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Tropical cyclones in the spectral element configuration of the Community Atmosphere Model

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Abstract

This paper explores the evolution of idealized tropical cyclones in the Community Atmosphere Model CAM 5 with the spectral element (SE) dynamical core at grid spacings of 111, 55 and 28 km. Over 10 simulation days the storms become increasingly intense and compact with increasing resolution. The experiments reveal unrealistically strong tropical cyclone intensities of minimum surface pressures ranging from 845 to 865 hPa and absolute maximum wind speeds greater than 100 m s^{-1} at the highest resolution, especially when small physics time steps are used. This unphysical behavior is related to the manner in which the physics time step is applied in CAM 5. The analysis indicates that the behavior of the physics parameterizations, namely the partitioning between convective and large-scale precipitation, at small time steps contributes to this intensity.

Keywords: **tropical cyclones; GCM; high-resolution**

1. Introduction

The simulation of tropical cyclones using general circulation models (GCMs) is a rapidly growing field and it is expected that next-generation GCMs utilizing quasi-uniform meshes will aid in this expansion. Examples of modeling efforts that utilize icosahedral, or geodesic, meshes to simulate tropical cyclones are Fudeyasu *et al*. (2008) and Yamada *et al*. (2010), which employ the Nonhydrostatic ICosahedral Atmospheric Model (NICAM) (Tomita and Satoh, 2004). In addition, the Geophysical Fluid Dynamics Laboratory (GFDL) finite-volume (FV) cubed-sphere model (Donner *et al*., 2011) has been used for tropical cyclone climatology studies (Zhao *et al*., 2009) and for the assessment of the interannual variability of tropical cyclones (Chen and Lin, 2011). These quasi-uniform mesh GCM simulations are typically run at horizontal resolutions of 50 km or less, with the NICAM simulations often run at nonhydrostatic scales of less than 10 km. Furthermore, climatological high-resolution GCM studies of tropical cyclones have been performed with conventional latitude–longitude meshes (i.e. Oouchi *et al*., 2006 and Wehner *et al*., 2010).

While GCMs have shown skill in the ability to simulate tropical cyclones both on climatological and shorter-term time scales, there is still concern on the reliability of GCMs for tropical cyclone assessments. The impact of GCM design choices of numerical schemes, mesh, diffusion properties and physical parameterizations on simulated storms remains unclear. Idealized studies by Reed and Jablonowski (2011c,2011b) have investigated the impact of different physical parameterization suites, as well as variations in the convection scheme, on the simulation of a tropical cyclone in the Community Atmosphere Model (CAM) with the FV dynamical core (Neale *et al*., 2010). The development of CAM is led by the National Center for Atmospheric Research (NCAR). The current version of CAM, version 5, now includes a next-generation spectral element (SE) dynamical core that utilizes a cubed-sphere mesh. SE provides enhanced parallel scalability, making it a viable choice for massively parallel modern computer architectures. The goal of this paper is to evaluate the potential of CAM 5 SE to simulate the main characteristics of a tropical cyclone using an idealized initialization technique presented in the study by Reed and Jablonowski (2011a). Specifically, this study investigates the impact of horizontal resolution and the physics time step on tropical cyclone simulations. The resolutions are representative of current and future CAM 5 SE model configurations for long-term climate simulations. The time step assessment is an important step toward understanding how this model design choice in the physics component of the GCM influences the development and intensity of the simulated tropical cyclones, especially at forthcoming high horizontal resolutions of about 28 km.

The paper is structured as follows. Section 2 provides a description of both the model and simulation design used for this study. The results are presented in Section 3, including a discussion of the impact of horizontal resolution, initial-data uncertainty and the physics time step. Section 4 discusses the conclusions and future research.

2. Methods

2.1. Model

The model used for this study is CAM 5, documented in Neale *et al.* (2010), in combination with the SE dynamical core. The SE core is implemented on a cubed-sphere grid and is a new dynamical core option included in CAM 5. The model design is documented in Taylor and Fournier (2010) and Dennis *et al.* (2012). SE utilizes a continuous Galerkin method in the horizontal directions and polynomials of degree 3 are selected to provide a fourth-order accurate horizontal discretization. The SE package includes a horizontal diffusion scheme based on fourth-order hyper-diffusion with an additional second-order dissipation near the model top. The model is run with the full physics parameterization suite in aqua-planet mode as proposed by Neale and Hoskins (2000), but with globally constant sea surface temperatures of 29 °C.

