Understanding Cloud and Convective Characteristics in Version 1 of the E3SM Atmosphere Model

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Abstract This study provides comprehensive insight into the notable differences in clouds and precipitation simulated by the Energy Exascale Earth System Model Atmosphere Model version 0 and version 1 (EAMv1). Several sensitivity experiments are conducted to isolate the impact of changes in model physics, resolution, and parameter choices on these differences. The overall improvement in EAMv1 clouds and precipitation is primarily attributed to the introduction of a simplified third-order turbulence parameterization Cloud Layers Unified by Binormals (CLUBB) along with the companion changes in the model cloud parameterizations. The low-resolution (1°) and high-resolution (0.25°) were required to achieve optimal performance in EAMv1. Increasing vertical resolution also results in a considerable underestimation of high clouds over the tropical warm pool, primarily due to the selection for numerical stability of a higher air parcel launch level in the deep convection scheme. Increasing horizontal resolution from 1° to 0.25° without retuning leads to considerable degradation in cloud and precipitation fields, with much weaker tropical and subtropical short- and longwave cloud radiative forcing and much stronger precipitation in the intertropical convergence zone, indicating poor scale awareness of the cloud parameterizations. To avoid this degradation, significantly different parameter settings for the low-resolution (1°) and high-resolution (0.25°) were required to achieve optimal performance in EAMv1.

Plain Language Summary The Energy Exascale Earth System Model (E3SM) is a new and ongoing U.S. Department of Energy (DOE) climate modeling effort to develop a high-resolution Earth system model specifically targeting next-generation DOE supercomputers to meet the science needs of the nation and the mission needs of DOE. The increase of model resolution along with improvements in representing cloud and convective processes in the E3SM atmosphere model version 1 has led to quite significant model behavior changes from its earlier version, particularly in simulated clouds and precipitation. To understand what causes the model behavior changes, this study conducts sensitivity experiments to isolate the impact of changes in model physics, resolution, and parameter choices on these changes. Results from these sensitivity tests and discussions on the underlying physical processes provide substantial insight into the model errors and guidance for future E3SM development.

1. Introduction

The Energy Exascale Earth System Model (E3SM), formerly known as the Accelerated Climate Modeling for Energy, is a new and ongoing U.S. Department of Energy (DOE) climate modeling effort to develop a high-resolution Earth system model specifically targeting next-generation DOE supercomputers to meet the science needs of the nation and the mission needs of DOE (Bader et al., 2014). Its Atmosphere Model version 0 (EAMv0) is based on the Community Atmosphere Model version 5.3 (CAM5.3; Neale et al., 2012), which has a resolution of 1° in horizontal and 30 layers in vertical, but it adopts the SE dynamical core (Dennis et al., 2012) and makes a few adjustments to the physical parameter settings to achieve energy...
balance (Mahajan et al., 2018). The EAM version 1 (EAMv1) was developed from EAMv0 with significant increase of model resolution and notable changes to its physical parameterizations. The current high-resolution configuration for EAMv1 (EAMv1H, hereafter) is 0.25° in horizontal and 72 layers in vertical to marginally resolve mesoscale convective systems and better describe vertical structure of atmosphere. During the development of version 1, it is mostly run at 1° and 72 layers, the low-resolution configuration (EAMv1L, hereafter), which can also be used for various scientific applications.

The update in physics is mainly focused on improving the model representation of aerosols, clouds, convection, and their interactions. This includes a simplified third-order turbulence closure parameterization (CLUBB; Cloud Layers Unified By Binormals; Golaz et al., 2002; Larson, 2017; Larson & Golaz, 2005) that unifies the treatment of planetary boundary layer turbulence (PBL), shallow convection, and cloud macrophysics to remove the unrealistic separation among these physical processes, which is characteristic of most climate models. The use of an assumed joint subgrid probability density function (PDF) in the design of CLUBB provides flexibility in representing a variety of turbulent and cloud regimes. CLUBB is paired with the same deep convection scheme used in CAM5, which was developed by G. J. Zhang and McFarlane (1995) (ZM hereafter) with a dilute CAPE (convective available potential energy) modification by Neale et al. (2008), and an updated microphysical scheme, the version 2 of Morrison and Gettelman (2008; MG2008; Gettelman et al., 2015; Gettelman & Morrison, 2014; MG2) for treating turbulence, clouds, and convective processes. The MG2 is further modified by using a classical nucleation theory based ice nucleation (IN) parameterization for the heterogeneous ice formation in mixed phase clouds (Wang et al., 2014). Other major updates include the 4-mode version of the Modal Aerosol Module (Liu et al., 2016), the unified treatment for convective transport and scavenging of aerosols (Wang et al., 2013), the resuspension of aerosol particles from evaporated raindrops to coarse mode, the representation of marine organic aerosols, and a linearized ozone chemistry (Linoz2) mechanism (Hsu & Prather, 2009; McLinden et al., 2000) for representing stratospheric ozone and its radiative effects in the stratosphere (Bader et al., 2014).

The changes in physical parameterizations and model resolution have led to quite significant model behavior changes from EAMv0 to EAMv1, particularly in simulated clouds and precipitation. Examples include the underestimation of stratocumulus near the west coasts of major continents in the subtropics in EAMv1, the substantially reduced high clouds over the tropical warm pool (TWP), as well as other notable regional changes in clouds and precipitation. Understanding what causes the model behavior changes will provide substantial insight into model errors and guide future EAM developments.

The goal of this study is to provide a better understanding of cloud and convective processes as simulated in EAMv1. Specifically, we would like to understand how convection and clouds in the model respond to the new physics and resolution increases (particularly in the vertical) and what are the impacts of model tuning (necessary to maintain the top-of-atmosphere [TOA] radiation budget) on simulated clouds and convection. Note that climate model sensitivity to horizontal resolutions has been studied quite extensively (Bacmeister et al., 2013; Wehner et al., 2015), whereas sensitivity to vertical resolution is relatively less explored (Richter et al., 2014). The improved understanding will be beneficial to the global climate modeling community since climate model resolution is being continuously increased in both the horizontal and the vertical as computer power increases.

This study is the first step toward improving our understanding of model behavior changes from EAMv0 to EAMv1. The analysis focuses here on the simulated mean state of clouds and precipitation. Sensitivity tests as shown in Table 1 are conducted to isolate the respective role that the new model cloud parameterizations, model resolution changes, and model tuning have played during the development of EAMv1. More details about these sensitivity testses are discussed in the next section. Discussion on diurnal and intraseasonal variabilities of model clouds and precipitation as well as an in-depth process-level analysis of model behaviors will be reported in separate studies.

The manuscript is organized as follows. Section 2 provides more details about the new turbulence and cloud parameterizations, as well as insights on model tuning and intermediate model configurations that are constructed for sensitivity tests. Section 3 analyzes notable changes seen in simulated clouds and precipitation in the evolution from EAMv0 to EAMv1 and discusses what processes primarily contribute to these changes. The discussion is primarily on the model behavior changes in the low-resolution model, but model sensitivity to the horizontal resolution change is also briefly presented. Section 4 highlights
impacts of some key adjustments in the deep convection scheme on model simulations. Summary and discussion are given in section 5.

2. Cloud and Turbulence Parameterizations, Model Tuning, and Configurations

2.1. Update in Cloud and Turbulence Parameterizations

As mentioned earlier, there are significant changes in turbulence, cloud, and convection related parameterizations from EAMv0 to EAMv1. These processes are now represented by CLUBB paired with ZM and MG2 in the new model. Since the analysis is emphasized on clouds and precipitation and the major model tuning was done for parameters used in these schemes, we provide more details on these schemes to help better understand new model behaviors and model tuning.

2.1.1. Turbulence, Shallow Convection, and Cloud Macrophysics—CLUBB

Cloud Layers Unified By Binormals is a third-order assumed PDF closure that can represent boundary layer processes, shallow convection processes, and cloud macrophysics with one parameterization call and one
equation set. CLUBB assumes a PDF shape that is double Gaussian, which allows for both stratocumulus and cumulus clouds to be represented with a single PDF (Bogenschutz et al., 2010; Larson et al., 2002). The joint PDF is trivariate for temperature, moisture, and vertical velocity. The widths and skewness of the PDF are determined by the higher-order moments predicted by CLUBB. CLUBB predicts the variances of temperature, moisture, and vertical velocity as well as the covariances between these variables. In addition, CLUBB predicts the third-order moment of vertical velocity, which is used to determine the skewness of vertical velocity. To mitigate computational cost of predicting the third-order moments of temperature and moisture, the skewness of temperature and moisture is assumed to be proportional to the skewness of vertical velocity. The CLUBB parameterization contains many tunable parameters for the pressure correlation, dissipation, and skewness closures that appear in CLUBB’s predictive equations. However, only a few were tuned to help achieve radiation balance and reduce model errors particularly in cumulus and stratocumulus in EAMv1 as listed in Tables A1 and A2. These include $C_1$ and $C_2rt$ for the dissipation of $\bar{w}^2$ and total water mixing ratio, respectively; $C_8$, a constant associated with the damping of $\bar{w}^2$; $C_{14}$, a constant in Newtonian damping of $\bar{w}^2$ and $\bar{v}^2$; as well as $C_{k10}$, a momentum diffusion factor.

