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Impact of physical parameterizations on idealized tropical cyclones in the Community Atmosphere Model

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[1] This paper explores the impact of the physical parameterization suite on the evolution of an idealized tropical cyclone within the National Center for Atmospheric Research's (NCAR) Community Atmosphere Model (CAM). The CAM versions 3.1 and 4 are used to study the development of an initially weak vortex in an idealized environment over a 10-day simulation period within an aqua-planet setup. The main distinction between CAM 3.1 and CAM 4 lies within the physical parameterization of deep convection. CAM 4 now includes a dilute plume Convective Available Potential Energy (CAPE) calculation and Convective Momentum Transport (CMT). The finite–volume dynamical core with 26 vertical levels in aqua-planet mode is used at horizontal grid spacings of 1.0°, 0.5° and 0.25°. It is revealed that CAM 4 produces stronger and larger tropical cyclones by day 10 at all resolutions, with a much earlier onset of intensification when compared to CAM 3.1. At the highest resolution CAM 4 also accounts for changes in the storm's vertical structure, such as an increased outward slope of the wind contours with height, when compared to CAM 3.1. An investigation concludes that the new dilute CAPE calculation in CAM 4 is largely responsible for the changes observed in the development, strength and structure of the tropical cyclone. **Citation:** Reed, K. A., and C. Jablonowski (2011), Impact of physical parameterizations on idealized tropical cyclones in the Community Atmosphere Model, *Geophys. Res. Lett.*, *38*, L04805, doi:10.1029/2010GL046297.

1. Introduction

[2] Recent studies have shown the ability of General Circulation Models (GCMs) to simulate the development and evolution of tropical cyclones. These GCM studies range from short-term studies to long-term climate studies. For example, *Atlas et al.* [2005] and *Shen et al.* [2006] used NASA's hydrostatic finite-volume GCM at horizontal resolutions of 0.25° and 0.125°, or 28 km and 14 km in equatorial regions, to simulate selected Atlantic hurricanes for a duration of 5 days. Climate studies, including those by *Oouchi et al.* [2006], [*Bengtsson et al.*, 2007] and *Zhao et al.* [2009], aim at understanding how tropical cyclones simulations will be altered by a warmer future climate. Since modern computing architectures now allow very high horizontal resolutions, that will soon approach the transition to non-hydrostatic scales, the use of GCMs to model tropical cyclones is likely to become even more prominent. This raises the question of how well their dynamical cores and physical parameterizations are suited to model the evolution of these rather extreme storms.

[3] The use of GCMs to simulate tropical cyclones presents numerous challenges, including the small size of the storms, the interaction of large-scale and small-scale processes and the parameterization of sub-grid scale physical processes. Such physical processes include the representation of convection [*Smith*, 2000] and the surface and planetary boundary layers [*Hill and Lackmann*, 2009]. These processes play a paramount role in tropical cyclone development. The choice of the parameterization schemes highly influences the ability of a GCM to simulate tropical storms. This paper sheds light on the impact of one particular physical parameterization. It analyzes the sensitivity of a tropical cyclone to changes in the deep convection scheme in the National Center for Atmospheric Research's (NCAR) Community Atmosphere Model (CAM). In addition, the impact of a change in the cloud macrophysics is assessed.

[4] *Reed and Jablonowski* [2011] introduced an analytic initialization technique for GCMs to simulate the development of a single, initially weak vortex into a tropical cyclone. Such a vortex is placed into an idealized environment within an aqua-planet setup with a constant sea surface temperature (SST). They observed that high-resolution CAM version 3.1 (CAM 3.1) model runs, with horizontal grid spacings of 0.5° or less, are able to simulate the growth of the initial vortex into a tropical cyclone.

[5] Recently, NCAR released an updated version of CAM, version 4 (CAM 4), in which changes were made to the physical parameterizations. The changes focused on the deep convection scheme. This paper aims to evaluate the impact of the individual enhancements within CAM 4 on the ability of the model to simulate tropical cyclones. The analytic initialization technique introduced by *Reed and Jablonowski* [2011] provides a basis for such a comparison. Section 2 briefly reviews the design of the models CAM 3.1 and CAM 4 and Section 3 introduces the simulation design. Section 4 compares the simulations of the initially weak vortex into a tropical cyclone and explores the impact of the individual enhanced parameterizations within CAM 4. Section 5 discusses the conclusions and future research.

