Global Radiative–Convective Equilibrium in the Community Atmosphere Model, Version 5

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ABSTRACT

In the continued effort to understand the climate system and improve its representation in atmospheric general circulation models (AGCMs), it is crucial to develop reduced-complexity frameworks to evaluate these models. This is especially true as the AGCM community advances toward high horizontal resolutions (i.e., grid spacing less than 50 km), which will require interpreting and improving the performance of many model components. A simplified global radiative–convective equilibrium (RCE) configuration is proposed to explore the implication of horizontal resolution on equilibrium climate. RCE is the statistical equilibrium in which the radiative cooling of the atmosphere is balanced by heating due to convection.

In this work, the Community Atmosphere Model, version 5 (CAM5), is configured in RCE to better understand tropical climate and extremes. The RCE setup consists of an ocean-covered Earth with diurnally varying, spatially uniform insolation and no rotation effects. CAM5 is run at two horizontal resolutions: a standard resolution of approximately 100-km grid spacing and a high resolution of approximately 25-km spacing. Surface temperature effects are considered by comparing simulations using fixed, uniform sea surface temperature with simulations using an interactive slab-ocean model. The various CAM5 configurations provide useful insights into the simulation of tropical climate as well as the model’s ability to simulate extreme precipitation events. In particular, the manner in which convection organizes is shown to be dependent on model resolution and the surface configuration (including surface temperature), as evident by differences in cloud structure, circulation, and precipitation intensity.

1. Introduction

In an age of increasing computer power, so too comes the capability of routinely running atmospheric general circulation models (AGCMs) at increasingly high horizontal resolutions (i.e., grid spacing less than 50 km). Moving to such resolutions requires understanding, and likely improving, the performance of many components of these AGCMs, such as parameterizations of subgrid-scale physics and the interaction of physics and dynamics. Of particular interest is the role of convective parameterizations at these spatial scales and their impact on tropical dynamics and precipitation processes.

An emerging literature shows a widespread, largely unorganized, effort to develop methods for evaluating and improving high-resolution climate models (e.g., Tomita et al. 2008; Delworth et al. 2012; Jung et al. 2012; Bacmeister et al. 2014; Demory et al. 2014; Wehner et al. 2014). Idealized frameworks can be used to investigate how model assumptions impact behavior across scales. In this paper, we utilize a simplified global radiative–convective equilibrium (RCE) configuration to explore the implication of experimental design choices, mainly horizontal resolution, on equilibrium climate.

RCE is the statistical equilibrium in which the radiative cooling of the atmosphere is balanced by heating due to convection. The study of RCE has a fundamental place in our understanding of complex mechanisms in the earth system. In particular, RCE provides the basis for our understanding of Earth’s tropical climate. Early studies by Manabe and Strickler (1964) and Manabe and Wetherald (1967) developed a basic understanding for the connection between surface temperature and radiative forcing, forming the basis of what we refer to as RCE.
These studies demonstrated that Earth’s atmosphere can be approximated by RCE and they increased our understanding of climate sensitivity and the role of greenhouse gases. An overview of early radiative–convective modeling in this context can be found in the review by Ramanathan and Coakley (1978).

The idea that the basic state of the tropical atmosphere can, to a large extent, be explained by RCE has been foundational in the study of the tropics. RCE modeling has evolved greatly from the early one-dimensional models to more complex cloud-resolving models. Two-dimensional cloud-resolving models, such as Held et al. (1993), demonstrated that explicit representation of convective scales can eliminate many of the limitations inherent to parameterizing clouds and moist physics. In recent years a wide variety of studies in the context of RCE have been used to further our understanding of complex processes in the earth system (Romps 2011; Muller et al. 2011; Muller and Held 2012; Emanuel et al. 2014; Wing and Emanuel 2014; Khairoutdinov and Yang 2013). It is important to note that some of these studies have chosen to fix sea surface temperatures (SSTs) as opposed to treating the lower boundary condition as interactive. The choice of the surface boundary condition is understood to have implications for the resulting equilibrium and the time required to achieve RCE in modeling studies (Cronin and Emanuel 2013).