With CLUBB, macrophysical cloud properties (cloud fraction and cloud water mixing ratio) can be computed from the assumed PDF. In EAMv1, however, these are limited to liquid clouds because the version of CLUBB used does not include ice (Bogenschutz et al., 2013). Ice cloud fraction continues to be determined using a relative humidity (RH) based scheme (Gettelman et al., 2010). The threshold RH with respect to ice for ice cloud fraction to reach 100%, rhmaxi, was also tuned during the development to improve the simulation of high-level clouds and longwave cloud radiative forcing (LWCF).

2.1.2. Deep Convection—ZM With Dilute CAPE

Zhang and McFarlane (1995) is a simplified Arakawa and Schubert scheme (Arakawa & Schubert, 1974, hereafter AS). It is based on the same spectral rising plume concept as used in AS, but it assumes that cloud base mass flux for updrafts and draft-top mass flux for downdrafts all have the same initial mass and characteristic fractional entrainment rates. This simplifies the AS scheme to a bulk cloud ensemble model. The ZM scheme was designed primarily for deep convection. Model convection occurs whenever CAPE is larger than a threshold value (70 J/kg). Earlier studies showed that the CAPE trigger caused the model convection to be triggered too easily and too frequently (e.g., Xie et al., 2004; Xie & Zhang, 2000). The modified dilute plume calculation (dilute CAPE) described in Neale et al. (2008) acts to suppress convection, which leads to a large improvement of simulated intraseasonal variability. The diluted CAPE is used in ZM in both EAMv0 and EAMv1. Cloud production over the deep convection regions is controlled by the ZM scheme. Direct cloud amount produced by the deep convective scheme is diagnosed as a function of convective mass fluxes, modulated by the areal extent of the convective plume. High clouds over the deep convective regions are also impacted by detrainment from the ZM scheme, through RH-based cloud fraction scheme for ice clouds. The modified ZM scheme contains a number of tunable parameters. The parameters that were tuned for EAMv1 include convective entrainment rate ($dmdz$), the areal extent of updraft ($dp1$), rain evaporation ($ke$), auto conversion for deep convective clouds over ocean and land ($c0_\text{ocn}, c0_\text{Ind}$), a parameter for convective ice cloud effective radius ($\text{re}_\text{Ice_deep}$), maximum convective downdraft mass flux fraction that controls the strength of downdraft ensemble ($\alpha_{df}$), air parcel launch level ($\text{liflevel}$), and the number of neutral buoyancy crossing ($\text{capeten}$), that is, the maximum number of negatively buoyant layers for an air parcel to penetrate in the calculation of CAPE and convection top, as summarized in Table A2.

2.1.3. Cloud Microphysics—MG2 With a New Ice Nucleation Scheme

Version 2 of Morrison and Gettelman (2008) represents an update to the MG2008 microphysics scheme used in CAM5. It applies a prognostic treatment of precipitation to replace the diagnostic precipitation as used in MG2008 and allows aerosol-cloud interactions in shallow convective clouds to be considered (Gettelman et al., 2015; Gettelman & Morrison, 2014). The prognostic precipitation includes a two-moment approach for all hydrometeor categories, including cloud liquid water and cloud ice as well as rain and snow. Since CLUBB does not contain any mechanism to remove cloud water, the MG2 scheme operates on all clouds that are not handled by the deep convection scheme; this includes shallow cumulus clouds and both low-level and high-level stratiform clouds. In addition, a classical nucleation theory based IN parameterization, which considers the aerosol effect and estimates the IN rate more consistently for different IN mechanisms, is implemented in EAMv1 to replace the CAM5 temperature and supersaturation dependent IN scheme for the
heterogeneous ice formation in mixed phase clouds (Wang et al., 2014). The major tunable parameters in the cloud microphysics scheme include auto conversion size threshold for cloud ice to snow \( \text{micro_mg_dcs} \) and fall speed parameter for cloud ice \( \text{ice_sed_ai} \).

2.2. Model Tuning

During the EAMv1 development, it was found that the model is quite sensitive to the changes made in physics and model resolution. To obtain a reasonable TOA energy flux for coupled simulation applications and optimize model performance, significant tuning was performed. Note that retuning is often necessary when a climate model goes through major changes in its physical parameterizations and resolution (Hack et al., 2006; Hourdin et al., 2016; Schmidt et al., 2017; Zhao et al., 2018). The tuning has played a significant role in the simulation of clouds and precipitation in EAMv1. In this section, a brief overview of the tuning process is presented to help further understand which parameters and associated physical processes the models are most sensitive to and what the major impacts are. Experiments are then designed to attribute in an incremental fashion the model behavior in simulating clouds and convection to the major changes leading to EAMv1.

The focus of the tuning is on exploring simulation sensitivity to a few loosely constrained parameters used in model cloud parameterizations (e.g., CLUBB, ZM, and MG2), guided by using the perturbed-physics ensemble method as described in (Zhang et al., 2012; Qian et al., 2018), with the goal to identify a model configuration that yields the best simulation against observations while keeping the TOA energy budget balanced to avoid drift of climate. Tables A1 and A2 briefly summarize the tuning made to those parameters that have major impacts on the simulation of clouds and precipitation. The rationale of the tuning and the underlying physics as well as suggestions for future model improvements are briefly discussed here.

2.2.1. Major Tuning Made for Low-Resolution Model EAMv1L

The major tuning efforts for EAMv1L were to address large model biases introduced by the increase of vertical resolution from 30 levels to 72 levels. Figure 1a shows the distribution of the 30 layers and 72 layers in vertical with more details seen in Figure s1b and 1c for layers below 6 and 1.5 km, respectively. With the 72-layer resolution, EAMv1 has extended the model top from ~40 to ~60 km (~0.1 hPa). The higher model top is necessary for the model to capture features in the troposphere and stratosphere, such as Quasi Biennial Oscillation, Sudden Stratospheric Warming, Southern Annular Mode, and other stratosphere-troposphere interactions, which affect the mean state and interannual variability of the tropospheric climate. EAMv1 also significantly increases the vertical resolution within the PBL. Below 1.5 km, EAMv1 has 17 layers with the vertical resolution higher than 200 m, while EAMv0 only has 5 layers. The lowest layer has a thickness of near 20 m in EAMv1, significantly thinner than that in EAMv0 (100 m). The increased resolution allows EAMv1 to better capture the boundary layer structure and the gradient in geophysical fields near the inversion, providing a more accurate depiction of resolved-scale thermodynamics that spawns complicated interaction between land-surface fluxes, turbulence mixing, cloud microphysics, and radiation. Important dynamical characteristics; nonlinear features governed by cloud, aerosol, and dynamical interactions; surface-to-troposphere water vapor gradients; and cloud vertical extent will also be better resolved with the increased vertical resolution.
The increase of vertical resolution initially led to large model biases in global mean quantities and regional features, and they were equally substantial with or without the use of CLUBB. Specifically, global annual mean LWCF was weakened by about 4 W/m² with or without CLUBB, and shortwave cloud radiative forcing (SWCF) was weakened by 5 W/m² with CLUBB and nearly 8 W/m² without CLUBB. Global mean precipitation rates, which were already excessive compared to observations, were further increased. Weakening of LWCF was most severe in the tropics, where deep convection penetration depth became substantially shallower and production of convective high clouds was heavily reduced. This, in turn, reduces stratiform high clouds because of weaker detrainment from the reduced convective penetration. In addition, there were also significant dry biases in the tropical middle and upper troposphere due to insufficient convective penetration depth.

The large model sensitivity particularly in deep convective regimes to the increase of vertical resolution indicates the poor scale awareness of the ZM scheme. This is also somewhat expected since the scheme is not scale-aware by design. The assumption of quasi-equilibrium between convection and the large-scale forcing works well at a scale of ~100 km or larger, but convection becomes more stochastic at scales of ~25 km or smaller. Some of the key convection related properties, such as the level of the air parcel launch, free convection, melting, and neutral buoyancy, are now determined with higher precision and accuracy as vertical resolution increases. Changes in these convection properties can impact CAPE and the vertical structure of convective heating and drying, which in turn will impact the interaction between convection and its environment. In addition, increasing vertical resolution leads to some unavoidable adjustments in the implementation of certain physical parameterizations to optimize their performance, since the implementation and parameter calibration were initially done with the lowest vertical resolution grid. For example, the air parcel launch level \((\text{liftlevel})\) has been changed from the lowest model level to two levels above in ZM in EAMv1, partially because the lowest level becomes over 4 times thinner and most or all of the mass could be drawn when strong convection occurs.