2. Model Description

[6] In this paper we use two versions of NCAR's CAM, version 3.1 [*Collins et al.*, 2004] and version 4 [*Neale et al.*, 2010]. CAM is part of NCAR's Community Climate System Model (CCSM) that is routinely used for climate change projections. We utilize both CAM 3.1 and CAM 4 in a configuration with the mass-conservative finite–volume (FV) dynamical core in flux-form on a regular latitude-longitude

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Table 1. Physical Parameterization Suite Configurations

Case	Physical Parameterization Suite Configuration
1	Full CAM 3.1 physics suite
2	Full CAM 4 physics suite
3	CAM 4 physics suite with CAM 3.1 undilute CAPE calculation
4	CAM 4 physics suite with CMT turned off
5	CAM 4 physics suite with both CAM 3.1 undilute CAPE calculation and CMT turned off
6	Case 5 with an additional modification to match CAM 3.1 cloud macrophysics

grid [*Lin*, 2004]. An almost identical FV dynamical core with different physics parameterizations and SSTs was also used in the tropical cyclone studies by *Atlas et al.* [2005], *Shen et al.* [2006] and *Zhao et al.* [2009] (cubed-sphere grid). CAM 3.1 and CAM 4 are run with the identical ($\Delta\lambda$, $\Delta\varphi$) horizontal grid spacings of 1.0°, 0.5° and 0.25° and the default 26 vertical η-levels (L26). The three horizontal resolutions correspond to grid spacings of about 110, 55 and 28 km in the equatorial region. The dynamics time steps at these three resolutions are 180 s, 90 s and 45 s, respectively. The physics time step is ten times the dynamics time step. The models are run with the full physics parameterization suites and utilize the aqua-planet setup as proposed by *Neale and Hoskins* [2000], but with constant SSTs of 29°C.

[7] The CAM 4 physics package is mostly identical to the CAM 3.1 physics suite except for two main enhancements to *Zhang and McFarlane*'s [1995] deep convective parameterization. The first change is to the calculation of the Convective Available Potential Energy (CAPE). CAM 4 now assumes a dilute entraining plume [*Neale et al.*, 2008], replacing the standard undilute non-entraining plume method in CAM 3.1. The second enhancement is the addition of Convective Momentum Transport (CMT) in CAM 4 [*Richter and Rasch*, 2008].

3. Simulation Design

[8] The initialization technique for the model simulations is described in detail by *Reed and Jablonowski* [2011]. In all cases we initialize the model with a single, initially weak, warm-core vortex in an idealized background environment. The vortex has a radius of maximum wind (RMW) of about 250 km and a 20 m s^{-1} maximum initial wind speed located at the surface. Table 1 provides a description of the simulations presented in Section 4. Simulations are run with both CAM 3.1 (case 1) and CAM 4 (case 2) physics. To understand the impact of the individual changes additional simulations are run with the CAM 4 physics suite. These configurations include the CAM 4 physics suite with the new dilute plume calculation of CAPE turned off in favor of the CAM 3.1 undilute plume CAPE calculation (case 3), no CMT used (case 4), and both cases 3 and 4 together (case 5). An additional configuration, case 6, is used and is explained in Section 4. Each model configuration is run for 10 simulation days with the identical physics tuning parameter set. These adjustable parameters have been derived for CAM 4 climate simulations with the FV dynamical core at 1.0° resolution as documented by *Neale et al.* [2010].

4. Results: Evolution of the Tropical Cyclone

4.1. Comparison of CAM 3.1 and CAM 4

[9] Figure 1 displays the longitude-height cross section of the magnitude of the wind through the center latitude of the vortex at day 10 for simulations with CAM 3.1 physics (top row) and CAM 4 physics (bottom row) at all three resolutions 1.0°, 0.5° and 0.25°. At all resolutions the tropical

