

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

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7 **Key Points:**

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Abstract

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Plain Language Summary

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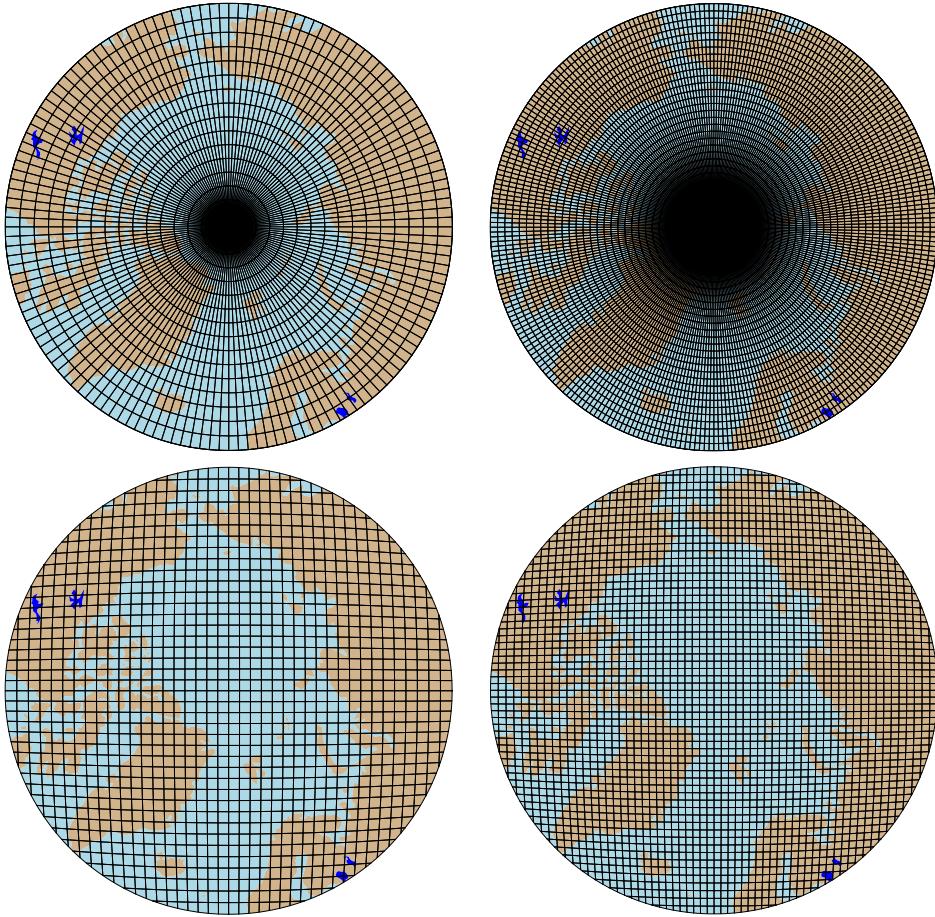
1 Introduction

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* (Williamson, 2007). 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 their impacts 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 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 (Jablonowski & Williamson, 2011). Polar filters are akin to a band-aid; they subdue the growth of unstable modes by applying 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 seems an unlikely outcome in practice.