The characteristics of such large biases in SWCF, LWCF, and precipitation suggest that large adjustments in cloud and convective schemes are needed when the model is tuned. The parameter that controls the rate of entrainment in the ZM scheme, \(\text{dmpdz}\), was reduced to increase the penetration depth of the deep convection. Convective precipitation efficiency, \(c_0_{_\text{ocn}}\) and \(c_0_{_\text{Ind}}\), was reduced to reduce excessive precipitation biases and allow more condensate in the convective clouds and detrainment from the convection. The areal extent of convective updraft, \(dp1\), was also reduced to achieve similar effect. The ice sedimentation rate, which is controlled by parameter \(\text{ice\_sed\_ai}\), and the detrainment ice particle size \(\text{re\_ice\_deep}\), were made smaller to allow ice particle to remain in the atmosphere longer, which acts to sustain larger high-level cloud amount and make clouds brighter. These tunings collectively served to reduce the major biases in both tropical and global mean LWCF, SWCF, and precipitation rate, as well as the dry biases in the tropical free troposphere. In tuning, close attention was also paid to the response in other regional features, such as precipitation biases over the TWP and the Amazon, SWCF biases over marine stratocumulus regimes over eastern ocean basins, and surface wind stress biases in the tropics and over the Southern Ocean (SO), among others. Tuning one specific feature can sometimes counteract other tuning effects. Multiple free parameters in the CLUBB scheme were also included in the tuning to improve the model performance in metrics related to low-level clouds and near surface properties, which can also indirectly impact other climate metrics through interaction with deep convection. The perturbed-physics ensemble method (Zhang et al., 2012; Qian et al., 2018) provided guidance regarding the behavior of parameters. The final tuning for the EAMv1L is a balancing act, taking into consideration as many metrics as possible and their global and regional characteristics. For the key quantities analyzed in this paper, it was found during the tuning process that it was more challenging to reduce biases in LWCF than in SWCF, especially at global scale, without incurring large changes in other climate metrics. Given that LWCF tended to be too weak, in addition to the parameters described above, the upper bound threshold RH for maximum (100%) ice cloud fraction and the threshold size of Aitken-mode sulfate aerosol for IN were both reduced to increase high-level cloud amount, thus reducing negative biases in LWCF.

### 2.2.2. Major Tuning Made for High-Resolution Model EAMv1H

The tuning for the high-resolution EAMv1H started with the settings for the well-tuned EAMv1L. Interestingly, several of the large biases in key global mean quantities that existed in the low-resolution model when higher vertical resolution was initially introduced reemerged after the horizontal resolution was increased from 1° to 0.25°. That comparable magnitude of response when the resolution in either direction is increased may also...
suggest a structural deficiency that is rooted in the representation of subcloud layer condition and initiation of convection because they are both intrinsically related to resolved-scale boundary layer properties that can be significantly influenced by the increase in either horizontal or vertical resolution.

Tuning of the high-resolution model was computationally expensive. A strategy relying on short-hindcast simulations (Ma et al., 2014; Xie et al., 2012) was used to examine model response to changes of parameters in order to expedite the tuning process. The tuning was further aided by the knowledge learned from the analysis of perturbed parameter sensitivity experiments and the tuning of the low-resolution counterpart. Since increasing horizontal resolution to 0.25° alone led to similarly weaker LWCF and SWCF, along with much stronger global mean precipitation, as for the low-resolution EAM v1 when the vertical resolution was increased, several parameters in the ZM scheme were further tuned to reduce the biases. This included reducing the entrainment rate parameter $dp_1$, precipitation efficiency $c_0\_ocn$ and $c_0\_Ind$, and areal extent of convective updraft $dp_1$. Convective rain reevaporation rate $ke$ was increased to reduce excessive precipitation and dry biases in tropical free troposphere. Though reducing $dp_1$ was effective in increasing high clouds and reducing LWCF biases, it also caused underproduction of low- and middle-level clouds in convectively active regions. To reduce reliance on $dp_1$, convective ice cloud particle size and the size threshold of Aitken-mode sulfate aerosol for IN were further reduced from EAMv1L to achieve similar effect. Tunable parameters in CLUBB, $C_1$, $C_8$, and $C_{14}$ were mainly used to fine-tune the clouds and SWCF over the stratoscumulus regimes in order to offset the negative effect due to the other tunings. The tuning made in EAMv1H has unfortunately led to significantly different parameter settings for low- and high-resolution configurations of EAMv1 as summarized in Table A1.

### 2.3. Model Configurations

Identifying behavior changes in clouds and convection is challenging with the standard EAMv1 because the information is mixed with changes made in many aspects of physical parameterizations, model resolution, and model tuning during the model development. In this study, some additional model configurations are constructed and analyzed in order to provide more insights into the notable differences seen between EAMv0 and EAMv1. These include the tests used to isolate the influence of CLUBB along with MG2 and the updated IN scheme (EAMv0\_C), vertical resolution change (EAMv0\_CL72), model tuning (EAMv0\_CL72\_param, EAMv1L\_Cape5Lift0, and EAMv1L\_Cape1Lift0), and horizontal resolution change (EAMv1H\_untuned). More information about these intermediate configurations and the purposes of these sensitivity tests are summarized in Table 1. Note that the introduction of CLUBB and MG2 into EAMv1 came with changes in several parameters associated with microphysical and deep convective schemes (namely, $dp_1$, $rhm_{axi}$, $micro\_mg\_dcs$, $c_0\ocn$, and $c_0\_Ind$) that was originally done when it was implemented in CAM5 in order to obtain a reasonable climatology of cloud, precipitation, and radiative energy budget following substantive changes to the key model physics in CAM5. The setting for these parameters is different from that used in EAMv0. The tunings discussed throughout the paper is relative to what are used in EAMv0\_C. But no retuning was applied to the intermediate configurations used for sensitivity tests in order to isolate the impact of the particular changes and avoid the influence of other changes that might be necessarily made to keep the TOA radiative energy budget balanced and model performance optimized.

### 3. Simulation of Clouds and Precipitation

Six-year AMIP-style climatology runs with present-day forcing from the IPCC AR5 emission data set (Lamarque et al., 2010) for year 2000 with 1° resolution configurations are conducted using present-day emissions along with climatological sea surface temperature and sea ice prescribed from the observations (repeating seasonal cycle without interannual variability). Given limited computational resources, only 15-month simulations with 0.25° configurations are performed. We expect some noise in the mean state obtained from the high-resolution results, but the main features shown in clouds and convection as present in this study are not expected to change since these fields are all related to fast atmospheric physics. As shown in earlier studies (Ma et al., 2014; Xie et al., 2012), there is strong correspondence in the fast physics related fields between short-term hindcasts and long-term climate simulations. The last 5 years from the low-resolution runs and last 12 months from the high-resolution runs are analyzed and evaluated using various observational data sets as summarized in Table 2. These include total precipitation rates from the Global Precipitation Climatology Project (Adler et al., 2003), SWCF and LWCF from the Clouds and the Earth’s Radiant
Energy System (CERES) Energy Balanced And Filled (EBAF) observations (Kato et al., 2013), collocated 3-dimensional cloud fraction distribution from CERES CALIPSO CloudSat Moderate Resolution Imaging Spectroradiometer (MODIS; C3M; Kato et al., 2011), in which CALIPSO stands for Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations and CloudSat is a spaceborne radar. Additional data sets include high cloud fraction from the MODIS (Pincus et al., 2012), and the low cloud fraction from Multi-angle Imaging SpectroRadiometer (MISR; Marchand et al., 2010).

3.1. Results From Low-Resolution Models

3.1.1. Clouds and Cloud Radiative Forcing

Bogenschutz et al. (2013) showed that the use of CLUBB as a unified treatment for PBL turbulence, shallow convection, and cloud macrophysics led to a more realistic transition from stratocumulus (Sc) to trade wind cumulus (Cu) regions in CAM5 with 1° and 30-layer resolution. This improvement is also clearly seen in EAMv1L. As indicated in Figure 2, the severely underpredicted Sc and Cu issue outside the coastal stratocumulus regions in EAMv0 (Figure 2b) is improved in EAMv1L (Figures 2c and 2d), as seen through the better agreement with the MISR estimates. This is particularly true for Sc except near the coasts where there is a substantial decrease of Sc in EAMv1L compared to EAMv0 (Figure 2d). Note that output from the MISR simulator (Marchand & Ackerman, 2010) is used in Figure 2 to facilitate model-observation comparison of low-level clouds, as MISR provides the most accurate retrievals of cloud top heights for low-level clouds among the available satellite cloud simulators contained in the Cloud Feedback Model Intercomparison Project Observation Simulator Package (Bodas-Salcedo et al., 2011; Kay et al., 2012). Since the MISR retrieval is only run over ocean, the results shown in Figures 2a–2d are for oceanic regions only. Similar results are seen in comparison with other satellite observations, such as the CALIPSO, and the International Satellite Cloud Climatology Project data (not shown).

