Impact of Parameterized Physical Processes on Simulated Tropical Cyclone Characteristics in the Community Atmosphere Model

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ABSTRACT

This study advances the understanding of how parameterized physical processes affect the development of tropical cyclones (TCs) in the Community Atmosphere Model (CAM) using the Reed–Jablonowski TC test case. It examines the impact of changes in 24 parameters across multiple physical parameterization schemes that represent convection, turbulence, precipitation, and cloud processes. The one-at-a-time (OAT) sensitivity analysis method quantifies the relative influence of each parameter on TC simulations and identifies which parameters affect six different TC characteristics: intensity, precipitation, longwave cloud radiative forcing (LWCF), shortwave cloud radiative forcing (SWCF), cloud liquid water path (LWP), and ice water path (IWP). It is shown that TC intensity is mainly sensitive to the parcel fractional mass entrainment rate (dmpdz) in deep convection. A decrease in this parameter can lead to a change in simulated intensity from a tropical depression to a category-4 storm. Precipitation and SWCF are strongly affected by three parameters in deep convection: tau (time scale for consumption rate of convective available potential energy), dmpdz, and C0_ocn (precipitation coefficient). Changes in physical parameters generally do not affect LWCF much. In contrast, LWP and IWP are very sensitive to changes in C0_ocn. The changes can be as large as 10 (5) times the control mean value for LWP (IWP). Further examination of the response functions for the subset of most sensitive parameters reveals nonlinear relationships between parameters and most output variables, suggesting that linear perturbation analysis may produce misleading results when applied to strongly nonlinear systems.

1. Introduction

Since Manabe et al. (1970) first identified a tropical cyclone–like vortex in a global climate model, atmospheric general circulation models (AGCMs) have been increasingly used to simulate tropical cyclones (TCs) in the current climate state and to predict their changes under future climate scenarios (Bengtsson et al. 1982; Krishnamurti and Oosterhof 1989; Broccoli and Manabe 1990; Wu and Lau 1992; Haarsma et al. 1992; Bengtsson et al. 1995, 2007; Zhao et al. 2009; Zhao and Held 2010, 2012; Murakami et al. 2013; Zarzycki et al. 2014; Walsh et al. 2015). While most previous studies focus on the statistics of simulated TCs such as global (or basin wide) genesis density, track distribution, frequency, interannual variability, and so on, attention in recent decades has been placed on simulating and forecasting the properties (e.g., track, life cycle, intensity) of specific tropical cyclones in global climate models. For example, Shen et al. (2006) used a global mesoscale-resolving model to study simulations of Hurricane Katrina (2005). Zarzycki and Jablonowski (2015) successfully forecast the recurvature of Hurricane Sandy into the northeastern United States 60 h earlier than the Global Forecast System (GFS) model. Xiang et al. (2015) also studied the prediction of Hurricane Sandy and Supertyphoon Haiyan in the Geophysical Fluid Dynamics Laboratory (GFDL) coupled model, and they indicated the potential for extended-range predictions of TCs. These results, and the rapid advancement of computational resources and numerical algorithms, suggest a possible growing trend in the use of global climate models for simulating and forecasting specific hurricanes in the next few decades, like with extratropical cyclones today (Jung et al. 2006; Zheng et al. 2013).

A detailed understanding of how the choice of model components (e.g., grid resolution, physical parameterization, dynamical core, etc.) of AGCMs affects simulated tropical cyclone characteristics would foster the
advancement of such realistic TC simulation and prediction. However, systematic examination of model sensitivity to changes in model components would require thousands of simulations. Because of the inherent complexity of model construction and the coexistence of various climate and weather systems in model output, using a full model to compute sensitivity is not feasible. Moreover, the compensating and interactive effect among various components in global climate models makes it difficult to study the effect of an isolated factor on targeted objects. The Reed–Jablonowski TC test case (Reed and Jablonowski 2011a) is specifically designed for this purpose and has the advantage of quickly identifying the key factors from the model constructions and ruling out those factors that exert little influence on simulated TCs. Moreover, use of a system in which there exists only a single TC allows us to isolate storm sensitivity to parameters from changes in the environment or the influence of the surface or other dynamical systems. Reed and Jablonowski (2011a,b,c, 2012) have successfully used this case to reveal the impact of grid resolution, dynamical cores, and physical parameterization packages on the development of tropical cyclones. However, the impact of detailed parameterized physical processes within the physical schemes on simulated TC characteristics remains unclear.