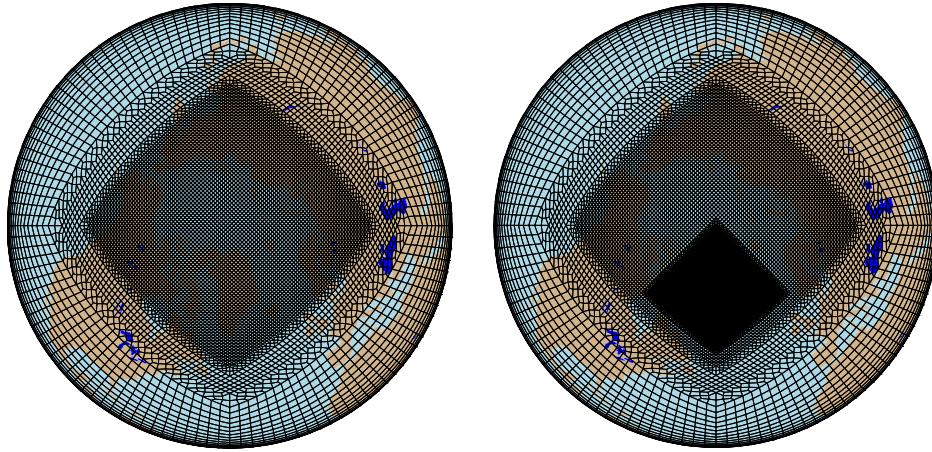
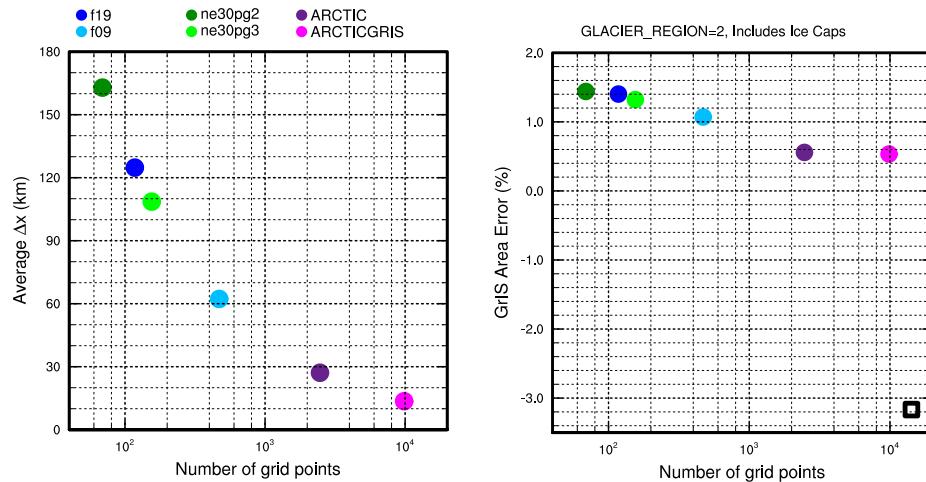
An alternative approach is to use unstructured grids. Unstructured grids allow for more flexible grid structures, permitting quasi-uniform grid spacing globally that eliminates the pole-problem entirely (e.g., Figure 1c). This grid flexibility also allows for variable-resolution or regional grid refinement. 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 (Bromwich et al., 2001; Smirnova & Golubkin, 2017; van Kampenhout et al., 2018). Synoptic scale storms are well represented

**Figure 1.** .

at typical GCM resolutions, but mesoscale Polar Lows are not. These 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 blankets 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* elevations descend rapidly toward the coasts, resulting in steep margins that facilitate orographic precipitation events, 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 high-latitude regions using the spectral-element and finite-volume dycores in CESM2.2, as these models treat the high-latitudes, e.g., the pole-problem, in very different ways. The manuscript 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.**

79 2 Methods

80 2.1 Grids

81 2.2 Dynamical cores

82 The atmospheric component of CESM2.2, the Community Atmosphere Model, ver-
 83 sion 6.3 (CAM; <https://github.com/ESCOMP/CAM/wiki>), supports a diverse number
 84 of atmospheric dynamical cores. These range from dycores using latitude-longitude grids,
 85 the finite-volume (FV; Lin, 2004) and eulerian spectral transform (EUL; Collins et al.,
 86 2006) models, and dycores built on unstructured grids, the spectral-element (SE; Lau-
 87 ritzen et al., 2018) and finite-volume 3 (FV3; Putman & Lin, 2007) models. The EUL
 88 dycore is the oldest dycore in CAM, and is the least supported of all the dycores in the
 89 current model. FV3 is the newest dycore in CESM, but it was not fully incorporated into
 90 CAM at the time this work commenced, and so is omitted from this study. The authors
 91 instead focus on the two most well supported dycores in CESM, SE and FV. The goal
 92 of this study is to characterize the representation of polar regions using the SE and FV

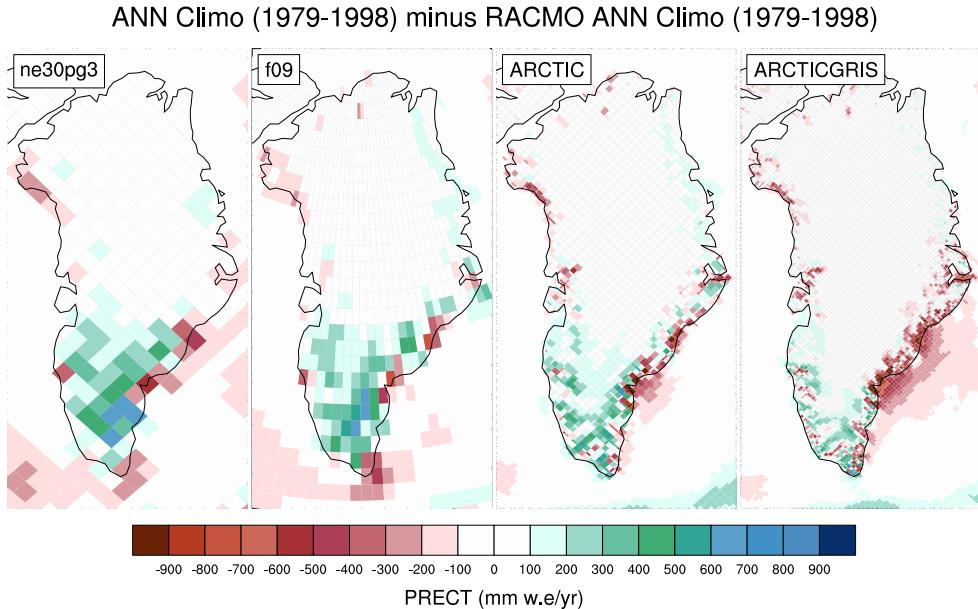
93 dycores, as these models treat the high-latitudes, e.g., the pole-problem, in very differ-
94 ent ways.

