Parameterized convection, grid-scale clouds and resolution sensitivity in the Community Atmosphere Model

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1. Introduction

An increasing number of atmospheric dynamical cores are being developed to maximize efficiency on massively parallel systems, permitting regionally-refined high-resolution ($\Delta x = 50$ km or less), or even globally high-resolution weather and climate simulations (Skamarock *et al.* 2012; Zängl *et al.* 2014; Harris *et al.* 2016; Ullrich *et al.* 2017; Lauritzen *et al.* 2018). Incorporating these advances into Atmospheric General Circulation Models (AGCMs) requires the development of physical parameterizations (*physics*) appropriate for the diversity of grid configurations that these dynamical cores are now able to support, referred to as scale-aware physics. The most common approach towards developing scale-aware physics has been through the lens of limited area, cloud resolving simulations (e.g., Plant and Craig 2008; Arakawa and Wu 2013; Song and Zhang 2018). Through subsequently filtering large-eddy simulation solutions to lower-resolution grids, a relationship between resolved and unresolved moments may be understood and ultimately parameterized. While this approach is likely necessary for developing scale-aware physics, it is not sufficient. Since the equations of motions have inherent scale dependencies, resolved dynamical modes are a function of the native grid resolution (Orlanski 1981; Weisman *et al.* 1997; Pauluis and Garner 2006; Jeevanjee and Romps 2016; Jeevanjee 2017). Scale-aware physics should also recognize native grid dependencies.

The sensitivity of the Community Atmosphere Model (CAM), and its predecessor, the Community Climate Model (CCM) to horizontal resolution is well documented. Despite thirty years of continual model development, there are robust sensitivities to resolution (hereafter *resolution* refers to *horizontal resolution*) which have persisted in all versions of the model. Total precipitable water decreases with resolution (Kiehl and Williamson 1991; Williamson *et al.* 1995; Williamson 2008; Rauscher *et al.* 2013; Zarzycki *et al.* 2014; Herrington and Reed 2017), which typically, but not always (see Williamson *et al.* 1995; Zarzycki *et al.* 2014), coincides with a reduction in cloud cover. Kiehl and Williamson (1991); Williamson *et al.* (1995) suggested that the drying of the atmosphere is consistent with the observed greater magnitude resolved vertical velocities with resolution, with greater subsiding motion increasing the export of dry air from the upper troposphere. This mechanism is consistent with an analysis of moisture budgets in CAM, version 4 (CAM4) across multiple resolutions (Yang *et al.* 2014; Herrington and Reed 2017).

It is well known that the magnitude of vertical velocities increase with resolution in atmospheric models. While the cause of this sensitivity is established in the cloud-resolving and large-eddy simulation literature (see Jeevanjee 2017, and references therein), only recently has the vertical velocity field in AGCMs and there sensitivity to resolution received attention, albeit with conflicting explanations (Donner *et al.* 2016; Rauscher *et al.* 2016; Herrington and Reed 2018). In this paper, it is shown that the vertical velocities in CAM, version 6 (CAM6) scale like Δx^{-1}, and that the inadequacy of this scaling to explain prior CAM behavior (Herrington and Reed 2017) is due to time-truncation errors arising from too large a physics time-step (Δt_{phys}) at higher-resolutions (Herrington and Reed 2018; Herrington *et al.* 2019). Furthermore, the Δx^{-1} scaling is entirely consistent with the mechanism of resolution sensitivity in cloud-resolving and large-eddy models, i.e., the inherent sensitivities of resolved dynamical modes to native grid resolution.

Another robust response of the CAM-lineage to resolution is an increase in grid-scale precipitation rates (also referred to as stratiform precipitation in the literature), at the expense of parameterized convective precipitation rates. This behavior is summarized in Figure 1, which is a bar-graph of the climatological grid-scale and convective precipitation rates in prior CAM/CCM convergence studies. The studies of Kiehl and Williamson (1991); Williamson *et al.* (1995); Williamson (2013) indicate that the tendency to reduce Δt_{phys} with resolution would by itself reduce the convective precipitation rates, however Figure 1 (top row) indicates that convergence studies with fixed Δt_{phys} still show a reduction in convection precipitation rates with resolution.

In this study, the reduction in convective precipitation rates in CAM6 is shown to result from the greater subsiding motion with resolution, leading to a more stable atmosphere in which the criterion for parameterized convection occurs less often. The feedback of the resolved vertical motion on the physics indicates that the root cause of resolution sensitivity in CAM arises from the sensitivity of resolved dynamical modes to native grid resolution. Section 2 describes CAM6 and the simulations used in this study. Section 3 contains a thorough analysis of the CAM6 simulations and Section 4 provides some discussion and conclusions.

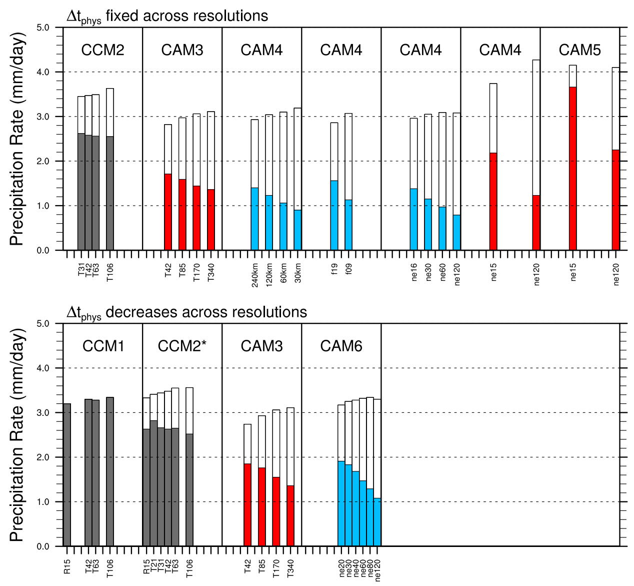

Figure 1. Bar-graph of the convective (solid) and grid-scale (white) climatological precipitation rates in prior CAM/CCM convergence studies. Each window contains a single convergence study, with identical x-axis; the approximate grid resolution. Colors indicate the model configuration; January ensemble (black) and aqua-planet configurations with SST profiles $QOBS$ (blue) and $CNTL$ (red) after Neale and Hoskins (2000). Studies included in this figure are Kiehl and Williamson (1991) (CCM1), Williamson *et al.* (1995) (CCM2), Williamson (2008) (CAM3), Rauscher *et al.* (2013); Zarzycki *et al.* (2014); Herrington and Reed (2017) (CAM4), Zarzycki *et al.* (2014) (CAM5) and this study (CAM6). CCM2* refers to the modified parameter experiment of Williamson *et al.* (1995), where parameters vary with resolution to reduce the dependence of cloud fraction on resolution.

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