The CAM 5 physics package contains deep and shallow convective parameterizations, as well as a moist boundary layer turbulence scheme. These are in addition to the parameterizations of cloud microphysics, cloud macrophysics, surface exchange, orographic gravity wave drag, the radiative effects of aerosols and parameterizations of short- and longwave radiation. We utilize the so-called Bulk Aerosol Model with prescribed aerosols. All simulations are based on an identical physics tuning parameter set from CAM 5 climate simulations with the default FV dynamical core at a resolution of 1.0°. The variant of CAM 5 employed here is a configuration (CAM 5.0.51 from April 2011) that closely resembles CAM 5.1 released in June 2011.

2.2. Simulation design

The tropical cyclone simulations are initialized by an analytic technique described in detail in the study by Reed and Jablonowski (2011a). The initialization of the vortex is built upon prescribed 3D moisture, pressure, temperature and velocity fields that are embedded into tropical environmental conditions. This background environment, including the moisture and temperature profiles and surface pressure, fits the observed mean hurricane season sounding for the Caribbean as described in Jordan (1958). The global background wind and wind shear are zero. The topography is also set to zero as required in aqua-planet experiments. For all simulations we initialize the model with a single, initially weak, warm-core vortex. The control 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. The vortex is in hydrostatic and gradient-wind balance in an axisymmetric form and is centered at 180 °E and 10 °N. As calculated in Reed and Jablonowski (2011a), the maximum potential intensity (MPI) based on the theory of Emanuel (1986) is approximately 66 m s^{-1} for the environmental conditions.

CAM 5 SE is run with the default 30 vertical levels at the standard horizontal resolutions $n_e = 30$, 60 and 120, where each of the six cube-faces has a grid of $n_e \times n_e$ elements. Including the degrees of freedom within each element, these resolutions correspond to average equatorial grid spacings of roughly 111 , 55 and 28 km, respectively. Various settings for each resolution are provided in Table 1, including the fourth-order diffusion coefficient K_4 and time steps. The model top is approximately at 2 hPa and there are nine full model levels between the surface and 700 hPa (roughly representing the boundary layer). At each resolution we perform a control simulation (following exactly Reed and Jablonowski (2011a)) and eight additional ensemble simulations where the control vortex is overlaid with random small-amplitude perturbations of the initial zonal and meridional wind velocities. The random perturbations are implemented globally and lie within the range of 2% of the initial wind speed at any given location. This nine-member ensemble gives insight into the robustness of the model simulations.

At the highest resolution ($n_e = 120$) additional simulations are performed with the control vortex to test the impact of the CAM 5 physics time step $\triangle t$ on the evolution of the tropical cyclone, mainly the extreme intensities simulated (shown in Section 3). Recent work by Williamson (2012) indicates that the effectiveness of the CAM 4 physical parameterizations (especially the convection schemes), when run at short physics time steps, is limited by the explicit time scales in which the schemes are formulated. While there are a number of differences between the CAM 4 parameterization suite used in Williamson (2012) and CAM 5 used in this study, the deep convection scheme remains unchanged. In our study the physics time step is decreased with increasing resolution, a common practice for resolution studies. A series of tests is performed by multiplying the $n_e = 120$ physics time step by a factor of two and four. These tests

Table 1. Horizontal grid resolutions, time steps and diffusion coefficients for the SE dynamical core in CAM 5. The physics time step $\triangle t$, the number of subcycles m, the subcycled time step ($\triangle\tau = \triangle t/m$) for the dynamical core and the fourth-order hyper-diffusion coefficient K_4 are provided.

Resolution n_e	No. of grid columns ncol	Grid distance at equator (km)	Subcycled time step $\triangle\tau$ (s)	Number of subcycles m (#)	Physics time step $\triangle t$ (s)	Diffusion coefficient K_4 (m^4 s^{-1})
30	48,602	111	360	5	1800	1.0×10^{15}
60	194,402	55	180	5	900	1.0×10^{14}
120	777,602	28	75	6	450	1.0×10^{13}

will be referred to as $\Delta t = 900$ s and $\Delta t = 1800$ s, respectively. Note, the $\Delta t = 1800$ s case provides a unique study as this is the Δt of the FV 1.0° tuning parameter set used here. These tests require the setting of the number of subcycles (i.e. the number of times the dynamical core is called each physics time step) to $m = 12$ and $m = 24$ for the $\Delta t = 900$ s and $\Delta t = 1800$ s cases, respectively. This ensures that the dynamics time step remains unchanged.