To better understand what causes the notable changes in low clouds, particularly the large reduction of coastal Sc in EAMv1L, sensitivity tests as described in Table 1 were conducted to track changes through model evolution. Results from selected configurations are shown in Figures 3a–3c. It is clear that the addition of CLUBB primarily accounts for the many encouraging features in the low clouds shown in EAMv1L; however, there is evidence that CLUBB leads to a considerable reduction of coastal Sc over the stratocumulus regions (Figure 3a) and low clouds over the Indo-West Pacific in the tropics as compared to EAMv0. Note that MG2 only plays a minor role here in influencing low cloud amount. A separate study indicates that the lack of coastal Sc might be because the area of low vertical velocity skewness assumed for Sc in CLUBB is too narrow and the annual mean skewness is too high. A sensitivity test with a reduced skewness, particularly in the subtropical coast regions, has led to a considerable improvement of coastal Sc. This additional tuning along with other improvement will be reported in a separate study. The lack of Sc in EAMv0_C is notably reduced with the increase of vertical resolution (EAMv0_CL72). Figure 3b shows a general increase of low clouds, particularly in the stratocumulus regions. This is likely due to a better representation of the boundary layer structure. It should be noted that the increase of vertical resolution also accompanies some adjustments to “capeten,” a parameter used in calculating CAPE and determining the depth of deep convection, and the air parcel launch level “liftlevel” (see Table 1 and section 4). The impact of these adjustments on low clouds is primarily over the Sc to Cu transition and trade wind cumulus regions as will be discussed in more detail in the next section.

Unfortunately, the improvement in Sc made by increasing vertical resolution (EAMv0_CL72) is largely lost after model tuning (EAMv0_CL72_param), which aims to improve TOA radiative budget and optimize

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<td>Observation</td>
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<td>Global Precipitation Climatology Project (GPCP; Adler et al., 2003)</td>
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<td>CERES-EBAF</td>
<td>Energy System (CERES) Energy Balanced And Filled (EBAF) observations (Kato et al., 2013)</td>
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<td>Moderate Resolution Imaging Spectroradiometer (MODIS)</td>
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<td>Multi-angle Imaging SpectroRadiometer (MISR)</td>
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<td>C3M</td>
<td>CERES CALIPSO CloudSat MODIS (C3M) (Kato et al., 2011), in which CALIPSO stands for Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations and CloudSat is a spaceborne radar</td>
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overall model performance as discussed earlier. It should be noted that there is no retuning applied to EAMv0_CL72_param, which just uses the same parameter setting as that used in EAMv1L. The difference between EAMv0_CL72_param and EAMv1L can be attributed to the changes in other physics such as the updated aerosols and the Linoz2 for representing stratospheric ozone and its radiative effects. As shown in

Figure 2. (a) Annual mean Multi-angle Imaging SpectroRadiometer (MISR) estimated low clouds, the biases against the observations from (b) EAMv0 and (c) EAMv1L, and (d) the differences between EAMv1L and EAMv0. The white color indicates the regions where differences are less than 2% in (b) and (c). Model clouds are from the MISR simulator. Note that the results shown in Figures 2a–2d are for oceanic regions only since the MISR retrieval is only run over ocean.

Figure 3. Differences in low clouds between different configurations. (a) EAMv0_C-EAMv0, (b) EAMv0_CL72-EAMv0_C, and (c) EAMv0_CL72_param-EAMv0_CL72. The white color indicates the regions that differences are less than 2%.
Figure 3c, the model tuning acts to offset the impact of increasing vertical resolution, which leads to an overall reduction of low clouds in the tropical region (30°S–30°N). Given that the tuning was done primarily for deep convection, the reduction of low clouds could be a result from the competition and interaction between shallow and deep convection. As discussed in section 2.2, it is noted that the reduction of $dp1$ could lead to a large reduction of clouds in the low and middle levels. Since the final tuning is a consideration of overall model performance, identifying which parameters dominate the tuning requires significantly more additional sensitivity tests. In summary, by tracking the evolution of EAMv1L development, it is clear that the degradation of coastal Sc in EAMv1L starts with the implementation of CLUBB and then is further exacerbated by model tuning and inclusion of other new physics.

The impact of CLUBB, vertical resolution, and model tuning on clouds is further demonstrated in Figure 4, which displays the cross section of cloud fraction along the Global Energy and Water Cycle Experiment Cloud Systems Study Pacific Cross-Section Intercomparison transect from the coast of California to the equatorial region (Teixeira et al., 2011) averaged over the summer season (June-July-August) to examine how well these models capture cloud regime transition. EAMv0 is able to capture the Sc cloud deck over the stratocumulus region (23°N–35°N) but largely underestimates the vertical extension of the Sc. EAMv0 also fails to simulate the evolution and transition of clouds from Sc to shallow Cu topped boundary layers in the trade cumulus regions (14°N–20°N) as presented in the observations from the C3M integrated data product (Kato et al., 2011). There is a general lack of cumulus south and west of the coastal stratocumulus region. In contrast, the transition is better represented in EAMv1L with notably increased low clouds along with a deeper boundary layer in the trade cumulus regions. However, there is a considerable reduction of low clouds off the California coast and a lack of clouds at low and middle levels (<6 km) over the (ITCZ) deep convection region in EAMv1L.

EAMv0_C clearly indicates that the use of CLUBB along with the companion changes is responsible for the increase of low clouds in the cumulus regions seen in EAMv1L. It is noticed that EAMv0_C improves not
only the transition from Sc to Cu but also the transition from Cu to deep convective clouds. There is a considerable amount of increase of clouds at low and middle levels (below 6 km) over the deep convection region, resulting in a better agreement with the observations at those levels. It is seen that high clouds over the deep convection regime are also increased in EAMv0_C, which exaggerates the positive bias in high clouds shown in EAMv0. The increase of high clouds over the deep convective regions is mostly due to the modification of convective environment by CLUBB and the use of smaller $dp_1$ for the ZM scheme. Away from the deep convective core regions that is under the influence of convective detrainment, the increase in high clouds is mostly attributable to a reduction in the threshold RH with respect to ice for ice cloud fraction to equal to 1.0 ($rh_{maxi}$). The parameter was reduced from 1.1 in EAMv0 to 1.05 in EAMv1 (Table A2) to increase high-level cloud amount with the goal to reduce the large negative biases in LWCF after increasing vertical resolution to 72 layers. The reduced value of $rh_{maxi}$ is used in all the intermediate configurations as well, including EAMv0_C.

Consistent with the earlier discussions, increasing vertical resolution further improves the transition from Sc to Cu. A more extensive and realistic cloud deck is also seen from the California coast to the cumulus regime (14 N–35 N) in EAMv0_CL72. The better simulated low clouds are accompanied by a reduction of the excessive high clouds as shown in EAMv0 and EAMv0_C over the cumulus and stratocumulus region, suggesting a reduced triggering of deep convective activities over the low cloud regions (more realistic). High clouds (>6 km) are largely reduced in EAMv0_CL72 compared to its 30-layer counterpart EAMv0_C, particularly over the deep convection region. The reduction of clouds at high levels is a robust feature with increasing vertical resolution because then water vapor is more easily confined to the surface and boundary layer, which in turn leads to a drier free troposphere as we will show later. In addition, this is also likely related to lifting the air parcel launch level to two levels above the surface in the deep convection scheme as vertical resolution increases (see section 4). In comparison with EAMv0_CL72, EAMv1L shows fewer clouds at low and middle levels while it produces more clouds above 8 km. There is a particular lack of clouds below 4 km in EAMv1L over the deep convection region. The difference seen between EAMv1L and EAMv0_CL72 is primarily due to the model tuning as demonstrated in EAMv0_CL72_param, which virtually reproduces the cloud structure shown in EAMv1L by using a similar parameter setting. A close look at the tuning suggests that several parameters related to ZM (Table A2) are primarily responsible for the change of cloud vertical structure: For example, the convective entrainment rate ($dmpdz$) and convective cloud fraction coefficient ($dp_1$) act to redistribute clouds in the vertical and reduced convective ice cloud effective radius ($Re_{ic, deep}$) helps sustain more high clouds.