In this study, RCE is investigated using the joint National Center for Atmospheric Research (NCAR) and Department of Energy Community Atmosphere Model, version 5.3 (CAM5). CAM5, documented in Neale et al. (2012), is a complete AGCM within the Community Earth System Model (CESM), which is routinely used for present-day and future climate simulations. The RCE setup consists of an ocean-covered Earth with diurnally varying, spatially uniform insolation with no rotation effects. CAM5 is run with the spectral element dynamics package at two horizontal resolutions: a standard resolution of approximately 100-km grid spacing and a high resolution of approximately 25-km grid spacing. The model is configured with either globally fixed, uniform SST or an interactive slab-ocean model for the surface condition. This study was motivated by the novel work of Popke et al. (2013), which investigated RCE using a different comprehensive AGCM, ECHAM6, coupled to a uniform mixed-layer ocean at a horizontal resolution of approximately 210 km. Held et al. (2007) offers a similar model setup, using Geophysical Fluid Dynamics Laboratory (GFDL) AGCM column physics in a large-domain Cartesian geometry model with prescribed SSTs at two horizontal resolutions of approximately 220 and 110 km. Such a setup with fixed SSTs is analogous to cloud-resolving model configurations. It should be noted that while the AGCM RCE setup has some similarities to the frequently used aquaplanet setup (Neale and Hoskins 2000), the resulting circulations and dynamics are very different owing to the lack of planetary rotation and latitudinal temperature gradients.

There are two main objectives of this study. First, we describe the characteristics of the RCE climate in CAM5 and the reliability of the RCE framework as a tool for model development. This also offers the capability to compare the differences in the simulated climate between the fixed-SST and interactive slab-ocean setups using the same AGCM. The CAM5 RCE simulations are also compared to similar larger-domain RCE studies (Popke et al. 2013; Held et al. 2007). The second objective is to study the impact of horizontal model resolution on the resulting RCE climate. In this context, this study suggests that the RCE configuration fills a gap in GCM development, offering a link to high-resolution modeling within the framework of an earth system model. Hence, this study contributes to the continued effort to identify methods to rationalize robust behaviors of the earth system through more simplified approaches to climate modeling and GCM development (Held 2005; Held et al. 2007; Medeiros et al. 2008; Reed and Jablonowski 2011, 2012; Popke et al. 2013; Medeiros et al. 2014).

This paper is organized as follows. Section 2 provides a brief description of CAM5, as well as an explanation of the experimental setup. The results are presented in section 3, including explorations of RCE structure, mean climate, circulations, and precipitation extremes. Section 4 provides some conclusions of the analysis of the global RCE context in CAM5, as well as discussion of the implications of the work and its usefulness to the AGCM community in general.

2. Experimental design

a. Model description

The model used for this study is CAM5 in combination with the spectral element dynamics package implemented on a cubed–sphere grid. The dynamical core design is documented in Taylor and Fournier (2010) and Dennis et al. (2012). The spectral element package makes use of a continuous Galerkin method in the horizontal directions and for a fourth-order accurate horizontal discretization it utilizes polynomials of degree 3. Included in the spectral element package is a horizontal diffusion scheme built on fourth-order hyperdiffusion with an additional second-order dissipation near the model top.

The CAM5 physics package contains deep (Zhang and McFarlane 1995) and shallow convective (Park and
Bretherton (2009) parameterizations, as well as a moist boundary layer turbulence scheme (Bretherton and Park 2009). The deep convective parameterization includes a dilute entraining plume (Neale et al. 2008) and convective momentum transport (Richter and Rasch 2008). These are in addition to the parameterizations of cloud microphysics, cloud macrophysics, surface exchange, and parameterizations of shortwave and longwave radiation described in detail in Neale et al. (2012). All simulations are based on an identical physics tuning parameter set from CAM5 climate simulations at a resolution of approximately 100 km. The variant of CAM5 employed here is a configuration (version 5.3) released in December 2013 as part of CESM1.2.1 (available at http://www.cesm.ucar.edu/models/cesm1.2/).

b. Experimental setup

For this study the model is configured in a manner similar to the aquaplanet setup proposed by Neale and Hoskins (2000) but with three main modifications to the insolation, sea surface temperatures, and rotation effects. In particular, to mimic Popke et al. (2013), the insolation is set to be diurnally varying, spatially uniform, and when averaged over the diurnal cycle it has a value of about 340 W m\(^{-2}\), which is approximately equal to the observed global annual-mean insolation. The planet’s rotational rate is set to zero to follow cloud-resolving model configurations of similar nature. Finally, the lower boundary condition of the aquaplanet has two configurations: a globally constant SST of 29°C or an interactive slab-ocean model (SOM) with a uniform depth of 50 m (Bitz et al. 2012). In addition to these three main adjustments, a uniform equatorial ozone vertical profile is used and direct and indirect effects of aerosols are removed by excluding aerosol from the radiative transfer calculation (direct) and fixing the cloud droplet number concentration to 1.0 \(\times\) 10\(^8\) m\(^{-3}\) (indirect). In the default mode, CAM5 utilizes prognostic aerosols, but, for the present idealized study, removing aerosol effects was deemed an attractive alternative that avoids the ambiguity of assigning aerosol emissions in this idealized configuration. Similar to Popke et al. (2013), the surface albedo is given a fixed value of 0.07.