3. Results and discussion

3.1. Resolution dependence

Figure 1 displays the wind speed at day 10 for the CAM 5 SE simulations using SE at $n_e = 30$, 60 and 120. The right column of Figure 1 displays the horizontal cross sections of the magnitude of the wind at 100 m. The left column of Figure 1 shows the longitude–height cross sections of the magnitude of the wind through the center latitude of the vortex. The center of the vortex is defined to be the grid point with the minimum surface pressure. At all resolutions, the initial vortex develops into a tropical cyclone-like vortex with a maximum wind speed near the surface at the RMW, a near-calm eye region and a warm core (not shown). In addition, at each resolution the height of the absolute maximum wind speed is approximately 1 km, which corresponds well with observations of 0.5 to 1.0 km for Hurricane Isabel in 2003 as shown in Bell and Montgomery (2008). Figure 1 shows that as the resolution increases, the storm becomes more intense and more compact by day 10, as evidenced by the smaller RMW. Previous studies using the limited area Weather Research and Forecasting (WRF) model, including Davis *et al.* (2008), Hill and Lackmann (2009a) and Gentry and Lackmann (2010), have shown similar increases in intensity and decreases in the RMW with increasing horizontal resolution. In addition, as the size of the RMW is reduced with increasing resolution the outward slope of the eyewall

