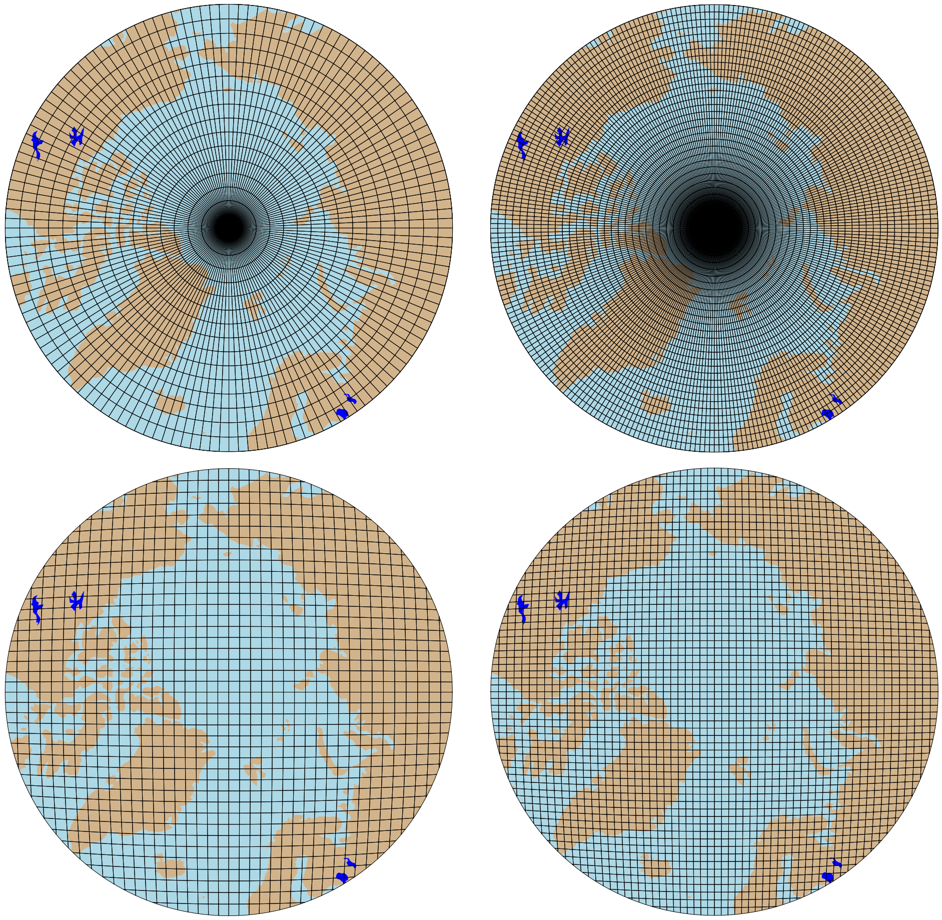

Figure 1. .

mesoscale systems are prevalent during the cold season, and produce gale-force winds that can induce large fluxes through the underlying sea-ice/ocean interface. The Arctic also contains the Greenland Ice Sheet (hereafter denoted as *GrIS*). While it sits on the largest island in the world (Greenland), GrIS is only marginally resolved at typical GCM resolutions. GrIS ablation zones exert a primary control on the mass balance of the ice sheet, but are on the order of 100km wide, and models struggle to resolve these narrow features. GrIS topography descends rapidly towards the coast, and these steep margins facilitate orographic precipitation events that contribute mass to the ice sheet, but which are not well resolved in GCMs. The Arctic is therefore well-suited to understand the impact of different grids and dycores on processes that are marginally resolved at conventional GCM resolutions.

The goal of this study is to characterize the representation of polar regions using the SE and FV dycores, as these models treat the high-latitudes, e.g., the pole-problem, in very different ways. The study is laid out as follows. Section 2 consists of documentation of the grids, dycores and physical parameterizations used in this study. The Arctic refined grids were developed by the author, and this section serves as their official documentation. Section 2 also contains a description of the experiments along with the observational datasets and post-processing software used for validating the models. Section 3 contains the results of the experiments and Section 4 provides some discussion and conclusions.