Low clouds have a large impact on TOA shortwave cloud forcing (SWCF). Figure 5 shows the observed annual mean SWCF from the CERES-EBAF estimate and biases in different model versions and configurations. In general, SWCF in EAMv0 is too strong over tropical land and neighboring oceans and too weak in the Sc to Cu transition regimes. These biases are notably reduced in EAMv1L, especially over Central and South Africa, the Indian Ocean and its adjacent lands, Central and South America, and the SO. This is consistent with the improvement seen in low clouds (Figures 2 and 3). However, EAMv1L has much weaker SWCF along the western coastlines of major continents due to the underestimation of Sc, and over the TWP partly due to the lack of low clouds in the deep convection regions as suggested by Figure 4. Consistent with earlier discussions, the problem worsens with the use of CLUBB, improves with the higher vertical resolution, then degrades again with the model tuning. With the same parameter setting used in EAMv1L, EAMv0_CL72_param produces almost identical biases as shown in EAMv1L, which indicates that the other new physical parameterizations of aerosols and ozone added to make EAMv1L have little impact on these quantities. Overall, the increase of vertical resolution (EAMv0_CL72) reduces the SWCF bias seen in EAMv0_C, specifically over land and the Sc regions off South America. The sign of SWCF bias over the Central Pacific in EAMv0_C flips from slightly overpredicted in EAMv0_C to slightly underpredicted in EAMv0_CL72. This is due to the general reduction of low clouds as vertical resolution increases over the region.

Figure 6 presents the observed annual mean LWCF from the CERES-EBAF estimate and biases in different model versions and configurations from the observations. LWCF is typically underpredicted in EAMv0 except over tropical lands and over the oceans adjacent to the Indian peninsula where LWCF is significantly overestimated (Figure 6b). In general, EAMv1L produces slightly smaller biases over both ocean and land except over the TWP where LWCF is too weak (Figure 6c). Over the SO, the Arctic, and tropical lands, LWCF is too strong compared to the observations. Again, the improvements seen in EAMv1L are largely due to the use
of CLUBB along with the use of MG2 and the updated ice microphysics scheme that improves the simulation of high cloud and its cloud microphysical properties. The global annual mean ice water path (IWP) simulated by EAMv1L (11.64 g/m²) is significantly smaller than that produced by EAMv0 (31.70 g/m²). Note that excessive ice cloud and insufficient liquid cloud have been an outstanding issue in CAM5 (Kay et al., 2016; Xie et al., 2013). The smaller IWP in EAMv1L is mainly due to the change of the ice-to-snow auto-conversion threshold \((dcs)\) from a constant value of 600 \(\mu\)m in EAMv0 to a temperature dependent one in EAMv1 in the updated ice microphysics scheme (Wang et al., 2014). Smaller IWP helps reduce the excessive LWCF seen in EAMv0. Interestingly, EAMv0_C shows an overall better agreement with the observations than both EAMv0 and EAMv1L. Increasing vertical resolution (EAMv0_CL72) leads to a decrease of LWCF almost globally compared to EAMv0_C, particularly over the tropical Indian and western Pacific oceans, which is related to the large reduction of high clouds over the regions as mentioned earlier and will be discussed more next. The model tuning (EAMv0_CL72_param) slightly increases LWCF, but a similar bias pattern remains. Differences between EAMv0_CL72_param and EAMv1L in LWCF are much larger than those in SWCF, suggesting a bigger role that other new features (e.g., the new aerosol physics) play in LWCF.

One outstanding issue with the LWCF in EAMv1L is the substantially weaker LWCF over the TWP, which becomes obvious after the vertical resolution is increased to 72 layers. This is partially due to less high cloud cover simulated in EAMv1L over the region as compared to both EAMv0 and the observations (MODIS; Figure 7) and the reduced IWP as discussed earlier. The reduction of high cloud over the TWP starts with the increase of vertical resolution and is exacerbated by the model tuning (Figures 8b and 8c). Changing the air parcel launch level as vertical resolution increases is primarily responsible for the reduction of high clouds over this region as will be shown later. Consistent with Figure 4, the addition of CLUBB along with

Figure 5. Annual mean Clouds and the Earth’s Radiant Energy System Energy Balanced and Filled shortwave cloud radiative forcing and the biases against the observations from various model configurations EAMv0, EAMv1L, EAMv0_C, EAMv0_CL72, and EAMv0_CL72_param. The white color indicates the regions where differences are less than 3 W/m².
the companion changes actually leads to an overall increase of high clouds, particularly over the tropical central Pacific, in comparison with EAMv0 (Figure 8a). This is different from Bogenschutz et al. (2013), which showed that the high cloud fraction in CAM5 with CLUBB is similar to the default CAM5. As we discussed earlier, this should be due to the use of a lower threshold value of $rh_{maxi}$ for ice cloud fraction and a smaller $dp_1$ in EAMv0_C, which increases high clouds.

3.1.2. Precipitation

Figure 9 displays annual mean Global Precipitation Climatology Project estimated precipitation and the biases against the observations from EAMv0 and EAMv1L. In general, both models show similar regional biases with excessive precipitation over large portions of the tropics but less precipitation over Amazon. However, the magnitude of the biases over the oceans adjacent to the Indian peninsula, tropical eastern Indian Ocean, and Amazon is smaller in EAMv1L. Compared to EAMv0, EAMv1L underpredicts precipitation over the Bay of Bengal, TWP, and South China Sea but overpredicts precipitation over the central to eastern portion of the Pacific ITCZ, the subtropical oceans, Northwestern Indian Ocean and Africa, and the SOs.

Figure 10 is used to attribute the major differences between EAMv0 and EAMv1L. The introduction of CLUBB along with MG2 appears to be mostly responsible for the lack of precipitation over the Bay of Bengal and TWP and the excessive precipitation over the equatorial central Pacific (Figure 10a). An earlier test with MG2 indicates that these changes should be largely due to the use of MG2, which led to a considerable reduction of precipitation over tropical Indo-West Pacific and a slight increase of precipitation over tropical central and eastern Pacific as well as over lands including the Amazon (not shown). This is consistent with Gettelman et al. (2015), which showed 5% reduction of precipitation in the zonal mean with MG2 between 30S and 30 N over the tropical and subtropical oceans. The quite large change of precipitation over the deep convective regimes with CLUBB+MG2 may also imply its interaction with deep convection is partially through influence on boundary layer structure and atmospheric instability. Increasing vertical resolution considerably
enhances the already overestimated precipitation in the tropics (Figure 10b), which is due to a large increase of large-scale precipitation (not shown). This problem has been largely addressed by the model tuning (Figure 10c), except for the subtropical oceans where excessive precipitation is attributable to both the increase in vertical resolution and the tuning. It is interesting to see that the use of CLUBB+MG2 (mostly

Figure 7. (a) Annual mean Moderate Resolution Imaging Spectroradiometer (MODIS) estimated high clouds, the biases against the observations from (b) EAMv0 and (c) EAMv1L, and (d) the differences between EAMv1L and EAMv0. Model clouds are from the MODIS simulator. The white color in (b) and (c) indicates the regions where differences are less than 2%.

Figure 8. Differences in high clouds between different configurations: (a) EAMv0_C-EAMv0, (b) EAMv0_CL72-EAMv0_C, and (c) EAMv0_CL72_param-EAMv0_CL72. The white color indicates the regions that differences are less than 2%.
increasing vertical resolution, and the model tuning all contribute to the reduction of the well-known dry bias in the Amazon region in EAMv0 and CAM5.

### 3.1.3. Zonally Averaged Annual Mean Temperature and Moisture

Figure 11 displays the zonally averaged annual mean temperature biases in EAMv0 and EAMv1L relative to ERAI as well as attributions from the changes made through model evolution. In comparison with the ERAI reanalysis data, EAMv0 produces large cold biases in the upper troposphere (>300 hPa) over the polar regions in both hemispheres and a large warm bias below 600 hPa near South Pole (Figure 11a). In the middle and low latitudes, EAMv0 presents moderate cold biases. The big changes from EAMv0 to EAMv1L are the significantly reduced cold biases in the upper troposphere in high latitudes and moderately increased cold biases in the middle and low latitudes, particularly in middle and high levels between 30°S and 30°N. The reduced upper tropospheric cold biases in the polar regions are due to both increase of vertical resolution and model tuning, while the increased cold biases in the upper troposphere in the tropical and subtropical regions are related to the use of CLUBB and other accompanied changes and model tuning (Figures 11d and 11f).