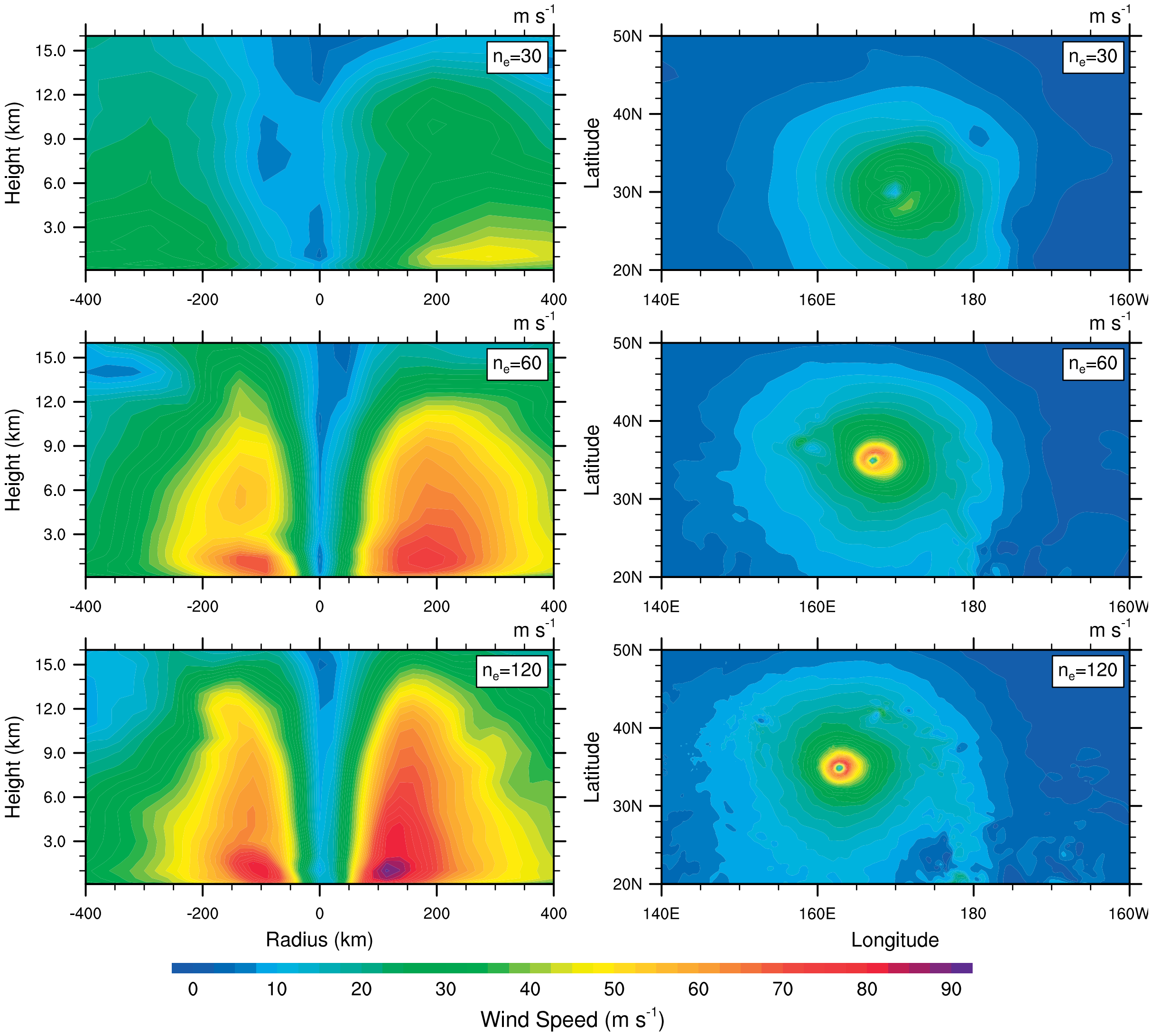

Figure 1. Snapshot of the tropical cyclone-like vortex at day 10 for CAM 5 SE at each horizontal resolution (as labeled). Left column: longitude–height cross section of the wind speed through the center latitude of the vortex as a function of the radius from the vortex center. Right column: horizontal cross section of the wind speed at a height of 100 m.

decreases. This is consistent with the observations presented in Stern and Nolan (2009) and the higher horizontal resolution WRF simulations shown in Gentry and Lackmann (2010) and Fierro *et al.* (2009).

At the highest resolution ($n_e = 120$), the cyclone becomes very strong with a maximum wind speed at 100 m of 73.18 m s^{-1}, corresponding to a category 5 hurricane on the Saffir–Simpson scale. At the higher resolutions, the simulations show more small-scale features. However, even at the highest resolution the RMW (roughly 100–150 km) is still large compared to observations, suggesting that even higher GCM resolutions are required to simulate hurricanes and important eyewall processes (e.g. vortex Rossby waves) adequately. Note, for all simulations the vortex experiences beta-drift toward the north-west (Holland, 1983).

Figure 2 displays the ensemble spread of CAM 5 SE for all resolutions. The evolution of the (a) minimum surface pressure and (b) the maximum 100 m wind speed for the control vortex are shown as the solid line and the dashed lines represent the ensemble root-mean-square deviation (RMSD) from the control vortex case. Figure 2 provides valuable insight into the expected variance and thereby the uncertainty estimate of the control case simulation with respect to the initial-data uncertainty. As the initial vortex develops into a tropical cyclone the perturbations in the initial conditions produce a spread, as represented by the ensemble RMSD, in the evolutions of the storms on the order of about 1–5 m s^{-1} in the low-level wind speeds and about 5–7 hPa in the minimum surface pressures at day 10. The maximum RMSD often occurs earlier in the evolution and is on the order of 3–9 m s^{-1} and 6–17 hPa for the maximum wind speed and minimum surface pressure, respectively. As the resolution increases the deviations in the wind speeds and surface pressure occur earlier in the simulations, likely linked to the earlier onset of intensification of the cyclone. In general, the absolute spread in the ensemble simulation becomes larger with increasing resolution.

Again, from Figure 2 it is evident that as the resolution increases the maximum wind speed increases and the minimum surface pressure decreases. The lowest resolution simulations ($n_e = 30$) appear to never fully develop over the 10 simulation days. There is little hint of convergence in intensity of the cyclone with resolution at these grid spacings. The $n_e = 120$ ensemble simulations reach very low minimum surface pressures at days 6–8 in the range of 845–865 hPa. Such minimum pressures are lower than those observed in nature. The intense nature of tropical cyclones using the SE dynamical core has been documented before by Reed and Jablonowski (2012), in which a dynamical core intercomparison concludes that the SE core always produces stronger storms when compared with three other CAM 5 dynamics packages. This study utilizes the identical simulation design and model setup.