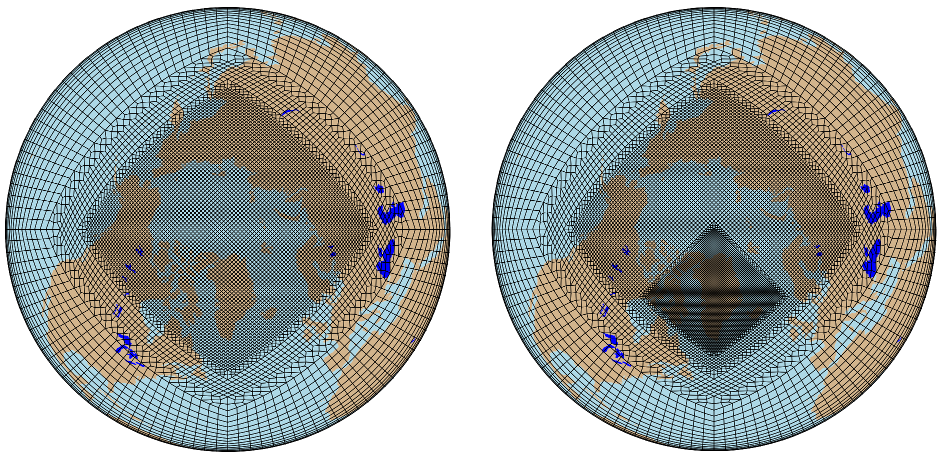

Figure 2. .

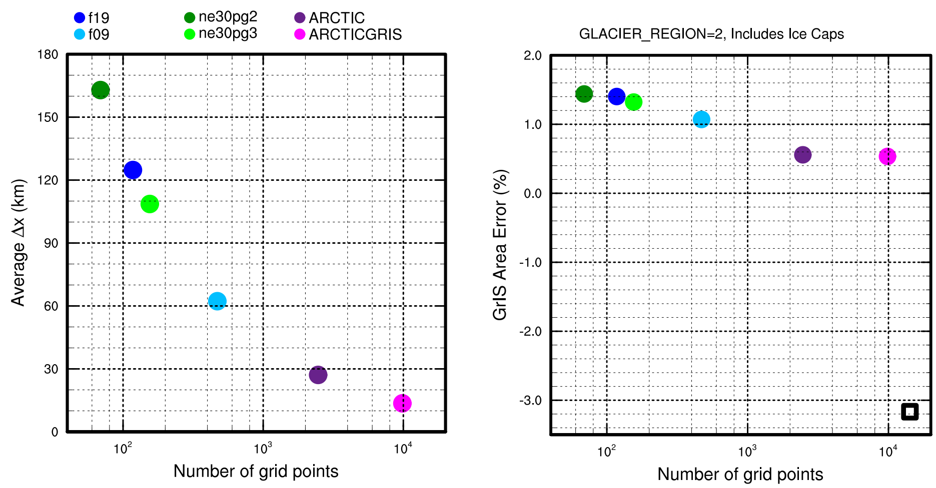

Figure 3. .

2 Methods

2.1 Grids

2.2 Dynamical cores

The atmospheric component of CESM2.2, the Community Atmosphere Model, version 6.3 (CAM; `https://github.com/ESCOMP/CAM/wiki`), supports a diverse number of atmospheric dynamical cores. These range from dycores using latitude-longitude grids, the finite-volume (FV; ?, ?) and eulerian spectral transform (EUL; ?, ?) models, and dycores built on unstructured grids, the spectral-element (SE; ?, ?) and finite-volume 3 (FV3; ?, ?) models. The EUL dycore is the oldest dycore in CAM, and is the least supported of all the dycores in the current model. FV3 is the newest dycore in CESM, but it was not fully incorporated into CAM at the time this work commenced, and so is omitted from this study. The authors instead focus on the two most well supported dycores in CESM, SE and FV. The goal of this study is to characterize the representation of polar regions using the SE and FV dycores, as these models treat the high-latitudes, e.g., the pole-problem, in very different ways.

2.2.1 Finite-volume model

The FV dycore is assessed using grids with Δx of 1° and 2° grid spacing (Δx refers to the average equatorial grid spacing). These are compared to the equivalent 1° SE grid, referred to as ne30pg3. This grid does not refer to the SE dycore proper, but a variant in which the dry dynamics are solved using the SE method, and tracer advection computed using the conservative semi-Lagrangian advection method (SE-CSLAM; ?, ?). In SE-CSLAM the physical parameterizations are computed on the finite-volume tracer advection grid. Optionally, one can compute the physics on a finite-volume grid that is $\frac{3}{2}\times$ Δx of the tracer-advection grid (?, ?). A comparison of the lower-resolution physics grid version of ne30pg3, referred to as ne30pg2, over the Arctic is included in this study. All variants of the SE dycore discussed herein are available as part of the CESM2.2 release.