The inherently multiscale nature of TCs, as well as the necessity to parameterize most key TC processes (e.g., convection, cloud formation and precipitation), indicates that the development of TCs in AGCMs is likely sensitive to the details of the physical parameterizations that govern clouds, convection, turbulence, etc. TCs are inherently multiscale systems, with key processes that range from microscale to synoptic, including individual convective updrafts, cloud microphysics, precipitation, turbulent mixing, surface momentum transfer, etc. (Emanuel 1986; Rotunno and Emanuel 1987; Houze 2014). The representation of these processes in numerical models plays an important role in accurately simulating the various aspects of tropical cyclones including cyclogenesis, intensification, track, structure, intensity, rainfall, cloud distribution, etc. (Chan 1984; Lord et al. 1984; McFarquhar and Black 2004; Fovell et al. 2009; Torn and Davis 2012; Bassil 2014; Goswami and Mohapatra 2014; Sanger et al. 2014; Sun et al. 2014; Wang 2014). Computational considerations (e.g., global domain and long integration times) require AGCMs to be run on grids that are too coarse to explicitly represent moist convective processes that govern TC evolution. The effects of subgrid-scale processes on the grid box mean state are represented via parameterization (Jakob and Miller 2003; Stensrud 2007), which relates the aggregate effects of small-scale processes to grid-scale model state variables. It means that only simplified physical processes are retained in AGCMs.

Furthermore, recent studies that mainly focus on the simulated or predicted statistics of TCs (Murakami et al. 2012a; Zhao et al. 2012; Kim et al. 2012; Zadra et al. 2014; Lim et al. 2015) in a global climate model confirm the importance of the individual parameterized physical process on TC simulation in global climate models. For example, Zhao et al. (2012) show that the simulated global number of TCs exhibits a nonintuitive response to incremental changes of the horizontal cumulus mixing rate. The inherent nature of TCs, the parameterization technique and previous literature all suggest the necessity to study the impact of numerous parameterized physical processes on the development of a single tropical cyclone–like vortex in global climate models, which is the goal of this study.

In addition to the TC intensity, we are also interested in the impact of numerous parameterized physical processes on simulated TC precipitation rate, longwave cloud radiative forcing (LWCF), shortwave cloud radiative forcing (SWCF), cloud liquid water path (LWP) and ice water path (IWP). The additional five physical characteristics are selected for two reasons: 1) they directly govern the properties of clouds and precipitation that are not explicitly resolved and rely on parameterization techniques, and 2) cloud and precipitation are essential components in a single TC system. The full set of Community Atmosphere Model (CAM) physical parameterizations are used so that the results are applicable to the Community Earth System Model (CESM) model. We will examine the impact of various parameterized processes across the majority of physical parameterization schemes in an AGCM, including representations of shallow convection, deep convection, moist turbulence, cloud microphysics, cloud macrophysics, and aerosol effect on TC simulations.

In summary, our goal is to examine the impact of various parameterized physical processes on the simulated TC characteristics during the evolution from an initial vortex seed to a mature TC-like vortex in AGCMs. Specifically, we would like to 1) identify the key physical parameters to the six different TC characteristics and rule out the minor parameters and 2) assess the functional form of the parameter-state dependence. This study contributes to a better understanding of how the design of the physical parameterization affects a specific dynamical system. It could help to instruct the simulation and short-term prediction of a particular TC in AGCMs. Beyond that, our results will have implications for the study of TC statistics in global climate models. Recent studies have confirmed the importance of physical parameters on the simulation and prediction
of TC statistics in AGCMs, but they only examined one or two parameters. They do not extend similar examination to other parameters. Thus, our study could serve as a reference to such future studies. It is also a necessary precursor to a more extensive multivariate sensitivity analysis, the results of which will be reported in a future study. The paper is organized as follows. Section 2 describes the TC test case. Section 3 introduces the simulation design. Section 4 presents the results. Section 5 summarizes the conclusions and discusses future work.

2. Reed–Jablonowski tropical cyclone test case

The Reed–Jablonowski tropical cyclone test case (Reed and Jablonowski 2011a) is illustrated in the National Center for Atmospheric Research (NCAR)–Department of Energy (DOE) CAM version 5.1.1 in our study. It is a well-tested tool that has been used to evaluate how the choice of model configuration (e.g., model resolution, dynamical core, physical parameterizations) affects the simulation and representation of tropical cyclones in AGCMs. Figure 1 gives a depiction of how it works. It is a special type of idealized initial condition defined in analytic form and consists of a warm-core vortex seed embedded in a quiescent global environment. Figures 1a and 1d show the structure of the vortex seed. Both the vortex seed and environment are three-dimensional with the former constructed to adhere to gradient wind balance and hydrostatic balance. The setup utilizes an aquaplanet with a sea surface temperature set to a constant 29°C everywhere. When initialized with this balanced state and integrated for 10 days, the model produces a tropical cyclone–like vortex. Figures 1b and 1e show the intensification stage after 5 days of integration of the initial vortex seed in CAM 5.1.1. Figures 1c and 1f show the vortex at day 10. It mimics the process of developing a preexisting vortex seed into a storm-like vortex in an AGCM over a short time period. The TC test case, and others like it, can reveal how realistically a particular model configuration simulates a single type of weather system. In practice, this is typically done by varying a part of the model (e.g., vertical resolution) and comparing the output with a control run. Our control run utilizes the configuration defined in Reed and Jablonowski (2011a).