For this study the model is run at two horizontal resolutions, ne30 (~100-km grid spacing) and ne120 (~25-km grid spacing), where “ne” represents the number of elements. The former represents a standard resolution used in CAM5 for climate simulations in the nature of the Coupled Model Intercomparison Project, phase 5 (CMIP5), and the latter represents a next-generation resolution anticipated to be used operationally in the coming decade. When combined with the two different lower boundary conditions described in the previous paragraph, a total of four simulations will be utilized in this study. The simulation length varies depending on the experiment. For the prescribed SST simulations, at both resolutions, the model is integrated for 6 years. The first year of each prescribed SST simulation is disregarded to allow ample time for model spinup and these simulations will be labeled as ne30 and ne120. When using the SOM setup the model is integrated for 11 years, as a much longer model spinup (~6 years) is required for the slab-ocean temperature to equilibrate from an initial global constant of 29°C. The spinup is discussed in more detail in section 3b. The runs with the SOM will be referred to as ne30_SOM and ne120_SOM. In all cases, the last 5 years of the simulation are used for analysis.

3. Results and analysis

In this section we investigate the structures, circulations, extremes, and some aspects of the mean climate in the RCE world simulations. In particular, we study the impact of increasing horizontal resolution from the standard resolution to the next-generation high resolution. Furthermore, we review the influence of the surface boundary condition (i.e., prescribed SST and interactive slab ocean) on the RCE climate in CAM5. The analysis sheds light on the sensitivity of the physics parameterizations to resolution and usefulness of the idealized RCE test bed as a tool for model development.

a. Structure

As mentioned in section 1, this study was in part motivated by the recent work of Popke et al. (2013), which was the first of its kind to study RCE in a comprehensive AGCM. Previous to their analysis, there was little understanding of the behavior of RCE in this context. In the same spirit as Popke et al. (2013), we first seek to develop a feel for the types of structures and circulations that develop in CAM5. Figure 1 shows the monthly-averaged cloud cover and near-surface wind vectors (left column) and total precipitation (right column) for a randomly selected month and for each of the four simulations in this study. From Fig. 1, it is evident that in all simulations the convection has organized into clusters with the appropriate circulation. In general, areas of high cloud fraction correspond with areas of precipitation and low-level convergence, as seen in the near-surface winds. These convective clusters are surrounded by large areas of subsidence in which the cloud cover and precipitation is low in the presence of low-level divergence.

When comparing the four experiments in Fig. 1 it is clear that the structure and circulation vary greatly among the simulations. The most striking example of
This variance is the comparison of the different resolutions in the prescribed SST case (top two rows of Fig. 1). At the ne30 resolution, there is one dominant convective cluster within the entire global domain that meanders slowly around the globe (shown later). The rest of the global domain is dominated by convergence toward the main cluster. In general, the globe is covered by clouds and light precipitation. The existence of a single cluster in the RCE context is not novel and it has been shown in other RCE studies (e.g., Bretherton et al. 2005; Wing and Emanuel 2014), albeit at cloud-resolving resolutions. As the resolution is increased to ne120 the structure becomes finer and the convection has arranged into ribbons of intense precipitation and convergence. In between the areas of convection are distinctive regions of subsidence with very little cloud fraction and no precipitation. The sharp boundary in the monthly average between the regions of precipitation and the regions dominated by subsidence indicates that these convective structures are relatively long-lived. Not only has the structure changed with resolution, but the intensity of convection has also increased at the higher resolution. This can be seen qualitatively from the increase in the magnitude of the monthly-averaged precipitation and the length of the wind vectors indicating strong divergent and convergent circulations among the convective clusters.

The addition of an interactive surface temperature, in this study the SOM, has a profound impact on the...
structure and circulations in the RCE world. This can be seen by comparing the top two rows with the bottom two rows in Fig. 1. The most noticeable difference, when comparing at a given resolution, is that the interactive surface in the SOM experiments leads to break up the convective clusters allowing for more spatial variability. For example, the single dominant convective cluster that was apparent in the ne30 simulation with the prescribed SST (top row) is no longer in existence in the SOM experiment (third row). Instead, the globe is now covered by numerous convective clusters that are slightly weaker, as evident by the reduced cloud fraction and precipitation rates. Qualitatively, the same is true in the high-resolution case in that the horizontal scale of the convective clusters has decreased and there is less evidence of large-scale coherent structure. One potential explanation for this is the introduction of the interactive surface helps to break up the convective clusters through a negative feedback process in which the deep convection within the cluster produced an optically thick cloud shield, reducing the shortwave flux reaching the surface, which allows the surface temperature to cool and convection to wane. In addition, the surface temperature is allowed to evolve to a different, in this case colder, equilibrium temperature in the SOM configuration (discussed in section 3b), which is also expected to contribute to the difference in behavior of convection between the prescribed SST and SOM simulations (Wing and Emanuel 2014).