2.2.2 Spectral-element model

The SE dycore (not SE-CSLAM) supports regional grid refinement via its variable resolution configuration. Two variable resolution meshes were developed as part of the CESM2.2 release that contains grid refinement over the Arctic. The ARCTIC grid is a $\Delta x = 1°$ grid with $\Delta x = \frac{1}{4}°$ regional refinement over the broader Arctic region. The ARCTICGRIS grid is similar to the ARCTIC grid, but additionally contains a patch covering the big island of Greenland with $\Delta x = \frac{1}{8}°$ resolution. These Arctic refined grids are depicted in Figure 2. The surface mass balance of the GrIS is compared across all grids and dycores in this study, and the ARCTCGRIS grid is certainly at an advantage due to its higher resolution over the ice sheet.

2.3 Physical parameterizations

2.4 Experimental desing

2.5 Observational datasets

2.5.1 ERA5

2.5.2 LIVVkit 2.1

2.6 TempestExtremes

2.7 StormCompositer

3 Results

3.1 Tropospheric temperatures

3.2 Inter-annual variability

3.3 Synoptic-scale storm characteristics

3.4 Orographic gravity waves emanating from Greenland

3.5 Katabatic winds emanating from Greenland

3.6 Greenland surface mass balance

4 Conclusions

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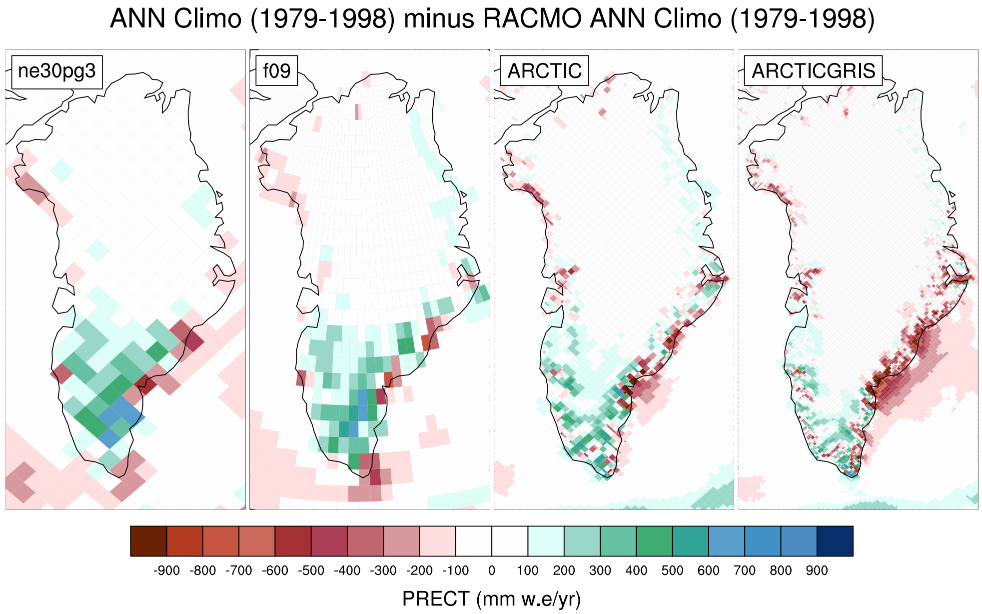
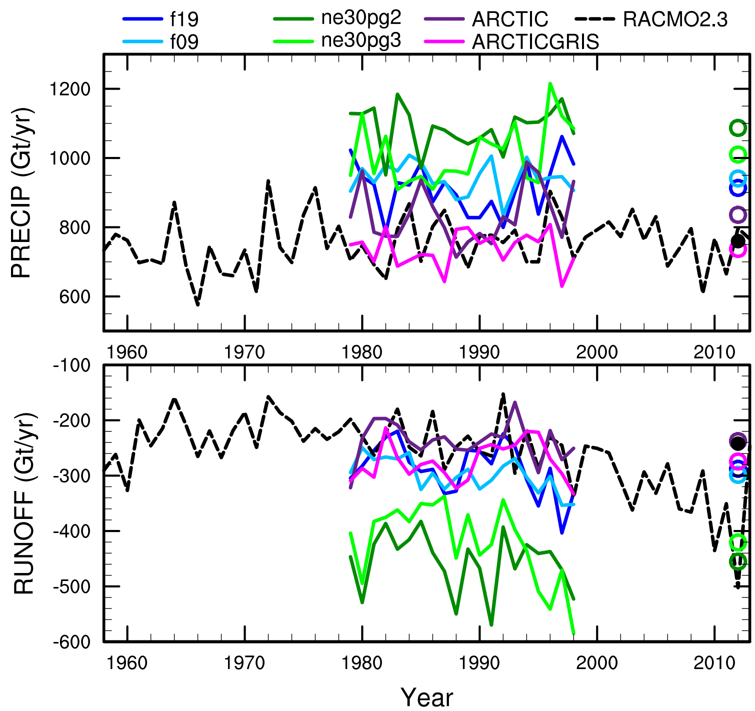


Figure 4. .

computer (doi:10.5065/D6RX99HX), were provided by the Computational and Information Systems Laboratory (CISL) at NCAR.