The test case concept has been demonstrated to be successful in evaluating TC simulations (Reed and Jablonowski 2011a,b,c) and has also been applied in tests of other dynamical systems (e.g., baroclinic waves; Polvani et al. 2004; Jablonowski and Williamson 2006). The use of test cases for model evaluation and intercomparison has the advantage of being computationally efficient. In this study, we use the TC test case to evaluate the effect of parameterized processes on TC development in NCAR–DOE Community Atmosphere Model version 5.1.1 (CAM5) (Neale et al. 2010). The model physical parameterization suite is paired with the default finite volume (FV) dynamical core. The horizontal model resolution is
physical parameter, with all other parameters set to their default values. The initial condition that defines the tropical cyclone test case is the same in all simulations, and is consistent with the case represented by Reed and Jablonowski (2011a). One-at-a-time parameter perturbation design results in \( 24 \times 3 + 1 = 73 \) simulations in total. An additional 19 simulations were carried out to better sample the model response functions to key physical parameters. To evaluate the effect of internal model variability, additional four member perturbations runs are added to each case with slightly different initial conditions. Specifically, the location of initial vortex center is moved to the following four positions: \((9.5^\circ, 179.5^\circ), (9.5^\circ, 180.5^\circ), (10.5^\circ, 179.5^\circ), \) and \((10.5^\circ, 180.5^\circ)\).

The impact of parameterized physical processes is examined for six tropical cyclone characteristics at the mature stage of TC development. These are the day 9–10 time mean storm intensity (\(\text{m s}^{-1}\)), precipitation rate (\(\text{mm h}^{-1}\)), shortwave cloud radiative forcing (\(\text{W m}^{-2}\)) longwave cloud radiative forcing (\(\text{W m}^{-2}\)), cloud liquid water path (\(\text{g m}^{-2}\)) and cloud ice water path (\(\text{W m}^{-2}\)). The TC intensity is defined as the maximum wind speed at 100-m height above the surface (Reed and Jablonowski 2011a). The other five TC characteristics are directly output by the model and spatially distributed. To facilitate the comparison of the impact of parameterized processes, we measured them by computing area-weighted means over the tropical cyclone region. Detection of the tropical cyclone in the global field is straightforward in our case, as the output only contains one stormlike vortex. This is an additional advantage of an idealized test case framework.

We detect the tropical cyclone–like vortex via three simple steps: 1) find the minimum surface pressure, which is defined to be the storm center; 2) search the output field (e.g., precipitation rate) in a square latitude/ longitude region that spans \(\pm 20^\circ\) from the storm center; and 3) select those points that satisfy both of the two following criteria: (a) wind speed at 100-m height above surface greater than 6 \(\text{m s}^{-1}\) and (b) outgoing longwave radiation (OLR) less than 230 \(\text{W m}^{-2}\). Application of steps 1–3 results in a well-defined tropical cyclone, as illustrated in Fig. 2, which shows the simulated tropical cyclone characteristics in the control case. The wind, precipitation, LWCF, SWCF, and IWP fields all show the calm eye and spiral band features. The area-weighted
mean value of each quantity is computed from the ±20° region around the cyclone center.

4. Results

a. Impact of parameterized physical processes on simulated tropical cyclones

Parameterized physical processes, especially those associated with deep convection, contribute significantly to the simulation of TC characteristics in CAM 5.1.1 (Fig. 3). The specific parameterized process that has the greatest effect differs for the output metric of interest. Perturbation of one parameter at a time reveals that the simulation of TC intensity (Fig. 3a) is most sensitive to the parcel fractional mass entrainment rate (dmpdz), which denotes the strength of the mass exchange between the convective plume and environmental air. The range of TC intensities caused by the modification of this single process can be as large as 47.2 m s⁻¹, producing a...
change from a tropical depression to a category-4 tropical cyclone on the Saffir–Simpson scale. In contrast, perturbation of all other parameterized processes leads to a change of simulated TC intensity within $10.0 \text{ m s}^{-1}$, which is quantified as the absolute difference between maximum and minimum simulated TC intensity while perturbing the selected physical parameter throughout its range. The two parameters ($C_u$ and $C_d$) that control the upward and downward convective momentum transport have a small effect on the TC intensity. Reed and Jablonowski (2011b) show that the inclusion of the convective momentum transport process in CAM does not affect TC intensity much. Hogan and Pauley (2007) find that it can influence TC track.