Given the different RCE behavior and precipitation intensities shown among the four configurations, Table 1 provides a quick look at the global-mean total precipitation averaged over the length of each simulation. The mean precipitation gives an impression of the intensity shown among the four configurations, Table 1 (Wing and Emanuel 2014). Additional discussion of the breakdown of the precipitation processes is provided in section 3d.

To understand further if the simulated RCE is behaving realistically, Fig. 3 shows the total kinetic energy (KE) as a function of the two-dimensional total spherical wavenumber for the four simulations at 850 hPa. Kinetic energy at a wavenumber is associated with the spherical harmonics of vorticity and divergence at that wavenumber. KE spectra provide an indication of the scale of motions present in the simulations. The KE spectra are in approximate agreement across the experiments for wavenumbers 10-40. There is disagreement in the spectra at the lowest wavenumbers (<10), but it is difficult to make any conclusions as the sample rate at these wavelengths is relatively small. At higher wavenumbers, the effects of truncation leading to differing slopes becomes obvious as the impact of resolution is noticeable with the ne120 simulations demonstrating the ability to resolve smaller-scale structures, as expected. At the highest-resolved scales for each resolution, the prescribed SST simulations consistently contain slightly more energy, indicating a systematic increase of energy at these scales. However, despite the significant differences

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Total precipitation (mm day(^{-1}))</th>
<th>Convective precipitation (mm day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ne30</td>
<td>4.0</td>
<td>3.8</td>
</tr>
<tr>
<td>ne120</td>
<td>4.8</td>
<td>2.4</td>
</tr>
<tr>
<td>ne30_SOM</td>
<td>4.0</td>
<td>3.8</td>
</tr>
<tr>
<td>ne120_SOM</td>
<td>3.6</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Fig. 2. Hovmöller diagram of 6-hourly instantaneous total precipitable water at the equator for each resolution and surface boundary condition (see labels) for the last 5 years of each simulation.
in the structure of the convective clusters with the two surface boundary conditions, the impact of the SOM on the KE spectra is small for a given resolution. This is to be expected as the surface conditions should have little impact on the scales that CAM5 can resolve. It should be noted, that the model KE spectra approximately yield a slope of $-5/3$ for the majority of spectra, which is consistent with observations (Nastrom and Gage 1985) for mesoscale dynamics and turbulence. In the absence of planetary rotation and land, the simulations lack large-amplitude planetary waves and therefore the characteristic $-3$ slope at low wavenumbers ($\leq 40$) seen in observations (Nastrom and Gage 1985) and typical global model simulations with rotation [e.g., the aquaplanet setup; Blackburn et al. (2013)].

b. Mean climate

Given that the model appears to be operating appropriately in RCE, we now focus on additional aspects of the mean equilibrium climate. Figure 4 shows the evolution of the globally averaged surface temperature for the two SOM experiments. As mentioned in section 2 the spinup for the SOM experiments is on the order of 6 years and the resulting surface temperature varies for the two resolutions used here. The ne30 simulation equilibrates to an average temperature of 26.4°C, while the high-resolution ne120 experiments reach a much colder temperature of 21.6°C. Both of these values are lower than the prescribed temperature of 29°C and their values are also indicated on the right axis of Fig. 4. Additional prescribed SST simulations using these colder average temperatures (see appendix) demonstrate that decreasing the fixed SST acts to substantially decrease convection and inhibit aggregation, resulting in a different RCE climate than in the SOM runs and suggesting that an interactive surface can play an important role in the convective behavior.