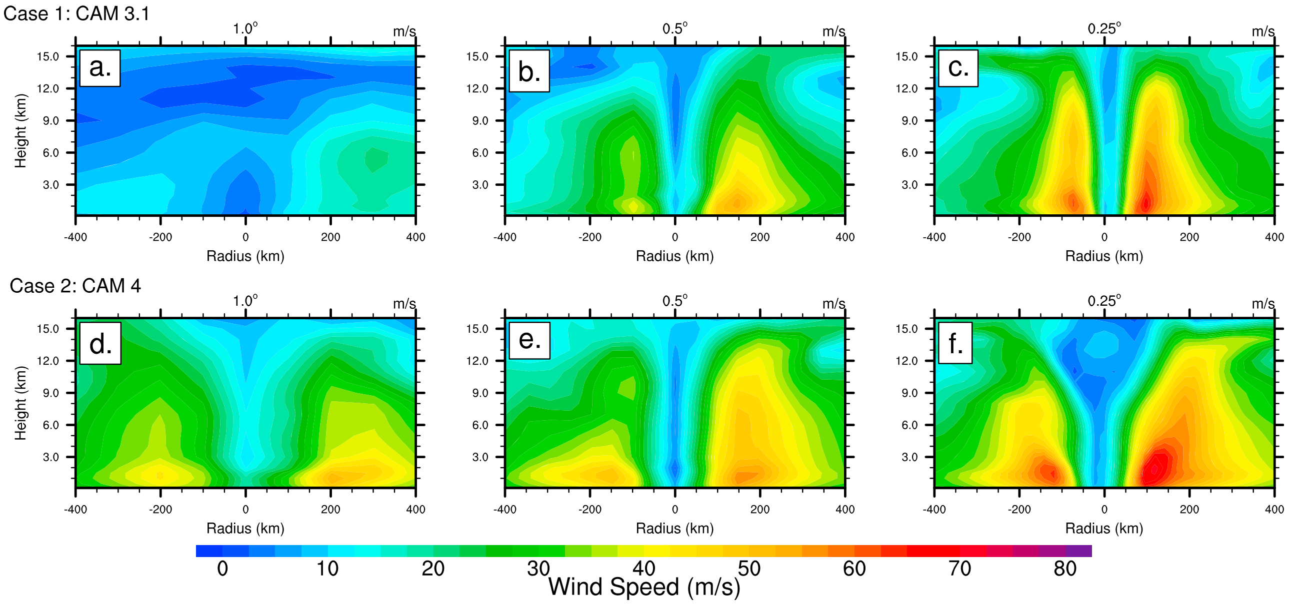

Figure 1. Snapshot of the longitude-height cross section of the wind speed through the center latitude of the tropical cyclone as a function of the radius from the vortex center at day 10. Top row: Results of case 1: CAM 3.1 physics simulations at the resolutions of (a) 1.0°, (b) 0.5° and (c) 0.25°. (d–f) Results of case 2: corresponding CAM 4 physics simulations.

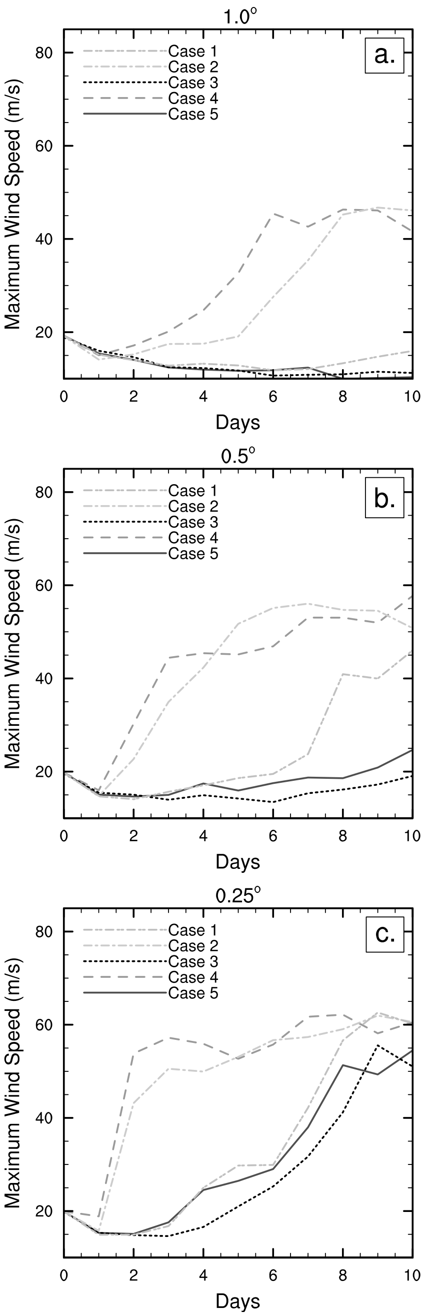

Figure 2. Time evolution of the maximum wind speed at 100 m for configuration 1 through 5 listed in Table 1 at resolutions (a) 1.0°, (b) 0.5° and (c) 0.25°. Cases 2 and 4 use the new (diluted) CAPE calculation.