The TC precipitation rate (Fig. 3b) is most sensitive to the time scale for consumption of the convective available potential energy ($\tau$), second most sensitive to parcel fractional mass entrainment rate ($\text{dmpdz}$), and third most sensitive to precipitation conversion efficiency ($C_0_{ocn}$). Yang et al. (2013) examined the tropical precipitation to several physical parameters in ZM deep convection scheme using CAM 5 and found that the simulated convective precipitation is most sensitive to $\tau$, $\text{dmpdz}$, and alfa (initial cloud downdraft mass flux). Alfa plays a relatively less important role in TC precipitation; instead, $C_0_{ocn}$ plays a relatively more important role in TC precipitation compared to tropical convective precipitation. Interestingly, the TC intensity is weakly influenced by changes in $\tau$ and $C_0_{ocn}$. This shows that one can change the $\tau$ and $C_0_{ocn}$ to tune the TC precipitation while leaving TC intensity unperturbed.

Generally, LWCF is not strongly affected by changes in the selected physical parameters (Fig. 3c). It is most
sensitive to the precipitation conversion efficiency (C0_ocn). The parameterized processes in cloud microphysics also play a considerable role in affecting TC LWCF simulation. For example, the threshold size separating cloud ice from snow (Dcs). This parameter controls the fraction of cloud ice that remains suspended versus falling to the surface. A larger threshold leaves more ice particles in upper tropospheric clouds, which leads to larger LWCF. The empirical fall speed parameter for ice (ai) and snow (as) also determines the value of simulated TC LWCF. Larger parameters indicate larger fall speeds and hence greater ice and snow particles settling and lower value of LWCF. The remaining physical parameters have minimal impact on LWCF. Yang et al. (2013) show that tropical mean (0–360°E, 30°S–30°N) LWCF is most sensitive to tau and dmpdz and has very minor sensitive to C0_ocn.

The TC SWCF (Fig. 3d) is most sensitive to the parcel fractional mass entrainment rate (dmpdz), which is also the parameter that most influences TC intensity. In addition to dmpdz, the simulated TC SWCF is sensitive to changes in C0_ocn and tau, and to lesser extent cldfrac_rhminl in the cloud macrophysics scheme. Changes in all other parameters cause minor changes in simulated TC SWCF. Yang et al. (2013) shows the tropical mean SWCF is most sensitive to C0_ocn and tau while it has minor sensitivities to dmpdz among the parameters in ZM scheme. In addition, Zhao (2014) revealed that both...
cumulus entrainment rate and convective microphysics can strongly affect SWCF, and through this impact cloud feedback and climate sensitivity.

While changes in deep convective precipitation efficiency (C0_ocn) have a minor influence on TC intensity, they cause significant uncertainty in TC LWP (Fig. 3e). The change can be as much as 10 times the control value. Perturbation of most parameters causes TC LWP to change considerably great. Only six physical parameters produce a weak impact on simulated TC LWP: Cu, Cd, rpen, as, wsubimax, and cldfrc_rhminl. Yang et al. (2013) shows that tropical mean IWP is most sensitive to C0_ocn and dmpdz.

The TC IWP (Fig. 3f) is also most sensitive to changes in the precipitation conversion efficiency over ocean (C0_ocn). The three most important physical parameters for IWP are C0_ocn, Des, and tau. In total, 12 physical parameters show considerable impact: C0_ocn, ke, dmpdz, tau, Cu, criq, kwp, Des, as,cdnl,eii, and wsubimin. The remaining 12 physical parameters show little impact on simulated TC IWP: alfa, capemt, Cd, rpen, rkm, aumax, ai, qcvar, wsubimax, a2l, cldfrc_rhminl, and cldfrc_rhminh. Yang et al. (2013) show that tropical mean LWP is most sensitive to C0_ocn and dmpdz.

The five-member ensemble simulations are conducted to quantify the internal noise of models. Solid blue lines show the mean values, and the dotted lines show the response function from each member. Overall, we see that cldfrc_rhminl plays a minor role in cloud properties (LWCF, SWCF, LWP and IWP) of tropical cyclones, Zhang et al. (2012) shows that smaller cldfrc_rhminl can lead to better simulation of both low clouds and high clouds in CAM 4. Their study also shows that smaller alfa result in a better simulation of high clouds.

b. Response function analysis

The above section has shown the relative influence of changes to a set of predefined physical parameters on TC simulation. We now quantify the response function of six simulated TC characteristics to changes in their most sensitive parameters by adding more sampling points. The resulting relationships are shown in Fig. 4. Figure 4a depicts changes in TC intensity resulting from changes in parcel fractional mass entrainment rate as it is varied between its minimum and maximum value. As the magnitude of dmpdz decreases, the TC intensity decreases from a category-4 tropical cyclone to a tropical depression. The response function shows that the uncertainty in simulated TC intensity from the internal model configuration can be large, and that tuning the physical parameters by perturbing them in small increments may yield misleading results.