The pathway to equilibrium is different for the two SOM cases. The ne120_SOM experiment is strongly driven by the radiative imbalance inherited from the prescribed SST simulation (discussed in more detail in Table 2) and therefore rapidly cools in the first couple of years, but...
the radiative forcing on the ne30_SOM run is weaker, so there is a more secular trend in the first years of that simulations. Around year 5, an abrupt reorganization of the large-scale circulation occurs in the ne30_SOM simulation during which the global-mean surface temperature drops by about 2 K in less than 6 months. Investigating the transition (not shown) indicates that this abrupt change is associated with the breakdown of the single large convective cluster and the transition to the more filamentary structure shown in Fig. 1. We note that after this transition the variability of the global-mean surface temperature in the ne30_SOM simulation is larger than before the transition and larger than the equilibrated ne120_SOM simulation. Whether this indicates that the (relatively) disaggregated RCE state in ne30_SOM is unstable is not clear. The relative stability of the ne120_SOM equilibrium likely is connected with the cool surface temperature and weak circulation, but the lack of abrupt transitions of the state is also likely a result of the ne120 resolution being resistant to very large convective clusters (and therefore there are not abrupt transitions from that strongly aggregated state).

To help understand these differences, Table 2 provides some additional details of the radiative balance at equilibrium for each of the four experiments, including the globally averaged surface temperature, net shortwave and outgoing longwave radiation at the top of the model, and the shortwave and longwave cloud forcing. When comparing the shortwave and longwave radiation at the top of the model for each of the simulations there are some notable differences. For the interactive SOM experiments, the net shortwave radiation approximately balances the outgoing longwave radiation. This is to be expected as the surface temperature is meant to evolve to achieve equilibrium. However, in the prescribed SST experiments this is not necessarily the case. At ne30, the top of the model is in approximate radiative balance, but, at ne120, the model is far from radiative equilibrium. This is consistent with common knowledge that, in order to reach true RCE, an interactive surface temperature is required. It is important to note that it is commonplace to set up climate simulations following the Atmospheric Model Intercomparison Project (AMIP) protocols (Gates 1992; Gates et al. 1999) with prescribed observed SSTs. In addition, the modeling of RCE with prescribed SSTs is also prevalent in the cloud-resolving modeling community. This study offers the very useful ability to compare a fixed versus an interactive surface temperature in RCE using a comprehensive AGCM.

The imbalance in the prescribed RCE cases can provide insight into the RCE in the SOM cases. Focusing on the ne120 experiments, it is apparent that starting with a SST of 29°C (which is the fixed temperature in the prescribed case and the initial temperature in the SOM case) results in radiative imbalance at the top of the model. In particular, the outgoing longwave radiation is larger than the net shortwave radiation. As a result if the surface temperature is allowed to evolve, as in the case of ne120_SOM, one would expect that the temperature would decrease owing to excess loss of energy to space. This imbalance can in part be inferred from the structure seen in Fig. 1. Since the convective clusters are much finer in scale with distinct borders at ne120 compared to ne30, there exist large regions of virtually no clouds where radiation is lost to space. This can be seen in Table 2 where the longwave cloud forcing (LWCF) for the ne120 simulations is always less than that for the ne30 simulations. This is conceptually consistent with the work by Pierre-humbert (1995), which remarks that the subtropics act as radiator fins for the planet. In the global RCE context, the ribbons act like the intertropical convergence zone and the cloud-free areas are analogous to the subtropics. In this configuration with no rotation, the subtropic-like areas become even more crucial to radiative balance owing to the lack of baroclinicity in the extratropics, ultimately leading to a cooler surface temperature.

As mentioned, the globally averaged surface temperature for the SOM experiments is less than the surface temperature of 29°C used in the prescribed simulations. This is likely to impact the analysis presented in this study, as the behavior of convection has a clear link to surface temperature (Wing and Emanuel 2014). However, one of the goals of this study is to examine the effect of an interactive surface on the nature of RCE within CAM5 and the impact of horizontal resolution on this. In general, it appears that in a mean climate sense at ne30 the representation of RCE is
rather similar for both the prescribed SST and SOM experiments. However, at the high ne120 resolution, the model behaves rather differently in RCE owing to the impact of resolution on the structure and circulations of convection. In fact, it is clear that the ne120_SOM experiment accentuates the resolution dependencies of the CAM5 physics parameterizations.

c. Circulations

From the initial analysis in section 3a, it is seen that the convective clusters in the RCE simulations are relatively long lived, indicating that stable large-scale circulations have developed. The probability density function of the mass-weighted vertically averaged pressure velocity for each experiment is shown in Fig. 5. Analogous to Popke et al. (2013), the pressure velocity is the mass-weighted average from 925 to 200 hPa, though monthly means are used in this study. The use of monthly means acts to limit the variability in the pressure velocity leading to a narrowing of the distributions, but given the long-lived nature of the structures the CAM5 simulations it is believed that monthly averages are sufficient.