cyclones simulated with CAM 4 physics (case 2) are stronger with a higher maximum wind speed by day 10 than those cyclones simulated with CAM 3.1 physics (case 1). Figure 1 also shows that at 1.0° the CAM 4 simulation produces a tropical cyclone with a broad RMW. In CAM 3.1 the initial vortex fails to intensify. This is in agreement with the 1.0° simulations of the control vortex of *Reed and Jablonowski* [2011], which also used CAM 3.1 but with a different physics tuning parameter set.

[10] Figure 1 indicates that the structure of the CAM 3.1 storm is rather different than that of the CAM 4 storm. At the 0.5° and 0.25° grid spacings, in which tropical cyclones develop in both versions, the overall size of the CAM 4 storm is larger as evidenced by the larger range in which the strongest wind speeds occur. This is especially evident for the 0.25° grid spacing. The CAM 3.1 storm has a slightly smaller RMW than the CAM 4 storm and produces a much narrower area of vertical development. In addition, there is a noticeable difference in structure at higher altitudes. At 0.25° the CAM 3.1 simulation produces vertical development near the RMW that is almost directly vertical. The CAM 4 simulation also has an area of vertical development near the RMW, but the contours of constant wind speed start to slope more outward at higher altitudes (above 7 km).

[11] Figure 2 shows the time evolution of the maximum wind speed at 100 m for each configuration listed in Table 1 at each resolution from 1.0° (top) to 0.25° (bottom). The wind speed is linearly interpolated to this height level using the wind speeds and heights of the two surrounding model levels. The lowermost model level always lies below 100 m, which avoids extrapolation. Figure 2 reveals that all simulations experience an initial weakening of the storm, most likely due to surface friction and the lack of secondary circulation in the initial vortex [*Reed and Jablonowski*, 2011]. Figure 2 confirms that by day 10 the magnitude of the maximum wind speed at 100 m is greater for the CAM 4 simulations (case 2) than for the CAM 3.1 simulations (case 1) at all resolutions, except in the 0.25° simulations when the day-10 maximum wind speeds are roughly the same. Again, Figure 2 shows that no tropical cyclone forms for the 1.0° simulation with CAM 3.1. At the other two resolutions (0.5° and 0.25°) the manner in which the cyclone intensifies is substantially different. After day 1 the CAM 4 storms begin to intensify rapidly (shown by the increase in maximum wind speed) while the CAM 3.1 storms do not start to intensify until much later, depending on the resolution. Despite this difference in intensification, the full CAM 3.1 and CAM 4 simulations at 0.25° approach approximately the same value of maximum wind speed by day 10. This may suggest that an intensity limit has been reached for the grid spacing of 0.25°.

[12] Due to the idealized nature of this study (i.e., no vertical wind shear, no background flow, constant SSTs, etc.) it is difficult to judge which path (CAM 4 or CAM 3.1) to development is more accurate. *Kaplan and Demaria* [2003] stated that 83% of all category 4 and 5 hurricanes from 1989 to 2000 underwent rapid intensification, defined to be a wind speed increase of 15.4 m s^{-1} over a 24 hour period, at least once. At 0.25° both the CAM 3.1 and CAM 4 cyclones reach category 4 strength, yet only the CAM 4 simulation undergoes rapid intensification, with an increase of about 27.4 m s^{-1} from day 1 to 2. However, this magnitude of rapid intensification is rare. Of the 2621 cases explored by *Kaplan and Demaria* [2003] only 7 were events with increases greater than 27 m s^{-1} over a 24 hour period. While the CAM 3.1 cyclone never classifies as undergoing rapid intensification, its largest increase of 14.4 m s^{-1} from day 7 to 8 is close to the threshold and might be more typical.