95 2.2.1 *Finite-volume model*

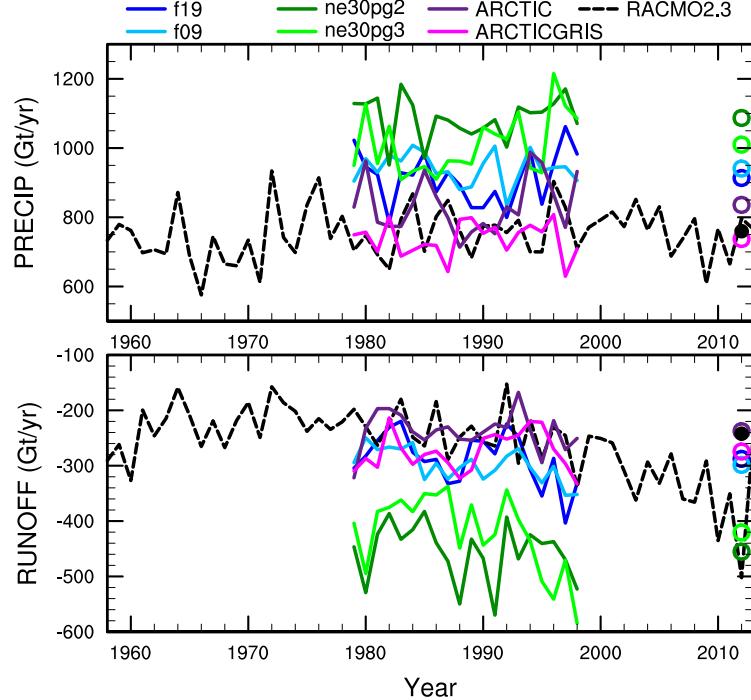
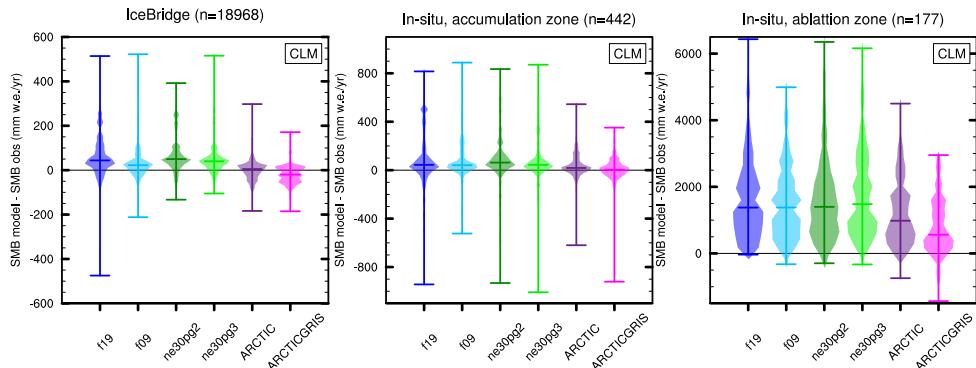
96 The FV dycore is assessed using grids with Δx of 1° and 2° grid spacing (Δx refers
97 to the average equatorial grid spacing). These are compared to the equivalent 1° SE grid,
98 referred to as ne30pg3. This grid does not refer to the SE dycore proper, but a variant
99 in which the dry dynamics are solved using the SE method, and tracer advection com-
100 puted using the conservative semi-Lagrangian advection method (SE-CSLAM; Lauritzen
101 et al., 2017). In SE-CSLAM the physical parameterizations are computed on the finite-
102 volume tracer advection grid. Optionally, one can compute the physics on a finite-volume
103 grid that is $\frac{3}{2} \times \Delta x$ of the tracer-advection grid (Herrington et al., 2019). A compari-
104 son of the lower-resolution physics grid version of ne30pg3, referred to as ne30pg2, over
105 the Arctic is included in this study. All variants of the SE dycore discussed herein are
106 available as part of the CESM2.2 release.