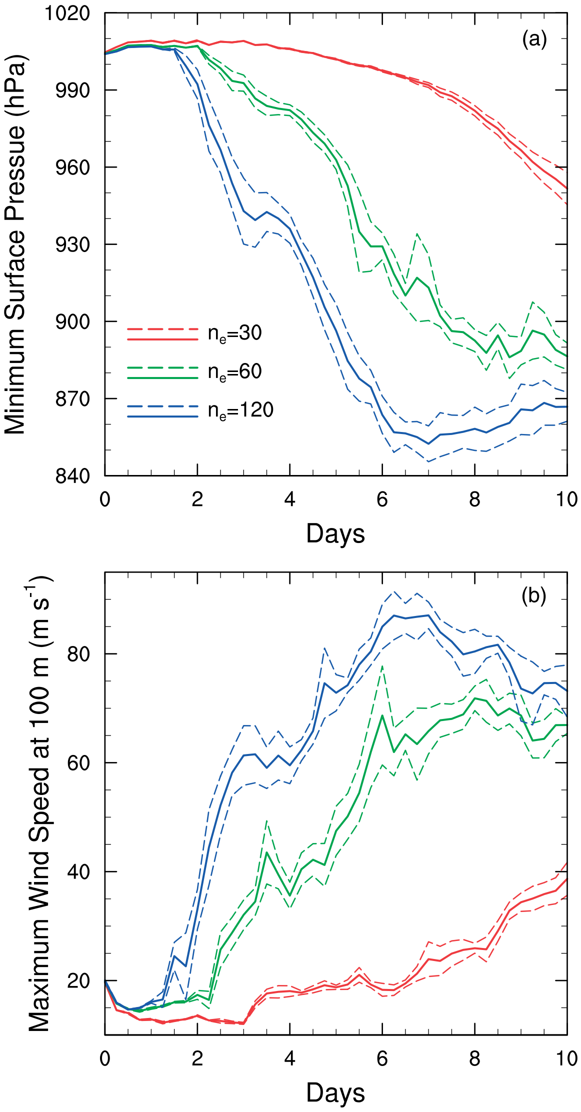

Figure 2. Time evolution of the (a) minimum surface pressure and (b) maximum wind speed at 100 m of the tropical cyclone at the horizontal resolutions of $n_e = 30$ (red), 60 (green) and 120 (blue) with CAM 5 SE. The solid lines represent the control case and the dashed lines represens the variance as determined by the ensemble RMSD.

An additional study comparing differing CAM physical parameterization packages demonstrates that CAM 5 simulates stronger tropical cyclones at horizontal grid spacing less than 60 km than the previous CAM 4 version (Reed and Jablonowski, 2011b). While these low pressures may partially be a result of the favorable, idealized conditions, they should be concerning. One of the goals of this paper is to shed light on a model design choice and its potential impact on these strong intensities.

3.2. Sensitivity to physics time step

Physics parameterization suites are known to impact the evolution and intensity of tropical cyclones in GCMs (Reed and Jablonowski, 2011c, 2011b). In addition, Williamson (2012) has called into question the fidelity of convective parameterizations in CAM 4

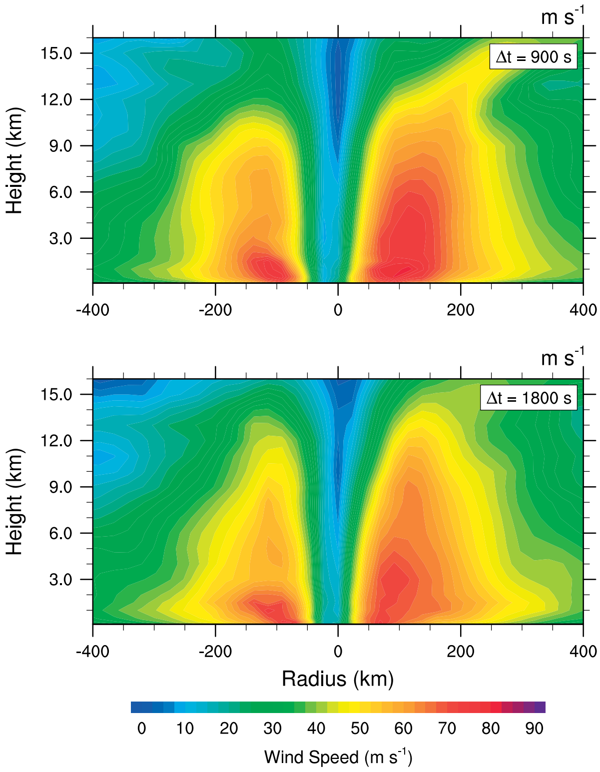

Figure 3. Snapshot of the longitude–height cross section of the wind speed through the center latitude of the tropical cyclone as a function of the radius from the vortex center at day 10. Results at $n_e = 120$ resolution for the $\triangle t = 900$ s and $\triangle t = 1800$ s simulations with CAM 5 SE (as labeled).