Figure 4b quantifies the relationship between simulated TC precipitation rate and time scale of the consumption rate of CAPE (tau). As tau increases, the precipitation rate increases as well; however, the response function is nonmonotonic, exhibiting minor change beyond tau of $1.4 \times 10^5$ s$^{-1}$ and a subsequent increase above approximately $2.8 \times 10^5$ s$^{-1}$. Qian et al. (2015) shows that global mean precipitation does not respond linearly and monotonically to parameter change. Tau is the prescribed time scale that determines the rate of CAPE consumption, once moist convection has been initiated. Larger values of tau lead to longer prescribed time scales for CAPE consumption. This leads to weaker upward mass flux from the subcloud layer into the cloud [Eq. (A4)]. This indicates smaller entrainment from the environment and thus less dry air mix into the convective plume, which implies less moisture loss inside the cloud. Less moisture loss allows for a larger precipitation rate.

Figure 4c shows that the simulated TC LWCF decreases with larger precipitation conversion efficiency (C0_ocn), consistent with the fact that increased precipitation should result in less water arriving in the
upper troposphere and consequently less cirrus cloud. Figure 4d shows that the magnitude of SWCF decreases with increasing parcel fractional mass entrainment rate (dmpdz). This is consistent with the change of TC intensity. Increasing dmpdz leads to a more stable atmosphere, limiting the growth of deep convective clouds, and leading to smaller magnitude SWCF. The LWP (Fig. 4e) and IWP (Fig. 4f) decrease with increasing precipitation conversion efficiency (C0_ocn). When C0_ocn is in the range from 0.001 to 0.01 m$^{-1}$, the LWP and IWP drop exponentially. The value of C0_ocn determines the conversion from cloud liquid water to rainwater in the updraft. Larger C0_ocn means more cloud liquid water converted into rainwater and subsequent precipitation. This leads to smaller cloud LWP and IWP. Yamada and Satoh (2013) examined the response of TC associated LWP and LWP to global warming and show that tropical averaged LWP (IWP) is reduced by approximately 0.86% (2.76%). The significant sensitivity of TC LWP and IWP to C0_ocn suggests that parameterized physical process would exert great uncertainty on such problems.

c. Further exploration

Figure 3 clearly identifies the important physical parameters to the six different TC characteristics and rules out the minor ones. Figure 4 characterizes the response function between the six TC characteristics and their
most sensitive parameters. Building upon these results, it is worthwhile to highlight two additional points.

First, one single physical parameter can have different impact on the six TC characteristics. Figure 5 shows the uncertainty ratio, which is defined as the uncertainty range divided by the control value of the six TC characteristics to the same physical parameter in three cases. For example, Fig. 5a shows that while C0_ocn causes significantly large uncertainty of LWP (≈1000%) and IWP (≈400%), it causes much smaller uncertainty of TC intensity, precipitation rate, and SWCF. This implies that it may be useful in modifying the LWP and IWP fields but is not as important to other fields, especially to TC intensity. The difference in sensitivity from one parameter can be further supported by parcel fractional mass entrainment rate (dmpdz) (Fig. 5b). It completely controls the TC intensity but has negligible effect on TC LWCF. Figure 5c also supports that an individual physical parameter can have different impact on different characteristics of simulated TCs.

Second, the maximum uncertainty ratio of the six TC characteristics is significantly different. The red bar in Fig. 5 marks out the largest uncertainty ratio for each characteristic. This ratio for LWCF is as small as 20%. However, the uncertainty ratio is significantly large for TC LWP and IWP. It is 40%–100% for TC intensity, precipitation rate, LWCF, and SWCF. However, it can be as large as 1000% for TC LWP and 500% for TC IWP (Fig. 5a). This shows that TC LWP and IWP are most affected by the physical parameters while LWCF is least...
controlled by them. The results also suggest that parameterizing the conversion from cloud liquid water to rainwater in the updraft of deep convection may be a source that causes the well-known uncertainty in cloud liquid and ice content in AGCMs.