107 2.2.2 *Spectral-element model*

108 The SE dycore (not SE-CSLAM) supports regional grid refinement via its variable
109 resolution configuration. Two variable resolution meshes were developed as part of the
110 CESM2.2 release that contains grid refinement over the Arctic. The ARCTIC grid is a
111 $\Delta x = 1^\circ$ grid with $\Delta x = \frac{1}{4}^\circ$ regional refinement over the broader Arctic region. The
112 ARCTICGRIS grid is similar to the ARCTIC grid, but additionally contains a patch cov-
113 ering the big island of Greenland with $\Delta x = \frac{1}{8}^\circ$ resolution. These Arctic refined grids
114 are depicted in Figure 2. The surface mass balance of the GrIS is compared across all
115 grids and dycores in this study, and the ARCTCGRIS grid is certainly at an advantage
due to its higher resolution over the ice sheet.

**Figure 4.**117 **2.3 Physical parameterizations**118 **2.4 Experimental desing**119 **2.5 Observational datasets**120 **2.5.1 ERA5**121 **2.5.2 LIVVkit 2.1**122 **2.6 TempestExtremes**123 **2.7 StormCompositer**124 **3 Results**125 **3.1 Tropospheric temperatures**126 **3.2 Inter-annual variability**127 **3.3 Synoptic-scale storm characteristics**128 **3.4 Orographic gravity waves emanating from Greenland**129 **3.5 Katabatic winds emanating from Greenland**130 **3.6 Greenland surface mass balance**131 **4 Conclusions**132 **Acknowledgments**

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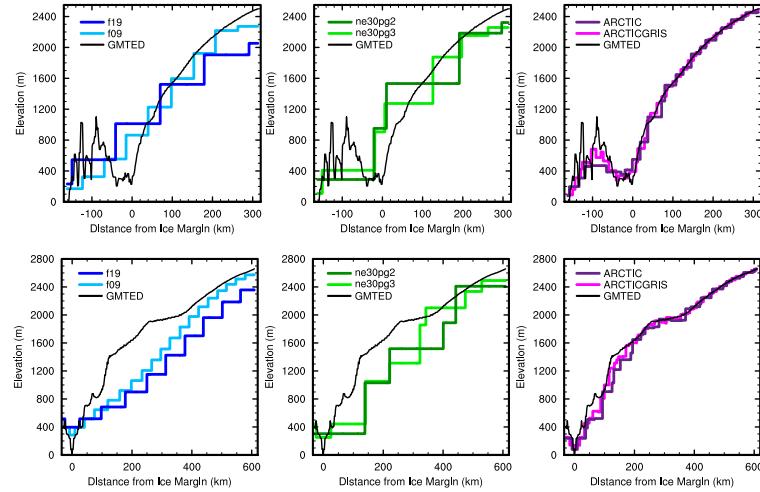
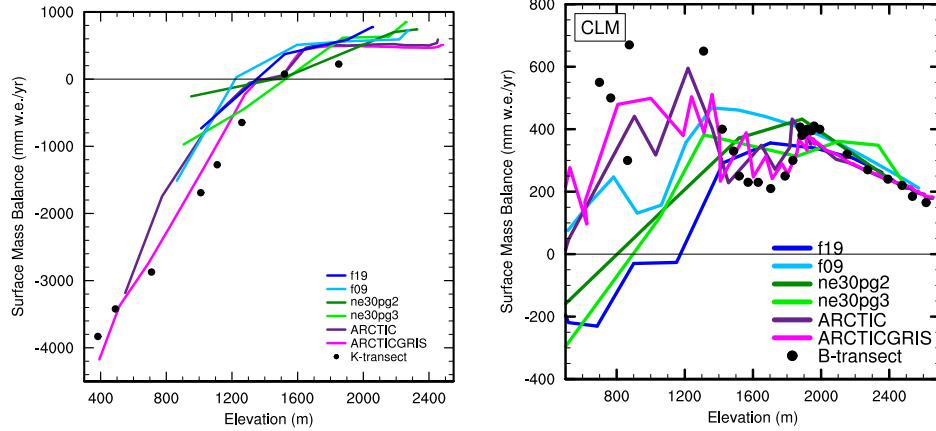
**Figure 5.****Figure 6.**

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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**Figure 7.** .**Figure 8.** .

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