Towards understanding why super-parameterization improves the simulated composite daily rainfall cycle in multi-scale climate modeling frameworks

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Introduction

The Multiscale Modeling Framework (MMF*) approach to climate modeling results in improved simulations of small-scale, fast (daily) rainfall variability, but understanding why is difficult. Analysis of the vertically integrated moisture budget provides several new clues to the physical processes involved.

*MMFs are global climate models (GCMs) that represent sub-grid cloud and boundary layer processes using nested cloud resolving models (superparameterization) in each grid column instead of conventional statistical parameterizations. The MMF (SPCAM3) and GCM (CAM3) compared in this study are identical except for their treatment of the sub-grid scale.

Improved daily rainfall cycle

Figure 1 shows that superparameterization improves the simulated space-time structure of the daily rainfall cycle in climate models. As in the observations, the spatial pattern that statistically explains most diurnal rainfall variation in the MMF is a land-sea mask. What is it about convection in the MMF that results in improved diurnal variability over both the land and the ocean?

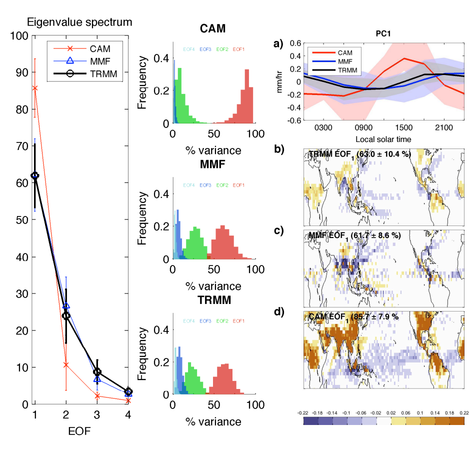

Figure 1: Left panels) Eigenvalue spectrum for the composite JJA diurnal cycle of precipitation as simulated by CAM and MMF, and as observed in TRMM 3B42 and normalized histograms of the percent variance attributable to the first four EOFs in a 2000-member bootstrapping ensemble of EOF calculations. (Right panels) (a) Principle component (PC) time series of the leading EOF of the composite boreal summer diurnal cycle of precipitation as simulated by CAM (red) and MMF (blue), compared to TRMM observations (black). Solid lines and shading denote the mean +- one standard deviation of the ensemble of EOF calculations. (b)-(d) Ensemble mean spatial structure of EOF$_1$ for (b) TRMM data, (c) the MMF, and (d) CAM.

Role of convective heating & convective moistening

Figure 2 contrasts the daily cycle of heating and moistening due to convection in the two models along a coastal transect intercepting the Gulf Stream.

Over land the day time improvement of peak timing in the MMF has been explained as a result of morning shallow convective diurnal entrainment humidification (DeMott et al., 2007) as has been seen in 3D CRM studies (Guichard et al. 2004; Bretherton 2007). This process appears to be ubiquitous over MMF land surfaces and can be seen in Figure 2 (e.-g.) as convective humidification atop a thin shallow convective heating layer in Figure 3 (e.-g.). In contrast to the MMF, the CAM convection package almost exclusively acts to remove moisture.

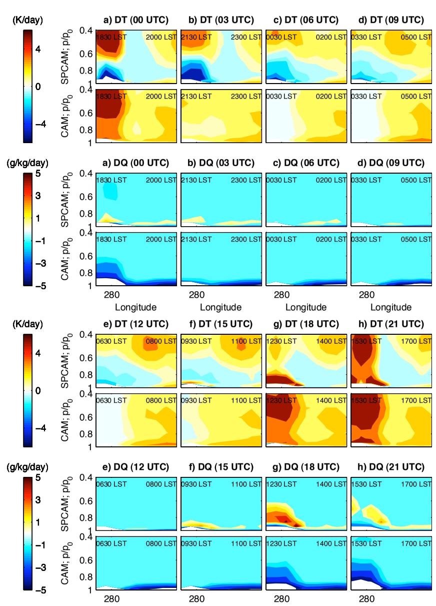

Figure 2: Height-longitude section contrasting the diurnal chronology of convective heating and convective moistening in the SP-CAM and the CAM, along a zonal transect straddling the Gulf Stream and eastern United States (275E to 300 E, averaged over 34 N to 40 N). The quantities shown are tendencies exerted by convection in the physics package, i.e. by nudging towards the nested CRM in the SP-CAM and as diagnosed by conventional parameterization in CAM. The vertical coordinate is normalized pressure (σ = p/1000 hPa), and the land component at the western edge of the transect is identifiable as a blanked out region at the base of the domain.