As inferred from section 3a, the four different RCE experiments have varying vertical velocity distributions. For all simulations the distributions are negatively skewed. From Fig. 5, it is seen that increased resolution acts to further skew the distribution with both surface boundary conditions. The ne30 prescribed SST experiment has the broadest distribution with the lowest peak in the distribution of about 15 hPa day⁻¹ and the distribution is the most similar to reanalysis and conventional GCM simulations (Medeiros and Stevens 2011). This structure is consistent with that seen in Fig. 1, where the single convective cluster is surrounded by global-scale subsidence. The ne120 prescribed-SST case has the narrowest distribution with a peak in the distribution at 28 hPa day⁻¹. At both resolutions, the addition of the interactive slab ocean further skews the distribution negatively, indicating that, while the coupling of the surface temperature increases spatial and temporal variability, it also acts to amplify the large-scale circulation, particularly the magnitude in areas of subsidence.

Table 3 provides some additional insight into the vertical velocity in the RCE context. As indicated in Fig. 5, the mean upward and downward vertical velocities increase with resolution, with the ne120 experiment producing the largest mean upward velocity. This increase in vertical velocities is a result of the smaller resolved scales at ne120 and the resulting convective structures. At a given resolution, the interactive surface

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TABLE 3. Mean pressure velocity properties of RCE in CAM5.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mean pressure velocity in subsidence regions (hPa day⁻¹)</th>
<th>Mean pressure velocity in upwelling regions (hPa day⁻¹)</th>
<th>Area fraction of subsidence (%)</th>
<th>Area fraction of upwelling (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ne30</td>
<td>14.7</td>
<td>-26.6</td>
<td>63.8</td>
<td>36.2</td>
</tr>
<tr>
<td>ne120</td>
<td>24.7</td>
<td>-53.9</td>
<td>67.9</td>
<td>32.1</td>
</tr>
<tr>
<td>ne30_SOM</td>
<td>21.4</td>
<td>-33.8</td>
<td>60.2</td>
<td>39.8</td>
</tr>
<tr>
<td>ne120_SOM</td>
<td>26.6</td>
<td>-52.0</td>
<td>66.0</td>
<td>34.0</td>
</tr>
</tbody>
</table>

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FIG. 5. Probability density function of the mass-weighted vertically averaged pressure velocity (represented as a monthly mean) for each experiment.
acts to increase the mean intensity of subsidence, again indicating that coupling the surface temperature increases larger-scale circulation. This result holds true even when the prescribed simulations are run with a surface temperature equal to the equilibrium temperature from the SOM runs (not shown), indicating that the increase in subsidence in the SOM simulation is not straightforwardly a result of the colder equilibrium temperature. The addition of the SOM also acts to decrease the area of subsidence, while increased resolution increases subsidence regions. Therefore, the ne120 simulation with the largest mean intensity of upwelling has the smallest regions of upwelling, consistent with the narrow negatively skewed distribution seen in Fig. 5.

The long-lived circulations allow for an investigation of the regime dependence of clouds between subsidence and upwelling regions in RCE. Figure 6 shows the differences between the vertical structure of potential temperature, relative humidity, cloud fraction, cloud liquid water, and cloud ice in areas of upwelling and subsidence. For the subsidence regime, the plot represents the mean of all monthly profiles in which the mass-weighted pressure velocity (described above) is greater than 0.0 hPa day$^{-1}$, with the opposite (less than 0.0 hPa day$^{-1}$) being true for the upwelling regime. The ne30 experiments with both surface boundary conditions have very similar structures for all variables in both regimes. The ne120 experiments differ when comparing among the prescribed SST and SOM cases, which is undoubtedly due to the reduction of the globally averaged surface temperature by over 7°C in the SOM simulation (see the potential temperature profiles). Nonetheless, the vertical structures in the ne120 cases are rather consistent when the temperature difference is taken into account (i.e., downward shifts in the relative humidity, cloud liquid, and cloud ice due to the lowering of the freezing level).

The similarity in vertical structure for resolution across the surface boundary conditions indicates that the physics parameterizations are behaving consistently for each given resolution. This allows for an investigation of the impact of resolution on the clouds and their regime.

**Fig. 6.** Dynamically sampled vertical profiles of mean potential temperature, relative humidity, cloud fraction, cloud liquid water, and cloud ice. The monthly-mean data are separated into regions of subsidence (i.e., mass-weighted pressure velocity greater than 0.0 hPa day$^{-1}$) and regions of upwelling (i.e., mass-weighted pressure velocity less than 0.0 hPa day$^{-1}$).
dependencies in the RCE context. As expected, in regions of subsidence all profiles, regardless of resolution, have similar structures. In general, the subsidence regions are cloud free and exhibit low levels of mid-troposphere relative humidities. In particular, the cloud fraction profiles in the subsidence regime compare well to what one would expect in trade wind regions in standard CAM5 climate simulations. However, there are small differences among the subsidence profiles that may indicate different model behavior. For example, the ne120 simulation produces lower relative humidities and cloud fractions above the cloud base and extending through the troposphere. This is consistent with the results in section 3a where the convection organized into long-lived narrow bands separated by very distinct cloud boundaries from areas of subsidence and no precipitation. This suggests, along with the vertical velocity distribution in Fig. 5, large-scale circulation in the ne120 simulation with prescribed SST is stronger than the other simulations.