5. Discussion and conclusions

This study shows how the parameterized physical processes in cloud formation, convective development, and moist turbulence impact the simulation of TC intensity, precipitation rate, LWCF, SWCF, LWP, and IWP during the evolution from an initial vortex seed to an established tropical cyclone–like vortex in the Community Atmosphere Model 5.1.1 using the Reed–Jablonowski TC test case. Different aspects of simulated TCs are most sensitive to different physical processes. The TC intensity and SWCF are most sensitive to the parcel fractional mass entrainment rate in deep convection. The TC precipitation rate is most sensitive to the time scale of consumption rate of CAPE. The LWCF, LWP, and IWP are most sensitive to the precipitation efficiency. The responses of simulated TC variables to changes in the most sensitive parameters are quantified, and it is notable that none of the model output variables exhibits a linear response to changes in parameter values. Many appear to be exponential, and one (the CAPE consumption rate versus precipitation rate) is nonmonotonic.

As the test case mimics the process of developing a preexisting vortex seed into a TC-like vortex in AGCMs, it is not possible to compare the simulated output with observations and thus we cannot directly determine which set of parameters leads to an improved simulation. For this reason, we do not conduct parameter optimization in this study. The 10-day integration time is long enough for parameterized physical processes to exert an influence on the evolution of the TC; however, it is not long enough for the climate state to respond to the change of physical parameters, which may alter the simulation of TCs. Nevertheless, the results presented here can help to instruct the configuration of full AGCMs when they are used to study either the statistics of global TCs or the properties of a single TC as in recent studies. It improves our understanding of how the model design of physical parameterizations affects the TC evolution. Note that all of the results presented here were produced using grid spacing of 0.5° × 0.5°. We have tested the sensitivity of simulated output to changes in the most sensitive parameters using simulations with a grid spacing of 0.25° × 0.25° and confirmed that the large uncertainty of simulated TCs due to parameter uncertainty is retained at finer resolution.

While we only explore the importance of parameterized processes on a TC simulation using a one-at-a-time sensitivity analysis method, our results show that improving TC simulation and prediction via parameter adjustment in AGCMs is promising. Even so, a given physical parameter that affects a particular aspect of a simulated TC may also exert a strong effect on another aspect. For example, the change of C0_ocn has a considerable effect on TC precipitation, SWCF, LWP and IWP, but to varying degrees. This indicates that if a change of C0_ocn improves the representation of TC precipitation, it may worsen the representation of LWP. Changes in some parameterized processes have little impact on all characteristics of simulated TC such as a2l (moist entrainment enhancement parameter). Whether this should naturally be the case, or whether it is simply a result of parameterization design, is not clear because of insufficient understanding of the impact of physical processes on TC evolution from observations or high-resolution modeling. Nevertheless, the current study sheds light on the following issues: 1) uncertainties in the set of sensitive parameters may be an important source of uncertainty in current simulation and future projections of simulated TCs in AGCMs, 2) it may be possible to improve the representation and forecasting of an individual TC in AGCMs using parameter estimation, and 3) nonlinear relationships between parameters and model output indicate that parameter estimation that employs linear perturbation methodologies may yield results that are incomplete and/or misleading.

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APPENDIX A

Physical Explanation of the 24 Selected Parameters in CAM 5.1.1

We examined 24 parameterized physical processes in five schemes: the Zhang–McFarlane (ZM) deep convection scheme (Zhang and McFarlane 1995; Richter and Rasch 2008), the University of Washington (UW)
shallow convection scheme (Bretherton et al. 2004; Park and Bretherton 2009), the UW moist turbulence scheme (Bretherton and Park 2009), the Morrison–Gettelman (MG) two-moment cloud microphysics parameterization (Morrison and Gettelman 2008; Gettelman et al. 2010), and the cloud macrophysics scheme (Neale et al. 2010). Among them, eight parameters are selected from the deep convection scheme, five parameters from the UW shallow convection scheme, eight parameters from the MG cloud microphysics scheme, one parameter from the UW moist turbulent scheme, and two from the cloud macrophysics. In this appendix, we document each parameter, noting the scheme in which it is contained, and explaining the associated physical process (es).

a. Deep convection scheme

In CAM5, the deep convection parameterization is based on the work of Zhang and McFarlane (1995) and modified with the addition of convective momentum transports by Richter and Rasch (2008) and a modified dilute plume calculation following Raymond and Blyth (1986, 1992). Eight tunable parameters are selected from this scheme. They are \( C_0_{\text{ocn}}, \text{ke}, \alpha, \text{dmpdz, tau, capelmt, momcu, and momcd.} \)

\( C_0_{\text{ocn}} \) (\( C_0_{\text{ocn}} \)): Deep convective precipitation efficiency over ocean.

This is the autoconversion coefficient over ocean in the CAM deep convection scheme, and determines the conversion from cloud liquid water to rainwater in the updraft. The conversion from cloud liquid water to rainwater (\( R_r \)) is represented by the empirical formulation of Lord et al. (1982):

\[
R_r = C_0 M_u l, \tag{A1}
\]

where \( M_u \) is the updraft mass flux, \( C_0 \) is the conversion coefficient, and \( l \) is the cloud water content.