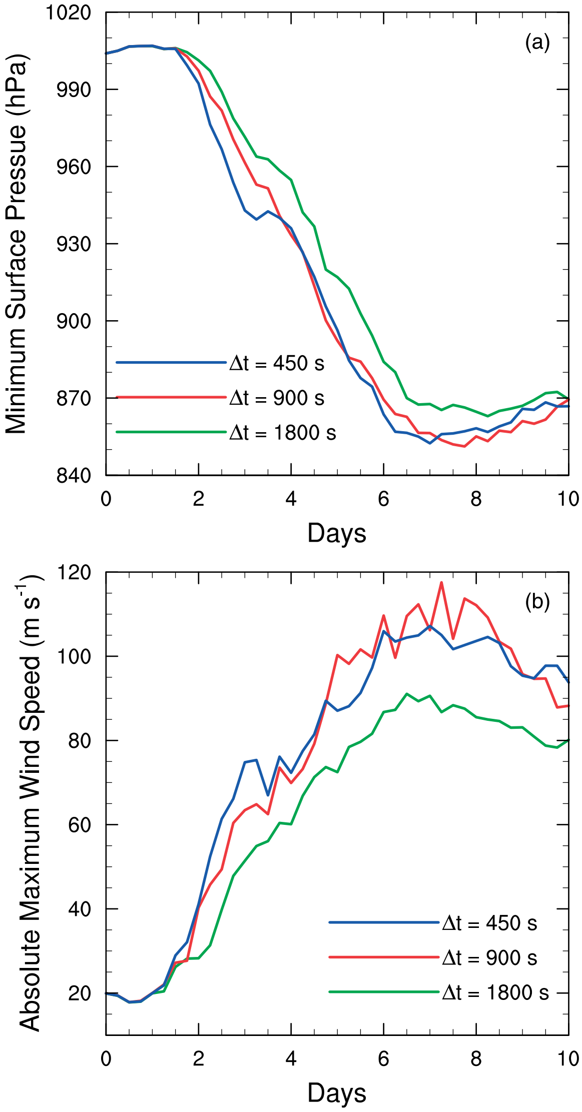

Figure 4. Time evolution of the (a) minimum surface pressure and (b) absolute maximum wind speed of the $\triangle t = 450$ s, $\triangle t = 900$ s and $\triangle t = 1800$ s simulations of CAM 5 SE at the horizontal resolution of $n_e = 120$.

when run at shortened physics time steps. Therefore, the very low minimum surface pressures seen in Figure 2 at the $n_e = 120$ resolution are investigated by altering the physics time step. Figure 3 displays the longitude–height cross sections of the magnitude of the wind through the center latitude of the vortex at day 10 at $n_e = 120$ for the tests in which the physics time step is increased to $\triangle t = 900$ s and $\triangle t = 1800$ s. From Figure 3 it is apparent that as the physics time step is increased by a factor of two and four the simulated tropical cyclone becomes weaker at day 10 (compared with Figure 1), as seen in the wind speed. Despite the change in intensity, the structure, including a relatively calm eye and the location of the RMW, remains approximately the same. This suggests that resolution and model mesh are most influential on the size and structure of the storm, while the physics forcing plays a crucial role in determining the intensity of the cyclone.

Figure 4 provides insight into the impact of the physics on the evolution of the tropical cyclone minimum surface pressure and absolute maximum wind speed. From Figure 4 it is apparent that the absolute minimum surface pressure for the $\triangle t = 900$ s simulation does not vary significantly from the $\triangle t = 450$ s simulation throughout the evolution of the storm, and appears to be within the initial-data uncertainty range. However, the $\triangle t = 1800$ s simulation does differ from the other two time step cases, especially earlier in the evolution of the storm where it is outside the uncertainty range. This suggests that the path to intensification is slightly different. These differences are more prominent in the evolution of the absolute maximum wind speed. Again, Figure 4 shows that the $\triangle t = 450$ s and $\triangle t = 900$ s are rather similar, while the $\triangle t = 1800$ s simulation produces significantly reduced wind speeds. For the $\triangle t = 450$ s and $\triangle t = 900$ s cases the absolute maximum wind speed reaches 105–115 m s^{-1}. In contrast, the $\triangle t = 1800$ s simulation peaks around 90 m s^{-1}. While such an intensity is still rather strong, the intensity of such a tropical cyclone might be more realistic. In addition, there is a slight delay in the onset of the intensification process with increased physics time step, but not of the magnitude seen with changes in resolution (Figure 2).

Following Williamson (2012), we note that in CAM 5 the deep convection scheme is implemented as a relaxation, with a relaxation time-scale of 1 h. The tendency terms from the convection scheme continuously nudge the model toward a convectively stable state with the given time-scale. Such a process should be relatively insensitive to the physics time step, and converge as the time step goes to zero. The CAM 5 large-scale (i.e resolved) condensation, which is applied sequentially after convection, is implemented as a hard adjustment. If represented as a tendency it is equivalent to a relaxation with the time-scale equal to the physics time step. In the study by Williamson (2012), it was shown that when the physics time step is smaller than the convective time scales (in CAM 4 physics), intense grid point storms develop, fed by intense latent heating due to the partitioning of the convection and large-scale condensation processes. In particular, when the physics time step is relatively short, the built-in time-scale of the convective parameterization inhibits the scheme from returning the model state back to saturation in a single application. As a consequence, the large-scale condensation scheme, with its hard adjustment, acts instead. This produces an unreasonable partition between the two processes at smaller time steps. Similar results are seen here with CAM 5.