4.2. Analysis of the Changes in the Deep Convection Scheme

[13] The impact of the individual enhancements to CAM 4 on the evolution of the initial vortex can be investigated by turning them off and on. Figure 2 displays that when the dilute CAPE calculation enhancement is turned off (case 3)

no tropical cyclone develops at 1.0°. At the 0.5° and 0.25° resolutions the intensification of the initial vortex is significantly altered when compared to the full CAM 4 simulations. The case 3 storm develops in a similar manner to that of the CAM 3.1 (case 1) storm. Figure 2 also shows that the CAM 4 without CMT (case 4) simulations are rather similar to the full CAM 4 versions (case 2) with some minor changes in the evolving storm's strength and intensification.

[14] Figure 3 provides insight into the impact of the individual enhancements in CAM 4 on the tropical cyclone structure. It depicts the longitude-height cross section of the magnitude of the wind through the center latitude of the vortex at day 10 for 0.25° simulations of case 3 through case 5. The enhanced outward-pointing radial slope of the wind speed contours only appears in case 4, and resembles the full CAM 4 physics simulation (case 2 as seen in Figure 1f). This is again an indication that the dilute CAPE calculation significantly alters the structure of the tropical cyclone. It also suggests that the changes in structure from CAM 3.1 to CAM 4 are systematic and robust rather than random fluctuations. Note that when both CAM 4 enhancements are turned off (case 5) the simulations have resemblance to case 3 as shown in Figures 2, 3a, and 3c.

[15] The results demonstrate that the way in which CAPE is calculated in CAM 4 has a larger impact on the differences between the full CAM 3.1 and CAM 4 simulations than does the addition of CMT. Since these two enhancements are the main differences between CAM 3.1 and CAM 4 we would expect the CAM 3.1 physics simulation (case 1) and the CAM 4 run without enhancements (case 5) to be almost identical. However, this is not the case. Figures 2b and 2c show that case 5 is always weaker in magnitude by day 10 in comparison to case 1.

4.3. Impact of Cloud Macrophysics

[16] The above mentioned difference is associated with an additional change in the cloud fraction state that is provided to the cloud macrophysics scheme. Namely, the cloud macrophysics scheme expects the atmospheric state from the previous time-level. In CAM 3.1 the cloud macrophysics scheme is provided the previous time-level state for all variables except the cloud fraction. This approach is corrected in CAM 4. Case 5 is altered to reproduce the manner in which CAM 3.1 handles the cloud macrophyics in CAM 4 (referred to as case 6). With this additional modification to the cloud macrophysics the results for case 6 (Figure 3d) are now more comparable to the CAM 3.1 physics simulation in Figure 1c (case 1) than are those of case 5. This is evidenced by the increase in the wind speed throughout the entire storm, including the maximum wind speed, in case 6. It verifies that the main differences from CAM 3.1 to CAM 4 are due to changes in the physics suite. It is not expected that the case 1 and case 6 simulations match exactly since there are numerous other minor modifications in CAM 4.

5. Concluding Remarks

[17] Changes in physical parameterizations within the same model have a profound impact on the simulation of tropical