\( \text{ke} (K_e) \): Tunable evaporation efficiency of precipitation.

An evaporation formula following Sundqvist (1988) has been employed to evaporate some precipitation directly to the grid-scale environment as it makes its way to the surface:

\[
E_k = K_e (1 - RH_k)R_k, \tag{A2}
\]

where \( R \) is the total precipitation flux at model layer \( k \), \( RH \) is the relative humidity of the environment, \( K_e \) is the evaporation efficiency, and \( E \) is the corresponding evaporation in that layer.

\( \alpha \) (\( \alpha \)): Maximum cloud downdraft mass flux fraction (fraction).

Convective-scale downdrafts are induced and fueled by the rainwater evaporation when there is precipitation produced in the updrafts. The strength of the downdraft flux is controlled by a proportionality factor \( \alpha \), which is derived based on the precipitation produced in the updrafts (PCP) and the evaporation in downdrafts (EVP), as shown:

\[
\alpha = \frac{\text{PCP}}{\text{PCP} + \text{EVP}}, \tag{A3}
\]

Such a relationship indicates that there is no downdraft if no precipitation is produced. It also ensures that evaporation in the downdraft does not exceed a fraction (\( \alpha_0 = 0.1 \)) of the total precipitation produced within the updrafts.

\( \text{dmpdz (PE}_{\text{ocn}} \) : Parcel fractional mass entrainment rate over ocean (aquaplanet setup in our simulations). It denotes the entrainment rate from environmental air to the convective plume.

\( \text{tau (}\tau\) \): CAPE consumption time scale. In the deep convective scheme, it is assumed that the moist convection occurs only when there is CAPE consumption.

\( \text{capelmt (CAPE}_{\text{0}) \) : Threshold value of CAPE for deep convection.}

The closure condition used in the ZM deep convection scheme is based on the concept that cumulus convection consumes the CAPE at a certain time rate. The cloud-base upward mass flux (\( M_b \)) is calculated as shown by

\[
M_b = \frac{\text{CAPE} - \text{CAPE}_{\text{0}}}{\tau F}, \tag{A4}
\]

where \( F \) is the CAPE consumption rate per unit updraft mass flux at the cloud base, CAPE\(_{\text{0}}\) is the threshold for deep convection, and \( \tau \) is a prescribed time scale during which CAPE in excess of CAPE\(_{\text{0}}\) is consumed by convection.

\( \text{momcu (}\text{Cu}\) \): coefficient controls the updraft convective momentum transport (CMT).

\( \text{momcd (}\text{Cd}\) \): coefficient controls the downdraft CMT. Richter and Rasch (2008) first incorporate momentum transport in convection scheme and they found that convective momentum transport changes the Coriolis torque and thus affect tropospheric climate. The CMT is represented following (Gregory et al. 1997) as

\[
P^u_G = -C_u M_u \frac{\partial P}{\partial p}, \tag{A5}
\]

\[
P^d_G = -C_d M_d \frac{\partial P}{\partial p}, \tag{A6}
\]

where \( C_u \) and \( C_d \) are tunable parameters. The values of \( C_u \) and \( C_d \) control the strength of updraft and downdraft convective momentum transport respectively. As these coefficients increase, so do the pressure gradient terms,
and convective momentum transport decreases. The addition of the pressure gradient term reduces the difference between in-cloud and environmental velocities, hence reducing the vertical momentum transport.

b. University of Washington shallow convection scheme

UWShCu$_{r_{\text{pen}}}$ ($r_{\text{pen}}$): Penetrative entrainment efficiency. This parameter regulates the ratio of penetrative entrained air mass to the air mass detrained from cumulus updrafts in the overshooting zone above the level of neutral buoyancy (LNB).

The rate of lateral mixing in the overshooting zone is specified as

$$
\varepsilon_i = r_{\text{pen}}\varepsilon_0, \quad (A7)
$$

where $\varepsilon_0$ is the fractional mixing rate; $r_{\text{pen}}$ = 10.0 is an empirical penetrative mixing enhancement factor parameter that crudely accounts for differences between penetrative and lateral mixing and is chosen to optimize the model simulation of the stratocumulus to trade cumulus transition.

cric (q$_{c,\text{max}}$): Maximum cumulus updraft condensate.

A crude precipitation sink for the updraft total water, which removes all updraft cloud water in excess of an arbitrary critical value q$_{c,\text{max}}$ = 1 g kg$^{-1}$ and increases the updraft liquid water potential temperature accordingly. If the cloud condensate mixing ratio exceeds q$_{c,\text{max}}$, all the excessive condensate is converted into precipitation.

kevp ($K_e$): evaporative efficiency.