Figure 5 displays the time evolution from day 2 of the 6-h average large-scale, convective and total precipitation rates averaged over a 8.25° × 8.25° region centered at the location of the minimum surface pressure for the three $\triangle t$ simulations. This size of the region in which the area-average is calculated is chosen to include the entire core of the tropical cyclone. From Figure 5, we observe that as the physics time step is increased to $\triangle t = 1800$ s, the convective precipitation rate increases and the large-scale precipitation rate decreases during the simulation, as the convection scheme acts more appropriately in returning the model state to saturation at the larger time step. In particular, during days 4–6 the convective precipitation rate of the $\triangle t = 1800$ s storm is up to approximately 70 % greater than that of the $\triangle t = 450$ s storm. The largest increases in the convective rain and decreases in the large-scale rain occur during the intensification of the storm (as seen in Figure 4). This contributes to the decreased maximum intensity of the $\triangle t = 1800$ s tropical cyclone since the large-scale condensation scheme, which is more efficient at converting excess atmospheric water vapor to latent heat in the core of the tropical cyclone, is contributing less to the thermodynamics of the storm. In addition, the total precipitation rate is reduced by an average of 0.22 mm h^{-1} from days 2–10 for the $\triangle t = 1800$ s case when compared with the default, furthering the indication that the decrease in intensity is due to a reduction in latent heating during intensification. Consistent with the intensity metrics in Figure 4, there are slight differences in the evolution of the precipitation rates for the $\triangle t = 900$ s simulation, but they are not significantly different from the default simulation (especially during intensification). This is an important finding as the model and parameterizations were originally designed to use $\triangle t = 1800$ s, indicating that the deep convection scheme is not performing adequately at smaller physics time steps. While it is possible that modifying $\triangle t$ impacts other physical parameterizations in CAM 5, the results presented here and in Williamson (2012) suggest that the interaction of the large-scale and convection schemes play a dominant role.

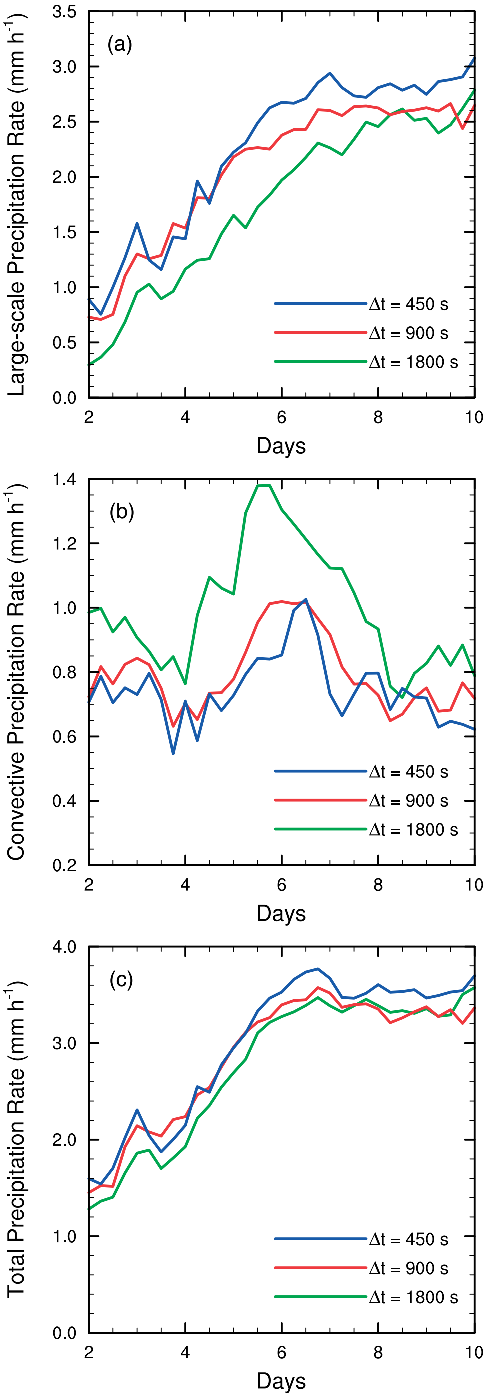

Figure 5. Time evolution of the area-averaged (a) large-scale, (b) convective and (c) total 6-h mean precipitation rates (mm h^{-1}) of the $\triangle t = 450$ s, $\triangle t = 900$ s and $\triangle t = 1800$ s simulations of CAM 5 SE at the horizontal resolution of $n_e = 120$.