The data presented in this manuscript is available at `https://github.com/adamrher/2020-arcticgrids`.



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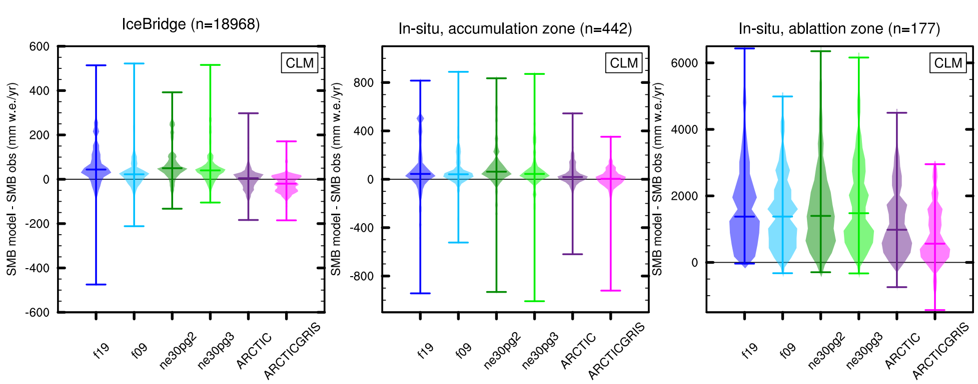

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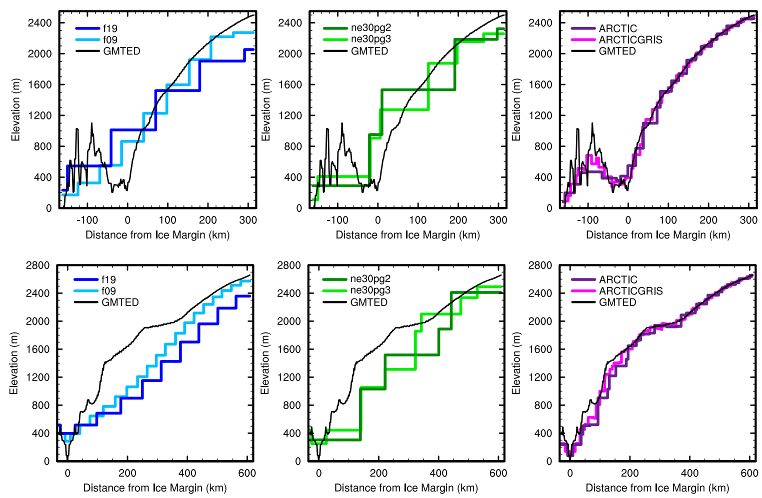

Figure 7. .

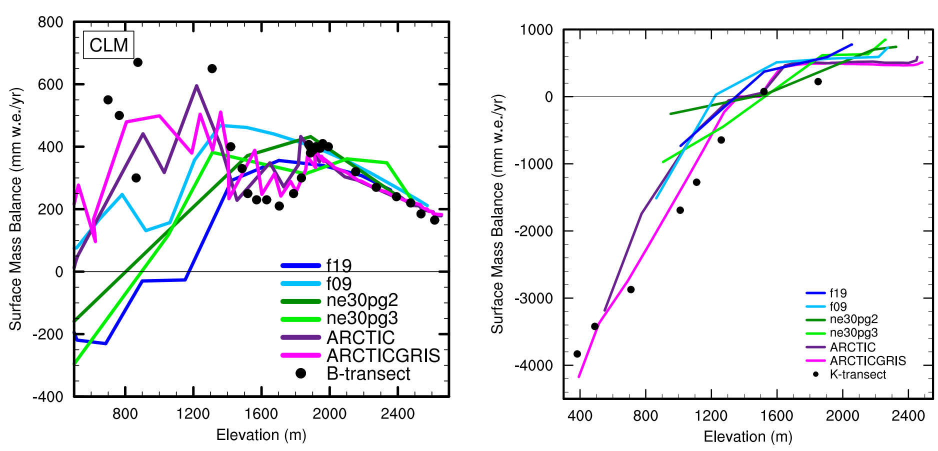

Figure 8. .