Figure 12 displays the zonally averaged annual mean RH biases in EAMv0 and EAMv1L relative to ERAI as well as attributions from the changes made through model evolution. EAMv1L is generally drier than EAMv0, particularly above 300 hPa in the polar regions and in the middle troposphere over tropical and subtropical
regions (Figure 12c). The increase of vertical resolution is clearly primarily responsible for this change (Figure 12e). It also results in more moisture trapped in the lower levels and less moisture being transported into middle and upper levels (Figure 13e) due to lower penetration of deep convection as vertical resolution increases. It is seen from Figure 13d that the use of CLUBB, along with the companion changes, helps reduce the moist biases shown in EAMv0 (Figure 13a) in the tropical and extratropical regions, while the tuning tends to offset the changes caused by the increase of vertical resolution (Figure 13f). The overall effect of all these changes leads to a dryer atmosphere, particularly in the middle and upper troposphere, in EAMv1L (Figures 13b and 13c) compared to EAMv0, consistent with Figure 12.

3.2. Results From High Horizontal-Resolution Models

The high-resolution model EAMv1H is running with 0.25° horizontal grid spacing and 72 layers in the vertical. It shares the same physics as the low-resolution model EAMv1L except for some necessary parameter adjustments as described in Table A1 to keep TOA radiative balance and reduce some outstanding regional model biases seen in its low-resolution counterpart and/or caused by increasing horizontal resolution. To separate the impact of model tuning from the increase of horizontal resolution from 1° to 0.25°, in this section, we will also discuss results from an intermediate high-resolution configuration without model tuning (EAMv1H_untuned).

Figure 14 shows model biases in SWCF, LWCF, and precipitation simulated by EAMv1H and EAMv1H_untuned. Compared to its low-resolution counterpart EAMv1L (Figures 5, 6, and 9), simply increasing horizontal resolution (EAMv1H_untuned) leads to considerable degradation of the cloud and precipitation fields. The error pattern resembles that in EAMv1L but with considerably larger magnitudes. Though net TOA flux in EAMv1H_untuned only has a small positive imbalance, TOA net shortwave and longwave radiative fluxes are off by 4.4 and 5.7 W/m², respectively, which are mostly due to cloud forcings being too weak, indicating the need for model tuning. The well-tuned high-resolution model EAMv1H considerably
improves simulations of clouds and precipitation in comparison with either EAMv1H_untuned or the low-resolution EAMv1L. Examples include the much improved SWCF in the stratocumulus regime, the substantially reduced bias in LWCF over tropical Indo-West Pacific, and the largely improved precipitation for both tropical and extratropical regions. As discussed in section 2.2.2, the improvement in SWCF are achieved through adjusting tunable parameters in CLUBB ($C_1$, $C_8$, and $C_{14}$—Table A2), while those in LWCF and precipitation are due to reducing the entrainment rate, precipitation efficiency, areal extent of convective updraft, and increasing convective rain reevaporation rate. Again, the final choice of parameter setting is a balancing consideration depending on overall performance metrics. This results in significant degradations in LWCF over tropical lands and adjacent oceans where LWCF is too strong associated with a large increase of high clouds and IWP.

The impact of horizontal resolution and model tuning on cloud forcing and precipitation is further demonstrated in the zonal mean plots in Figures 15a–15c. Without tuning, increasing horizontal resolution in EAMv1H_untuned results in much weaker SWCF and LWCF in the tropical and subtropical regions (35°S–35°N) and much stronger precipitation in ITCZ in both hemispheres, similar to what were found in Bacmeister et al. (2013). These issues have been well addressed through the model tuning. Results from EAMv1H agree much better with the observations than EAMv1L and EAMv1H_untuned in these examined fields. The improvement in precipitation in EAMv1H is primarily due to the reduction of convective precipitation (not shown). Consistent with earlier studies (Bacmeister et al., 2013; Boyle & Klein, 2010), convective precipitation decreases and large-scale precipitation increases with increasing horizontal resolution due to more precipitation processes being resolved as model grid size becomes smaller.

3.3. Annual Mean Climatological Properties of Clouds and Precipitation

Table 3 summarizes annual mean climatological properties of clouds, cloud radiative forcing, and precipitation produced by various configurations used in the sensitivity tests. These statistics are averaged over low

![Figure 12](image-url)
latitudes between 30°S and 30 N where we see the largest changes in clouds and precipitation from EAMv0 to EAMv1. In general, the changes in these statistics among the tested configurations are consistent with what have been discussed before. In comparison with EAMv0, both low- and high-resolution EAMv1 models produce few low clouds (worse) and more high clouds (better). The reduction of low clouds is primarily related to the use of a smaller value of $dp1$ to increase high clouds during model tuning, while the increase of high clouds is due to the reduction of $rhmaxi$, $dp1$, and $dmpdz$ as discussed earlier. Overall, EAMv1H shows the most realistic simulation of SWCF, LWCF, and precipitation compared to EAMv1L and EAMv0 and represents a significant improvement compared to its untuned version (EAMv1H_untuned) that largely underestimates SWCF and LWCF and overestimates precipitation. It is interesting to see that the increase of SWCF in EAMv1H is not from the increase of low clouds, but from a significantly increased liquid water path (from 39.36 to 59.67 g/m²) after model tuning. This again highlights the "too few and too bright" feature of the simulated low clouds in the low latitudes (Nam et al., 2012). The better simulated LWCF in EAMv1H is from both the increase of high cloud amount and IWP.

Even though the intermediate configurations are not tuned, the implementation of CLUBBB along with the companion changes (EAMv0_C) results in an overall moderate improvement of the cloud and precipitation fields in comparison with EAMv0. Both increasing vertical resolution and the follow-up model tuning have caused significant changes in these selected cloud and precipitation fields. Compared to EAMv0_C, EAMv0_CL72 shows a moderate increase (3.6%) in low clouds and decrease (5.4%) in high clouds, but much larger reduction in SWCF (18%), LWCF (20%), LWP (20%), and IWP (29%) and increase in precipitation (7.4%), indicating the necessity of retuning the model. The parameter adjustments as shown in EAMv0_CL72_param act to partially offset the changes caused by the increase of vertical resolution for most of the fields except for high clouds. Simply increasing horizontal resolution (EAMv1H_untuned) from the well-tuned low-resolution model EAMv1L leads to large reduction in high clouds (8.3%), SWCF (12.5%), and LWCF (21%). The model retuning (EAMv1H) has largely addressed the issue.

**Figure 13.** Zonally averaged annual mean moisture bias (g/kg) relative to ERAI in (a) EAMv0 and (b) EAMv1, as well as differences between different configurations: (c) EAMv1L-EAMv0, (d) EAMv0_C-EAMv0, (e) EAMv0_CL72-EAMv0_C, and (f) EAMv0_CL72_param-EAMv0_CL72. The white color indicates the regions that differences are less than 0.5 g/kg.
4. Impacts of “capeten” and Air Parcel Launch Level in ZM

As we mentioned earlier, the increase of vertical resolution also accompanies some adjustments in the ZM deep convection scheme to “capeten,” a parameter used in calculating CAPE and determining the depth of deep convection, and the air parcel launch level “liftlevel.” capeten defines the number of negative buoyancy layers that deep convection can penetrate. Our early study indicated that reducing the number could lead to an improved tropical intraseasonal variability and the winter season (December-January-February) Amazon rainfall in CAM5.5. In this study, capeten is changed from its default setting 5 in EAMv0 to 1 in EAMv1. liftlevel in ZM is lifted from the default setting 0 (the bottom model level, whose midpoint altitude is about 50 m) to 2 (two levels above the bottom, whose midpoint altitude is about 100 m) to avoid potential computational instability in long-term climate simulations. Since both changes could have a large impact on model deep convection, it is necessary to have a separate discussion to highlight their impacts on model simulations.

The impact of these two adjustments on cloud and cloud radiative forcing is shown in Figure 16, in which EAMv1L_Cape5Lift0 is constructed to be the same as EAMv1L except for restoring the default values of...
capeten and liftlevel as described in Table 1. The adjustments result in a notable increase of low clouds in the Sc/Cu transition regions and slight decrease of low clouds along the equator except for the eastern equatorial deep convection region where the reduction of low clouds could be up to 15%. SWCF is increased in the Sc/Cu transition regions associated with the increase of low clouds. Quite large changes (increase) in SWCF are also seen in the Indian Ocean and maritime continents. In general, the impact of the two adjustments is relatively large on high clouds and associated LWCF as well as precipitation compared to low clouds and SWCF since these fields are largely influenced by deep convection. It is seen that tropical convection is substantially suppressed over the TWP and the Eastern Pacific warm pool off the central American coast along with the reduced high clouds and LWCF, while enhanced precipitation and high clouds are seen over most tropical lands (including Amazon) and adjacent oceans, which results in a large increase in LWCF. Although the adjustments lead to a reduction of the dry bias over the Amazon, the overall impact is negative on high clouds and tropical precipitation. This is an area to reconsider in the future E3SM development. Additional tests including tuning need to be conducted to fully understand the impact of these two adjustments.