Cloud properties within the upwelling regions in Fig. 6 show very clear resolution dependence. The most noticeable difference is that, for similar cloud fractions in the upwelling regime, the ne120 simulations always have large amounts of cloud liquid, suggesting that there is a strong dependence on the model grid spacing. In addition, the RH minima in the midtroposphere are more pronounced in the ne120 simulations and are associated with a decrease in cloud fraction at these heights. This suggests that there are relatively dry regions above the freezing level with no detrainment into them. This most certainly indicates that the shallow and deep convection schemes are behaving very differently at ne120 than at ne30. In particular, shallow convective mixing below the freezing level is more efficient at the ne120 resolution. This is linked to the change in the contribution of parameterized convection to the total precipitation, which is shown in section 3d to vary with resolution.

d. Precipitation extremes

One of the principal motives for advancing to higher-resolution AGCMs is the expectation to better simulate extreme events such as precipitation extremes. In this section we demonstrate the usefulness of the CAM5 RCE setup to investigate how simulated topical precipitation extremes change with increasing resolution. Figure 7 displays the probability density functions of the 6-hourly-averaged total precipitation (solid lines) and convective precipitation (dashed lines) for each simulation. The data are grouped in 3 mm day$^{-1}$ bins.

Figure 7 demonstrates that the ne120 prescribed experiment produces the most extreme precipitation rates, approaching events of 1000 mm day$^{-1}$ (solid line). This is nearly double the rate of the most extreme events in the ne30 prescribed experiment. At both resolutions, the reduction in equilibrium SST in the SOM simulations acts to reduce the extremes in total precipitation rates. It is interesting to note that prescribed simulations using the equilibrium temperature from the SOM cases (not shown) act to decrease the precipitation rates even further compared with the SOM simulations, indicating that the change in precipitation rates for the SOM simulations is not just a consequence of the reduced average temperature.

The contribution of convective precipitation to the extreme events sheds further light on the behavior of the convective parameterizations. In general, as resolution increases the contribution of the parameterized convection decreases. Figure 7 shows that, for the ne30 simulations, the parameterized convection is contributing to extreme rates above 200 mm day$^{-1}$. However, in the ne120 simulations, the parameterized convection appears to be bounded below 100 mm day$^{-1}$, suggesting that large-scale parameterization is dominating for all extreme precipitation events.

Another way to quantify the contribution of parameterized convective precipitation to the total precipitation is to look at the globally averaged contribution of both, as summarized in Table 1. At ne30, the convective precipitation contributes approximately 95% of the
globally averaged precipitation with both surface-boundary-condition cases. At ne120, the convective precipitation only contributes about 50% of the total precipitation in the prescribed SST case. In the ne120_SOM case, roughly 61% of the total precipitation is from convective precipitation. However, in this case the total precipitation is significantly reduced when compared with the ne120 prescribed simulation, which is a result of the significantly decreased surface temperature. The convective precipitation, on the other hand, is comparable for both ne120 simulations (see Fig. 7 and Table 1), indicating that there is some sort of upper-bound constraint in the convection parameterizations at the high resolution (Williamson 2013). This constraint of the convection parameterization likely has dynamical impacts, seen by the noticeable differences in the RCE structures and circulations among the two resolutions. This is most evident in the profiles for the prescribed SST experiment shown in Fig. 6, where the temperature profile for the ne120 case is warmer than that for the ne30, indicating that the heating profiles resulting from the convective and large-scale precipitation schemes are different.