UWShCu treats evaporation of convective precipitation above cloud base, as in ZM deep convection scheme, which relates the vertical profile of rain evaporation rate $E$ (s$^{-2}$) to the vertical profiles of grid-mean relative humidity RH and the precipitation flux $R$ (kg m$^{-2}$ s$^{-1}$):

$$
E = K_e(1 - RH)R^{1/2},
$$

$$
K_e = 0.2 \times 10^{-5}[(\text{kg m}^{-2} \text{s}^{-1})^{-1/2} \text{s}^{-1}] . \quad (A8)
$$

Comparison of vertical profiles of precipitation flux with large-eddy simulations (LES) based on an ongoing Global Cloud System Study (GCSS) precipitating trade cumulus case suggests that the coefficient $K_e$ used in the deep convection scheme is also adequate for shallow cumulus.

rkm (c): Determine the amount of air that is involved in buoyancy-sorting $c$ = 8.0 for which the cumulus layer was only 1.5 km deep.

By decreasing $c$, one can make UWShCu resemble a deep convection scheme. To avoid competition between UWShCu and a separate deep convection scheme, it is therefore advisable not decrease $c$ below 4.

aumax ($a_{u,\text{max}}$): Maximum core updraft fraction.

In UWShCu, the shallow cumulus core updraft fraction is not allowed to exceed $a_{u,\text{max}}$ = 0.1 at any level. Since cumulus updraft fractional area is about twice of the core updraft fractional area, cumulus updraft fractional area should not exceed 0.2 by this constraint. Range is 0.05–0.15. If the cumulus core updraft fraction exceeds 0.15, the convection is arguably better represented as a stratocumulus layer and should be handled by the moist turbulence scheme.

c. Morrison–Gettelman two-moment cloud microphysics

Des ($D_\text{cs}$): The threshold size separating cloud ice from snow. This parameter works in conversion of cloud ice to snow. When the size of cloud ice is greater than $D_\text{cs}$, it is then treated as snow.

ai ($a_i$): Empirical fall-speed parameter for cloud ice. It determines the cloud ice particle terminal fall speed. Larger ai leads to larger ice particle terminal fall speed.

$$
V_i = a_iD_i^b \quad (A9)
$$

as ($a_s$): Empirical fall-speed parameter for snow. It determines snow terminal fall speed. Larger as leads to larger snow terminal fall speed.

$$
V_s = a_sD_s^b \quad (A10)
$$

cdnl: Cloud droplet number limiter. This is the maximum number of cloud droplets allowed in the model domain. It is a prognosed variable.

eii: Collection efficiency aggregation ice. Snow is accreted from cloud ice particle via continuous collection. This is the collection efficiency for collisions between cloud ice and snow. Larger eii means that cloud ice particle has larger chance to form snow when they are collided.

$
\text{qvar (v): Inverse relative variance of subgrid cloud water. In the MG two-moment cloud microphysics, the probability density function (PDF) of in-cloud cloud water follows a gamma distribution function. This is the parameter in the PDF function. Larger qvar typically comes with smaller autoconversion rate, immersion freezing, and rain accretion.}

wsbimin: Maximum subgrid vertical velocity for ice nucleation. It is a critical vertical velocity for ice nucleation.

wsbilmn: Minimum subgrid vertical velocity for liquid nucleation. It is a critical vertical velocity for liquid nucleation.
d. University of Washington moist turbulence scheme

Only one parameter is tunable in this scheme. 

\(a_2l\): moist entrainment enhancement parameter. It is relevant to entrainment efficiency, which is affected by mixtures of cloud-top and above-inversion air. At the convective layer (CL) top, the cooling promotes the sinking of mixtures into the CL, enhancing entrainment. At the base, the cooled mixtures tend to sink away from the CL, so entrainment is not enhanced. In other words, if \(a_2l\) is larger, the entrainment is better enhanced.

e. Cloud macrophysics

In cloud macrophysics, stratus cloud fraction is parameterized as a sum of relative humidity (RH)-based and stability-based cloud fractions. The RH-based stratus fraction is a quadratic function of grid-mean RH.

cldfrc_rhminh: Minimum relative humidity for high stable clouds.

In CAM5, the liquid stratus fraction is a function of grid-mean RH over water. Only when this RH is larger than the critical RH (cldfrc_rhminh), high stable liquid stratus (above 400 hPa) is formed. The cldfrc_rhminh is externally specified and used as a tuning parameter.

cldfrc_rhminl: Minimum relative humidity for low stable clouds.

Similar to cldfrc_rhminh, however, it is the critical relative humidity for low stable clouds (below 700 hPa).

APPENDIX B

Examples of Extreme Output Fields

Spatial patterns of the output fields in the extreme cases are shown in Figure B1.