To further separate the roles of capeten and liftlevel on these changes, an additional test, EAMv1L_Cape1Lift0, is conducted, with the same settings as in EAMv1L except for restoring the liftlevel value back to the model bottom level as in EAMv0 (Table 1). So differences between EAMv1L and EAMv1L_Cape1Lift0 reflect the impact of liftlevel and differences between EAMv1L_Cape1Lift0 and EAMv1L_Cape5Lift0 suggest the impact of changing capeten. The seasonal mean vertical profiles of clouds and diabatic heating (Q1) averaged over two representative convectively active regions (i.e., TWP for June-July-August and Amazon for December-January-February) are examined (Figure 17) for the regions highlighted in Figure 16e. Large differences are present over these two selected regions. For comparison, results from EAMv0 are also displayed in the figure. Over the TWP, the change in capeten has negligible impact on the reduction of high clouds (Figure 17a) since the vertical profiles of clouds produced by EAMv1L_Cape5Lift0 and EAMv1L_Cape1Lift0 are almost identical. This is probably due to the persistent instability in the TWP, which may be less sensitive to midtropospheric instability. The significant reduction in cloud produced by EAMv1L above 6 km is therefore due to the higher air parcel launch level. EAMv0 shows a clear trimodal structure in clouds with peaks at 1, 6, and 12 km. This is more consistent with the C3M observations than the EAMv1L models that only produce one peak in the upper troposphere and significantly underpredict low and middle level clouds. A close look at the problem found that the lack of low and middle level clouds in EAMv1 is primarily due to model tuning, such as the reduction of the areal extent of convective plume, similar to what has been shown in Figure 4.

Table 3
Annual Mean Climatological Properties Over 30°S–30°N for Low Clouds (CLDLOW, %), High Clouds (HGHCLD, %), SWCF (W/m²), LWCF (W/m²), Total Precipitation (PRECT, mm/d), Liquid Water Path (LWP, g/m²), and Ice Water Path (IWP, g/m²) Produced by Different Configurations

<table>
<thead>
<tr>
<th>Variable</th>
<th>OBS</th>
<th>EAMv0</th>
<th>EAMv1L</th>
<th>EAMv1H</th>
<th>EAMv0_CL72</th>
<th>EAMv0_CL72_param</th>
<th>EAMv1H_untuned</th>
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<tr>
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<td>21.26</td>
<td>23.64</td>
<td>24.52</td>
<td>21.73</td>
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<td>39.01</td>
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<td>44.08</td>
<td>43.20</td>
<td>40.87</td>
<td>36.14</td>
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<tr>
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<td>−49.76</td>
<td>−42.75</td>
<td>−45.13</td>
<td>−46.15</td>
<td>−37.77</td>
<td>−38.02</td>
</tr>
<tr>
<td>LWCF</td>
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<td>26.61</td>
<td>24.78</td>
<td>19.79</td>
<td>20.66</td>
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<tr>
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<td>35.21</td>
<td>28.14</td>
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<tr>
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<td>17.33</td>
<td>8.22</td>
<td>5.86</td>
<td>8.39</td>
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</tbody>
</table>

Figure 15. Zonally averaged annual mean (top) shortwave cloud radiative forcing, (middle) longwave cloud radiative forcing, and (bottom) precipitation. In the bottom panel, the solid lines are total precipitation rates and the dash lines are convective precipitation ratio.
capeten has a larger impact on Q1 than clouds as demonstrated in Figure 17c. Reducing the number of negative buoyancy layers that convection can penetrate will suppress convection as indicated by Q1, which shows a considerably weaker heating produced in EAMv1L_Cape1Lift0 than in EAMv1L_Cape5Lift0. However, the rise of liftlevel plays a much bigger role in the reduction of convection over TWP. The diabatic heating in EAMv1L is just about half of that in EAMv1L_Cape1Lift0. It is interesting to see that Q1 in EAMv1L exhibited a maximum around ~5 km, which is slightly lower than in EAMv0, EAMv1L_Cape5Lift0, and EAMv1L_Cape1Lift0 (~5.5 km). This suggests that the rise of liftlevel is primarily responsible for the lower heating peak in EAMv1L rather than the increase of vertical resolution over the TWP, but resolution increases have a larger role in the overall distribution of convective heating.

The change of capeten and liftlevel has an opposite role over the Amazon compared to that over the TWP region. Reducing the capeten value slightly reduces the high cloud amount but enhances the diabatic heating at all the levels. Similarly, increasing the air parcel launch level has a much bigger impact on convection, which is reflected by the much stronger diabatic heating produced by EAMv1L than EAMv1L_Cape1Lift0.
Interestingly, the maximum heating in Q1 in all the EAMv1 models appears at the same level around 5 km, lower than that in EAMv0. This is likely due to the finer resolution in the 72-layer models. The different roles that these adjustments, and particularly the rise of the air parcel launch level, have played on convection over these two regions likely reflect the differences in their underlying surface. Similar to what we saw over the TWP, these EAMv1 configurations have substantially underestimated clouds below 6 km and only show one peak in the upper troposphere. The lack of middle and low clouds over deep convection regions is an issue that needs to be addressed in the future development of EAM.

5. Summary and Discussion

The DOE E3SM atmosphere model (EAM) has undergone significant changes in physics, model resolution, and parameter settings during its development from its version 0 to version 1. This has resulted in notable changes in model simulated climate. To better understand the model behavior changes, in this study, we performed a number of sensitivity experiments to isolate the impact of these changes on model simulations. Our analysis was focused on the simulation of mean cloud and precipitation fields with the goal of providing insights into those outstanding model issues that are associated with cloud and convective processes.

Both the low- and high-resolution EAMs showed an overall improvement in the mean state of clouds, cloud radiative forcing, and precipitation in comparison with EAMv0. These include (1) increased stratocumulus (except near the coasts) and trade-wind cumulus as well as a better transition from Sc to Cu, which in turn lead to enhanced SWCF over these regions; (2) notably reduced biases in LWCF, especially over tropical land and adjacent oceans; and (3) notably improved precipitation over the oceans adjacent to the Indian peninsula and tropical eastern Indian ocean. EAMv1 continues to have dry biases over the Amazon region as...
EAMv0 does, but the magnitude in EAMv1 is smaller. Other outstanding issues with EAMv1 include the substantial reduction of Sc off the west coasts of major continents in the subtropics, the largely reduced high clouds over TWP, the general lack of low and middle level clouds over deep convection regions, as well as the dry bias in TWP and South East Asia. These issues are more severe in the low-resolution EAMv1.

Sensitivity tests showed that the addition of CLUBB, which provides a unified treatment of boundary layer turbulence, shallow convection, and cloud macrophysics, along with the use of a new version of cloud microphysical scheme (MG2) and a new IN parameterization, was primarily responsible for the improvements summarized above. There is evidence that the impact of these changes extends beyond low cloud regimes. Significant changes in clouds and precipitation over deep convection region also occurred, indicating strong interaction among boundary layer turbulence, shallow convection, and deep convection. However, the use of CLUBB led to an initial reduction of stratocumulus clouds, which was reversed with the increase in the number of vertical levels but was degraded again while tuning the model to get energy balance.

The increase of vertical resolution from 30 layers to 72 layers in EAMv1 resulted in large reduction of high clouds over tropical deep convection regimes, which contributes to the much weaker LWCF over TWP compared to both observations and EAMv0. It also led to excessive precipitation in the tropics. The positive impact of increasing vertical resolution is the considerable increase of Sc off the west coasts of North and South America. However, this improvement was offset by model tuning to reach energy balance and address other regional model errors. In general, the model tuning acted to offset the impact of increasing vertical resolution, which leads to an overall increase of high clouds and reduction of low and middle clouds in the tropical region (30°S–30°N). The reduction of clouds in the low and middle levels has been found largely due to the reduction of the areal extent of convective plume in the deep convection scheme. This tuning may need to be reconsidered in future model developments.

The increase of horizontal resolution from 1° to 0.25° without tuning led to considerable degradation of cloud and precipitation fields featured with much weaker SWCF and LWCF in the tropical and subtropical regions and much stronger precipitation in ITCZ in both hemispheres. The sensitivity of model results to both vertical and horizontal resolution change indicates that model physical parameterizations, and in particular the deep convection scheme, are not scale-aware. This has resulted in significant model tuning in order to keep TOA energy budget close to observations and optimize model performance. For the low-resolution model, the tuning typically acted to offset the effect of increasing vertical resolution, resulting in an overall improvement in model simulated climate. The degradations include the lack of low clouds in the stratocumulus regions and high clouds in the TWP. For the high-resolution model, model tuning led to considerably improved clouds and precipitation, including notable increase of Sc. Unfortunately, the poor scale awareness of model physics has resulted in different parameter settings for optimal performance of EAMv1 at low- and high-resolution during their development.