4. Discussion and conclusions

This study describes the setup of an RCE configuration in CAM5 similar to work presented in Popke et al. (2013) using a different AGCM. Overall, the RCE context behaves as expected, approximately representing characteristics of tropical climate. This is evidenced by the development of convective circulations—namely, convective clusters surrounded by large areas of subsidence—as well the simulation of a kinetic energy spectra that approximately yields a slope of $-5/3$, consistent with mesoscale dynamics. The RCE configuration proves useful in understanding the impact of increasing horizontal resolution from a typical global model grid spacing of about 100 km to a high resolution of about 25 km on the equilibrium climate. In particular, the increase in horizontal resolution has a profound effect on the structure and intensity of convection in CAM5, with the high-resolution ne120 simulation producing smaller-scale cloud structures with stronger circulations and precipitation intensity. The decreasing contribution of convective precipitation to total precipitation with increasing resolution indicates that the role of the convective parameterizations at a given resolution is an important component of the resulting climate. Furthermore, the study indicated that the use of an interactive slab ocean compared with a prescribed, uniform SST results in a different equilibrium climate, with increased variability in the structure and temporal scale of convection. An interactive slab ocean also acts to amplify the sensitivity of the parameterization suite to increasing resolution. A detailed investigation of the physical differences in the RCE climate, particularly those due to the resolution dependency of parameterizations, is not the intent of this study but will be a focus of continuing research.

The novel study of Popke et al. (2013) provides an opportunity to put the CAM5 RCE results in the context of another global model with a uniform mixed-layer ocean. When comparing the RCE structure in the CAM5 at ne30 with the slab ocean (third row in Fig. 1) to the RCE world structure at approximately 210-km resolution in Popke et al. (2013, their Fig. 2), there are noticeable differences in structure and intensity of precipitation. As noted, the CAM5 results demonstrate that, as the resolution increases, the structures become finer, but when comparing to the simulations in Popke et al. (2013), the CAM5 ne30_SOM structure appears to be larger in size. The temporal variance of convection in the two studies is also rather different, with the CAM5 ne30_SOM simulation exhibiting less variability. When comparing the mean climate of CAM5 ne30_SOM to the Popke et al. (2013) study, there are some similarities as both models produce a global-average surface temperature near 300 K. The circulations for the ne30_SOM also differ from the Popke et al. (2013) simulations, but there are some consistencies including the negatively skewed vertical velocity distribution. Furthermore, when comparing the prescribed SST CAM5 simulations with the work of Held et al. (2007), which uses a large-domain Cartesian geometry model with AGCM column physics and prescribed SST, additional differences are revealed. The structure of the CAM5 ne30 is very different to that of Held et al.’s (2007) case using approximately 110-km resolution, which, at a comparable resolution, produces smaller-scale structures for a similar prescribed SST. A detailed comparison is difficult as the value of the fixed surface temperature is known to impact the characteristics of the RCE state (Wing and Emanuel 2014).

The differences among this study and the works by Popke et al. (2013) and Held et al. (2007) indicate that the simulation of RCE at global-scale resolutions is sensitive to a variety of experiment (e.g., resolution, SST) and model (e.g., parameterizations, interactive surface) details. This study further establishes the RCE setup as a tool for global model development in that it offers an idealized platform to understand how model and experimental design choices impact the simulation of equilibrium climate. It is expected that additional process studies could help AGCM developers make more informed decisions for parameterization updates,
particularly those relevant to convective processes. In this context, such simulations will also shed new light on persistent model biases, particularly those in the tropics, that often hinder model development particularly at high resolutions.

This study further demonstrates the usefulness of reduced complexity test beds for model intercomparisons similar to the AMIP and aquaplanet setups that have become commonplace in the global modeling community. It is the authors’ hope that intercomparisons across models using the RCE framework would adequately highlight differences among models, especially as the community moves toward higher-resolution AGCMs. Additionally, the reduced-complexity would further help modelers understand these intramodel differences. An international coordinated effort would require the establishment of a community-defined experimental RCE setup and would greatly benefit the community as a whole.

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APPENDIX

Impact of Surface Temperature

To put the impact of the SST on the organization of convection in the prescribed surface configurations into context, two additional short simulations were run with the prescribed SST equal to the equilibrium temperature achieved in the SOM configuration at each resolution (referred to here as equSST). From section 3b, it is shown that the equilibrium SSTs in the SOM cases are significantly colder than the uniform 29°C SST in the default prescribed simulations (see Fig. 4). Similar to Fig. 1, Fig. A1 displays the monthly-averaged cloud cover (left column) and near-surface wind vectors and total precipitation (right column) for a randomly selected month for each of the equSST simulations. Consistent with cloud-resolving models with fixed SST (e.g., Wing and Emanuel 2014), the lower-SST simulations do not exhibit convective organization. This contrasts with the SOM results that do permit organized convection at the lower global-mean temperatures (Fig. 1) and

Fig. A1. As in Fig. 1, but for the two additional simulations with the prescribed SST set equal to the equilibrium SST from the SOM simulations.
supports the conclusion that surface coupling plays a significant role in the behavior of convection.

REFERENCES