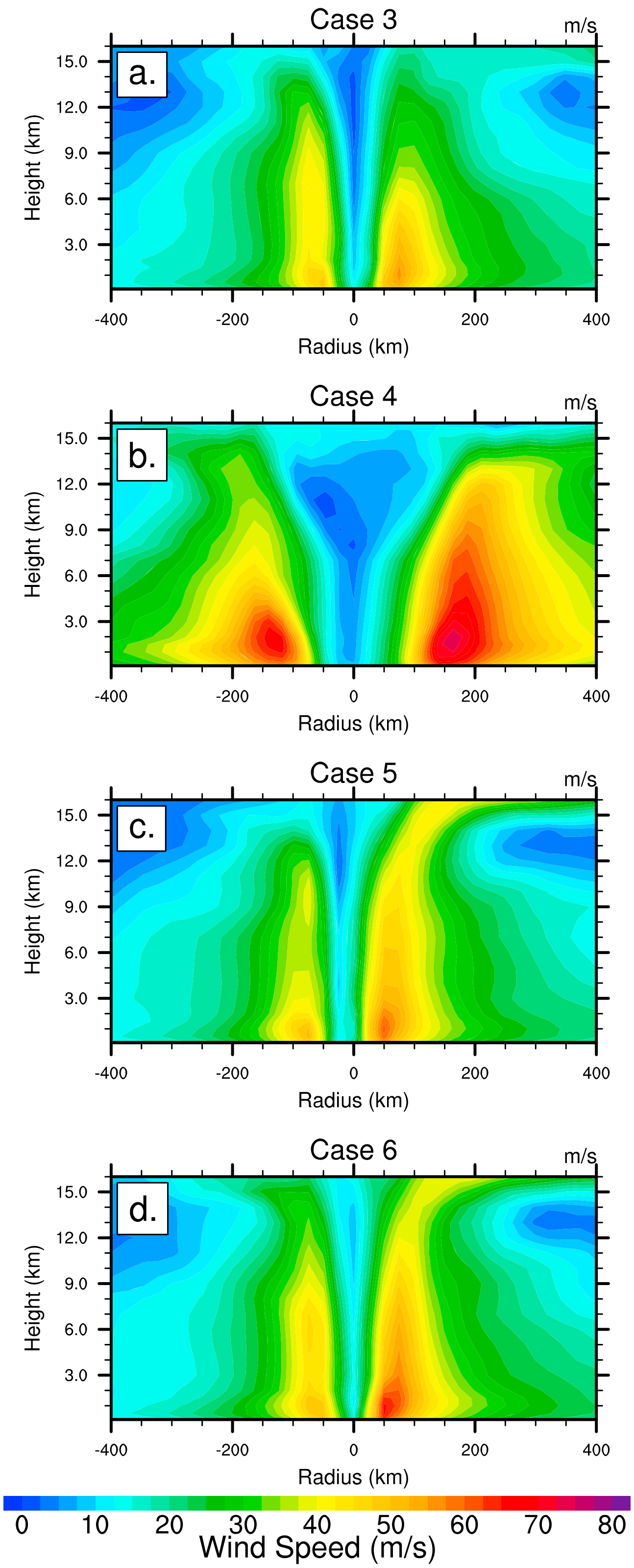

Figure 3. Snapshot of the longitude-height cross section of the wind speed through the center latitude of the tropical cyclone as a function of the radius from the vortex center at day 10. Results at 0.25° resolution for (a) case 3: CAM 4 physics with the CAM 3.1 undilute CAPE calculation, (b) case 4: CAM4 without CMT, (c) case 5: CAM 4 with the CAM 3.1 undilute CAPE calculation and without CMT and (d) case 6: case 5 with the additional modification to the cloud macrophysics.

cyclones. This paper shows that the development of the initial vortex into a tropical cyclone is significantly impacted by the choice of CAM 3.1 and CAM 4. For example, CAM 4 simulations produce a tropical cyclone in the 1.0° resolution case, whereas the cyclone in CAM 3.1 fails to develop. In addition, the CAM 4 simulations intensify earlier (after 1 day) and produce a stronger storm by day 10 when compared to the same CAM 3.1 simulations at the 0.5° and 0.25° grid spacings. It remains unclear as to which physics version produces a more realistic evolution of the very idealized tropical cyclone. By toggling the individual enhancements to *Zhang and McFarlane*'s [1995] deep convective parameterization introduced in CAM 4, it is evident that the new manner in which CAPE is calculated is largely responsible for the difference in the simulations. This enhancement in the CAPE calculation leads to the extreme rapid intensification of the initial vortex much earlier during the simulation, resulting in stronger and larger storms by day 10 at all horizontal grid spacings. The CAPE enhancement also appears to account for the difference in vertical structure of the tropical storm, as seen with the 0.25° simulations. An additional modification to the cloud macrophysics scheme is required to approximately match the CAM 3.1 and CAM 4 tropical cyclone simulations.

[18] This paper sheds light on the impact that the relatively small differences between NCAR's CAM 3.1 and CAM 4 have on idealized tropical cyclones. Even larger differences could be expected when comparing GCMs with very different physical parameterizations suites, like CAM version 5. In future work, we will perform similar studies that investigate the impact of different physics suites on the tropical cyclone development, intensity and structure. In addition, the effect of different GCM dynamical cores will be explored using identical physical parameterizations.

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