In addition to the tuning, two adjustments were made to the deep convection scheme in EAMv1. One is to reduce the number of negative buoyancy levels (capetens) that deep convection is allowed to penetrate from 5 to 1. The other is to lift the air parcel launch level (liflevel) from the model bottom level to 2 levels above. Results showed that these two adjustments, and particularly the rise of parcel launch level, could have significant impact on high clouds and precipitation as well as their vertical structure. They typically act to suppresses deep convection over tropical oceans and enhance convection over lands. Although the adjustments lead to a reduction of the dry bias over the Amazon, the overall impact is negative on high clouds and tropical precipitation. For example, the lack of high clouds in the TWP is primarily due to the change of liflevel as the vertical resolution increases to 72 layers. This is another area to reconsider in the future development.

This paper is the first step toward improving our understanding of model behavior changes from EAMv0 to EAMv1. It emphasizes the simulated mean state of clouds and precipitation. The factors discussed to attribute the mean states, namely, the incorporation of new physics, increase in resolution, and model tuning and adjustments, also show offsetting effects on the variabilities of key simulated physical quantities, such as characteristics of diurnal precipitation. Discussion on diurnal and intraseasonal variabilities of model clouds and precipitation will be reported separately. A more detailed process-level understanding on how clouds and convective processes would respond to the changes in model resolution, particularly in the vertical, is also being conducted by using the short-term weather hindcast approach (Ma et al., 2015; Phillips et al,
2004), in which the model is initialized with the ERA-Interim Reanalysis (Dee et al., 2011) and the Regionally Refined Meshes capability provided by the E3SM. Earlier studies (Ma et al., 2014; Xie et al., 2012) indicated that many features in the climate simulation of clouds and precipitation can be examined in a few days’ hindcasts. The hindcast approach allows an in-depth investigation of changes in cloud and convective properties after the model resolution is increased, such as the level of origin for air parcel ascending, level of free convection and neutral buoyancy, PBL height, convective downdrafts and updrafts, as well as the vertical structure of clouds and convective heating and drying. A better understanding of the newly developed DOE EAM will greatly benefit the community who will use EAM for climate studies and provides extremely useful guidance for future EAM development.

**Appendix A**

Parameter setting in EAMv1 model configurations.

### Table A1

<table>
<thead>
<tr>
<th>Tuned parameter</th>
<th>Brief description</th>
<th>EAMv1L</th>
<th>EAMv1H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deep convection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dmpdz</td>
<td>Convective parcel fractional entrainment rate for updrafts</td>
<td>−0.7e−3</td>
<td>−0.2e−3 (−)</td>
</tr>
<tr>
<td>C0_ocn</td>
<td>Autoconversion parameter for deep convective clouds over ocean</td>
<td>0.007</td>
<td>0.0035 (−)</td>
</tr>
<tr>
<td>C0_lnd</td>
<td>Autoconversion parameter for deep convective clouds over land</td>
<td>0.007</td>
<td>0.0043 (−)</td>
</tr>
<tr>
<td>ke</td>
<td>Convective rain evaporation</td>
<td>1.5e−6</td>
<td>6e−6 (+)</td>
</tr>
<tr>
<td>alfa</td>
<td>Maximum convective downdraft mass flux fraction that controls the strength of downdraft ensemble</td>
<td>0.1</td>
<td>0.2 (+)</td>
</tr>
<tr>
<td><strong>Cloud macrophysics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dp1</td>
<td>Convective cloud fraction coefficient that controls the size of ensemble convective plume</td>
<td>0.045</td>
<td>0.039 (−)</td>
</tr>
<tr>
<td>Re_ice_deep</td>
<td>Convective ice cloud effective radius</td>
<td>16e−6</td>
<td>12e−6 (−)</td>
</tr>
<tr>
<td>C1</td>
<td>Constant associated with the dissipation of $w^2$</td>
<td>1.335</td>
<td>1.50 (+)</td>
</tr>
<tr>
<td>C8</td>
<td>Constant associated with the damping of $w^2$ used in CLUBB</td>
<td>4.3</td>
<td>4.73 (+)</td>
</tr>
<tr>
<td>C14</td>
<td>Constant in Newtonian damping of $u^2$ and $v^2$ used in CLUBB</td>
<td>1.3</td>
<td>1.75 (+)</td>
</tr>
<tr>
<td><strong>Aerosols</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dust_emis_fact</td>
<td>Dust emission parameter</td>
<td>2.05</td>
<td>2.50 (+)</td>
</tr>
<tr>
<td>so4_sz_thresh_icenuc</td>
<td>Aitken mode sulfate aerosol size threshold for homogeneous ice nucleation</td>
<td>0.075e−6</td>
<td>0.05e−6 (−)</td>
</tr>
</tbody>
</table>

### Table A2

<table>
<thead>
<tr>
<th>Tuned parameter</th>
<th>Brief description</th>
<th>EAMv0</th>
<th>EAMv1L</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deep convection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dmpdz</td>
<td>Convective parcel fractional entrainment rate for updrafts</td>
<td>−1.0e−3</td>
<td>−0.7e−3 (−)</td>
</tr>
<tr>
<td>C0_ocn</td>
<td>Autoconversion parameter for deep convective clouds over ocean</td>
<td>0.0035</td>
<td>0.007 (−)</td>
</tr>
<tr>
<td>C0_lnd</td>
<td>Autoconversion parameter for deep convective clouds over land</td>
<td>0.009</td>
<td>0.007 (−)</td>
</tr>
<tr>
<td>ke</td>
<td>Convective rain evaporation</td>
<td>1.0e−6</td>
<td>1.5e−6 (+)</td>
</tr>
<tr>
<td>Tiedke_add</td>
<td>Perturbation added to the parcel buoyancy in ZM scheme</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>capeten</td>
<td>Capeten is the number of tentative CAPE computed—one for each neutral buoyancy crossing—to find the maximum cape of updraft plume for use in the ZM convective scheme.</td>
<td>0.1e−6</td>
<td>0.075e−6</td>
</tr>
<tr>
<td>liftlevel</td>
<td>The lowest possible launch level above the model’s bottom level</td>
<td>0.1e−6</td>
<td>0.075e−6</td>
</tr>
<tr>
<td><strong>Cloud macrophysics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dp1</td>
<td>Convective cloud fraction coefficient that controls the size of ensemble convective plume</td>
<td>0.025</td>
<td>0.045 (−)</td>
</tr>
<tr>
<td>rhmaxi</td>
<td></td>
<td>1.10</td>
<td>1.05</td>
</tr>
</tbody>
</table>
Table A2 (continued)

<table>
<thead>
<tr>
<th>Tuned parameter</th>
<th>Brief description</th>
<th>EAMv0</th>
<th>EAMv1L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re_ice_deep Cloud microphysics</td>
<td>Threshold RH with respect to ice for ice cloud fraction to equal to 1.0</td>
<td>25e−6</td>
<td>16e−6</td>
</tr>
<tr>
<td>Micro_mg_dcs Autoconversion size threshold for cloud ice to snow</td>
<td>Convective ice cloud effective radius</td>
<td>600e−6</td>
<td>T dependent (−)</td>
</tr>
<tr>
<td>Ice_sed_ai Aerosols so4_sz_thresh_icenuc</td>
<td>Fall speed parameter for cloud ice</td>
<td>700</td>
<td>500</td>
</tr>
<tr>
<td>Ice_sed_ai Aerosols Ice_sed_ai</td>
<td>Aitken mode sulfate aerosol size threshold for homogeneous ice nucleation</td>
<td>0.1e−6</td>
<td>0.075e−6</td>
</tr>
</tbody>
</table>

*** CLUBB parameters not available in EAMv0 but require tuning from EAMv0_CL72 to EAMv1L

C1 Constant associated with the dissipation of w^2 | 1.0 | 1.335 |
C2rt Constant associated with the dissipation of total water mixing ratio | 1.0 | 1.75 |
C8 Constant associated with the damping of \( \frac{w}{u^*} \) used in CLUBB | 4.2 | 4.3 (+) |
C14 Constant in Newtonian damping of \( \frac{u}{w^*} \) and \( \frac{v}{w^*} \) used in CLUBB | 1.0 | 1.3 (+) |
C_k10 Momentum diffusion factor | 0.6 | 0.3 |

References


Acknowledgments

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XIE ET AL.