Over the Gulf Stream, CAM convects too deeply at all times of day while the MMF convection is typically confined to a shallow layer near the surface; increased diurnal rainfall variability in the MMF here seems to be related to low cloud processes (not shown). As over land, convective humidification occurs in the MMF over the ocean.

New clues from column water budget diurnal analysis

Precipitation and moisture storage are only half of the column water budget. To improve our understanding of why the rainfall cycles are different in CAM and MMF it helps to look at the other budget terms as well. Conservation of total column water may be expressed as:

$$-\int \frac{\partial q}{\partial t} dz - \int \nabla \cdot (q\mathbf{v}) - PREC + QFLX = 0$$

–DQDT (depletion of stored vapor and cloud) QCONV (convergence due to advection) -PREC (removal by precipitation) QFLX (addition by evapotranspiration)

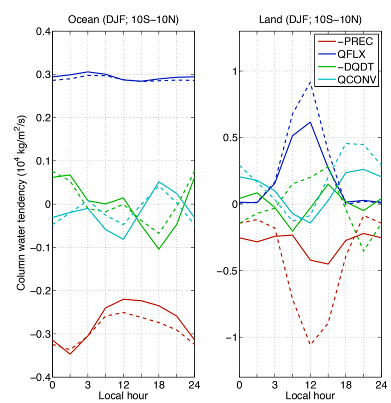

Figure 3: Composite DJF diurnal cycle of all components of the vertically integrated moisture budget, averaged over (left) ocean points and (right) land points within a latitude band from 10 S to 10 N, during DJF comparing CAM (dashed lines) to MMF (solid lines).

Over the tropical ocean, the MMF produces less daytime precipitation than CAM, but similar nocturnal rainfall. The diurnal latent heat flux cycle over the tropical ocean is similar in the two models so differences in storage and convergence are responsible for this diurnal rainfall difference. Which is more responsible? From 6-15 LST, water vapor is diverging in both models, but column water is increasing in CAM versus decreasing in the MMF. In all, decreased oceanic precipitation in the MMF relative to CAM from 6-20 LST is primarily explained by stronger water divergence during 6-15 LST and by stronger storage of water during 15-20 LST.

Over tropical land, the MMF exhibits more nocturnal and much less daytime rainfall than CAM. In the evening, latent heat fluxes are similar and both models tend to converge moisture. But while in CAM vigorous nocturnal convergence in CAM is balanced by recharging column moisture, in the MMF the storage term is small, such that relatively weak nocturnal moisture convergence is instead primarily balanced by enhanced precipitation relative to CAM. During daytime differences in storage are also key to the the weaker precipitation in the MMF. From 6-12 LST, CAM rains harder than the MMF over tropical land, balanced by reductions in the nocturnally accumulated water storage reservoir and high daytime latent heat fluxes. In the MMF, moisture is recharged during the first part of the day, and then depleted from 12-18 LST. In contrast, CAM depletes column moisture throughout this time. The differences in water storage and convergence in the two models are complicated.

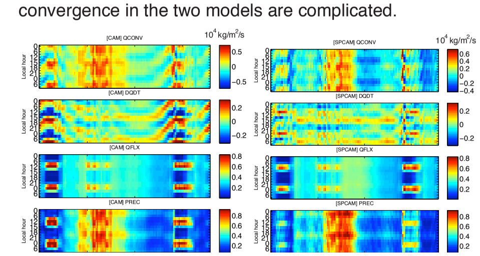

Figure 4: Local time - longitude section contrasting the composite DJF diurnal evolution of all components of the vertically integrated water budget in (left) CAM and (right) SPCAM, averaged from 10S to 10N. The daily cycle is repeated twice for clarity.

Figure 4 shows striking differences in the time-longitude structure of the composite diurnal cycle of water storage and water convergence in the MMF and CAM show striking differences in the tropics. In CAM there is an apparent large scale westward (eastward) propagation of a diurnally initiated convergence and storage signal from equatorial South America (Africa) into the eastern Pacific (western Indian ocean). The absence of this diurnal wavelike convergence and storage feature in the MMF may underly the over-ocean budgetary differences noted in Figure 3.

Summary

Daytime entrainment humidification (moisture storage) is thought to temper the amplitude and fix the timing of the overly vigorous diurnal rainfall cycle over land in the MMF relative to CAM. Water budget analysis further shows that at night time, and over the ocean, different representations of diurnal moisture convergence in the two models play a major role in differentiating simulated daily rainfall. In CAM a large-scale wave of diurnal moisture convergence and storage connects the vigorous over-land rainfall cycle to open ocean. This wave is not apparent in the MMF.

References:

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