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

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This paper describes...

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1. Introduction

An increasing number of Atmospheric General Circulation Models (AGCMs) are being developed to maximize efficiency on massively parallel systems, permitting regionally-refined high-resolution, or even globally high-resolution weather (Δx on the order of kilometers) and climate ($\Delta x = 50$ km or less) simulations (Skamarock *et al.* 2012; Zängl *et al.* 2014; Harris *et al.* 2016; Ullrich *et al.* 2017; Lauritzen *et al.* 2018). These models are built using unstructured meshes that while allow for substantial grid flexibility, requires physical parameterizations (*physics*) that behave consistently as the truncation scale of the model changes with different grid resolutions, referred to as scale-aware physics. The most common approach towards developing scale-aware physics has been through the lens of limited area, large-eddy simulations (e.g., Plant and Craig 2008; Arakawa and Wu 2013; Song and Zhang 2018). Through subsequently filtering large-eddy solutions to lower-resolution grids, a relationship between first- and higher-order moments (Germano 1992) 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 vary with 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 these native grid dependencies.

The sensitivity of the Community Atmosphere Model (CAM; Neale *et al.* 2012), 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. The atmosphere dries with increasing resolution, seen through the reduction in total precipitable water (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) and Williamson *et al.* (1995) suggested that the drying of the atmosphere is consistent with the greater magnitude resolved vertical velocities with increasing 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; Neale *et al.* 2010) 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 has been established in the large-eddy simulation literature (see Jeevanjee 2017, and references therein), only recently has the vertical velocity field in AGCMs and their sensitivity to resolution received attention, albeit with conflicting explanations (Donner *et al.* 2016; Rauscher *et al.* 2016; Herrington and Reed 2018). To generalize the relationship between vertical velocity and resolution, let α refer be the ratio of W_0, the vertical velocity scale of some reference grid spacing Δx_0, to W, the vertical velocity scale of any Δx. A power-law for α in Δx is then,

$$\alpha^{-1} = \frac{W}{W_0} = \left(\frac{\Delta x}{\Delta x_0}\right)^n, \tag{1}$$

where n is the power-law exponent.

Rauscher *et al.* (2016) derive an estimate $n = b - 1$ by combining a scale analysis of the continuity equation with a power law representation Δx^{2b} of the second-order structure function of the horizontal wind. Observations indicate that $b = \frac{1}{3}$ for scales less than about 1000 km (Cho *et al.* 1999), which according to the Weiner–Khinchin theorem, is equivalent to the observed $-\frac{5}{3}$ slope of the kinetic energy spectrum (Nastrom and Gage 1985) through the relation $-(2b + 1)$. Rauscher *et al.* (2016) argue that the emergent constraint on the slope of the kinetic energy spectrum in both models and observations indicates that $n = -\frac{2}{3}$.

For large-eddy simulations, the sensitivity of vertical velocities to resolution is explained through a scale analysis of the dynamical equations (Weisman *et al.* 1997; Pauluis and Garner 2006; Jeevanjee and Romps 2016). For hydrostatic scales relevant to AGCMs, a scale analysis of the Poisson yields $W \propto D^{-1}$, where D is the horizontal scale of the buoyancy perturbation (Herrington and Reed 2018). In CAM aqua-planet simulations, the largest source of buoyancy is associated with grid-scale cloud formation, whose horizontal extent are set by the effective resolution of the model, about $5 - 10\Delta x$, and so this gives $n = -1$ (Herrington and Reed 2018). In this paper, it is shown that the

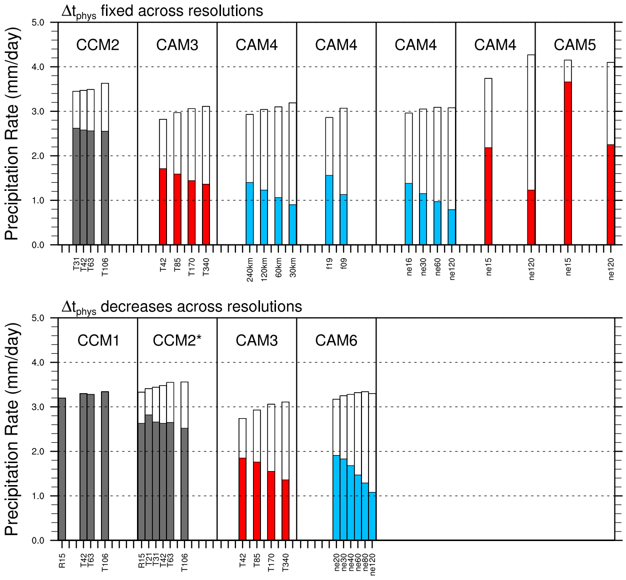

Figure 1. Bar-graph of the convective (solid) and grid-scale (white) climatological precipitation rates in prior CAM/CCM convergence studies. Each window contains a single convergence study, with identical x-axis; the approximate grid resolution. Colors indicate the model configuration; January ensemble (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.

resolution sensitivity of vertical velocities in CAM, version 6 (CAM6) are well described with $n = -1$, 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).

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) and 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.

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www.sunrise-setting.co.uk

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