3.3. Additional model design considerations

It is important to note that there may be other issues associated with the CAM 5 model design in the simulation of tropical cyclones. For example, there are known problems in the numerical simulation of the tropical cyclones with the turbulent exchange coefficients at high hurricane wind speeds (Braun and Tao, 2000; Davis *et al*., 2008; Hill and Lackmann, 2009a; Fierro *et al*., 2009). These studies are performed with limited area models at high horizontal grid spacings of 40 km and smaller. In such numerical studies it is possible for the exchange coefficients to become unrealistically large, contrary to observations (Powell *et al*., 2003; Black *et al*., 2007). An investigation of the surface sensible and latent heat fluxes (not shown) for the default CAM 5 SE $n_e = 120$ simulation indicates that the magnitude of the fluxes is similar to those shown in higher-resolution WRF studies (Hill and Lackmann, 2009b; Fierro *et al*., 2009) and satellite observations (Liu *et al*. 2011). However, there still may be resolution limitations, especially for the coarser grid spacings used in this study. Additional parameterizations, including convection and boundary layer schemes, are known to be important processes for tropical cyclone development (Braun and Tao, 2000; Smith, 2000; Hill and Lackmann, 2009a). Furthermore, other design choices not discussed in this paper, such as the vertical resolution of CAM 5, are likely to impact the simulation of tropical cyclones. A comprehensive investigation of the role of the individual parameterizations and vertical resolution on the evolution of tropical cyclones in CAM 5 SE will be a focus of future research.

4. Conclusion

An analytic tropical cyclone test case was implemented in order to understand the potential of the CAM 5 next-generation SE GCM to simulate tropical cyclones. CAM 5 SE was tested at its standard horizontal resolutions $n_e = 30$, 60 and 120, and in all cases a tropical cyclone developed during the 10-day idealized simulation. In general, the tropical cyclone becomes more compact, more intense and intensifies earlier with increasing resolution. In addition, as the resolution increases the ensemble spread, due to the initial-data uncertainty, increases and the onset of the spread occur earlier in the simulation. At the highest resolution, $n_e = 120$, the tropical cyclone becomes very strong, with minimum surface pressure in the range of 845–865 hPa. These very low pressures could be related to the dynamical SE component of the GCM, the interaction with the physics suite or the idealized nature of the simulations.

A sensitivity study at $n_e = 120$ in which the physics time step is increased by a factor of two and four provides more insight into the strong intensities of the simulated tropical cyclone. As the physics time step is lengthened to $\Delta t = 1800$ s the intensity of the storm is reduced, while the overall structure remains the same. This suggests that the interaction with the physics suite is contributing to the extreme intensities at the $n_e = 120$ resolution in a similar manner discussed in Williamson (2012). In particular, increases in the convective precipitation rate lead to reductions of the large-scale precipitation rate for the $\Delta t = 1800$ s simulation. Combined with an overall decrease in the total precipitation, there is a decrease in the release of latent heat, reducing the intensification and maximum intensity of the $\Delta t = 1800$ s storm. It is likely that full-decadal CAM 5 SE simulations would be sensitive to such model design choices (i.e. the inherent time scales in the physics parameterizations), leading to variations in tropical cyclone climatology depending on the choice of Δt. In addition, these model design choices may have broader implications and could significantly impact the simulation of other atmospheric phenomena, such as extratropical cyclones and frontal systems. The results caution against the use of physics time steps less than 1800 s in high-resolution versions of CAM 5 SE, as the built-in time scale formulation of the deep convection scheme appears to behave insufficiently.

As advances in computer architectures lead to new design choices, such as high-resolution quasi-uniform meshes, in the development of GCM dynamical cores it is important that these models be tested for their reliability in the simulation of smaller-scale atmospheric phenomena. The next-generation CAM 5 SE model has shown the ability to simulate tropical cyclones at high resolutions, yet it remains unclear how the physics parameterization suite will need to be designed for these new techniques. Much research needs to be done to ensure that future parameterizations (e.g. convection, boundary layer turbulence and surface fluxes) are not only modified for high-resolution GCMs, but are also built with consideration for simulating extreme events, such as tropical cyclones. Future work will investigate the ability of variable resolution meshes, including those with adaptive mesh refinement, in GCMs to simulate tropical cyclones. In addition, the sensitivity of the tropical cyclone simulations to the choice of physics–dynamics coupling will be explored.

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