Multivariate Probability Density Functions with Dynamics in the GFDL Atmospheric General Circulation Model: Global Tests

HUAN GUO
UCAR Visiting Scientist Programs, NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

JEAN-CHRISTOPHE GOLAZ, LEO J. DONNER, AND PAUL GINOUX
NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

RICHARD S. HEMLER
High Performance Technologies Group, DRC/GFDL, Princeton, New Jersey

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ABSTRACT

A unified turbulence and cloud parameterization based on multivariate probability density functions (PDFs) has been incorporated into the GFDL atmospheric general circulation model (AM3). This PDF-based parameterization not only predicts subgrid variations in vertical velocity, temperature, and total water, which bridge subgrid-scale processes (e.g., aerosol activation and cloud microphysics) and grid-scale dynamic and thermodynamic fields, but also unifies the treatment of planetary boundary layer (PBL), shallow convection, and cloud macrophysics. This parameterization is called the Cloud Layers Unified by Binormals (CLUBB) parameterization. With the incorporation of CLUBB in AM3, coupled with a two-moment cloud microphysical scheme, AM3–CLUBB allows for a more physically based and self-consistent treatment of aerosol activation, cloud micro- and macrophysics, PBL, and shallow convection.

The configuration and performance of AM3–CLUBB are described. Cloud and radiation fields, as well as most basic climate features, are modeled realistically. Relative to AM3, AM3–CLUBB improves the simulation of coastal stratocumulus, a longstanding deficiency in GFDL models, and their seasonal cycle, especially at higher horizontal resolution, but global skill scores deteriorate slightly. Through sensitivity experiments, it is shown that 1) the two-moment cloud microphysics helps relieve the deficiency of coastal stratocumulus, 2) using the CLUBB subgrid cloud water variability in the cloud microphysics has a considerable positive impact on global cloudiness, and 3) the impact of adjusting CLUBB parameters is to improve the overall agreement between model and observations.

1. Introduction

For decades, stratocumulus cloud systems have attracted intense and diverse research (e.g., Lilly 1968; Suarez et al. 1983; Klein and Hartmann 1993; Stevens et al. 2003; Bretherton and Park 2009; Mechoso et al. 2014). Stratocumulus clouds play a crucial role in Earth’s radiation balance because of their high reflectivity to incoming shortwave radiation and their large areal coverage (e.g., Randall et al. 1984; Warren et al. 1986, 1988; Slingo 1990). They are controlled by tight coupling and subtle balance between radiative cooling/heating, turbulence mixing, entrainment drying, microphysics, surface fluxes, and other processes (Wood 2012) and thus exert complex feedbacks on the climate system (Stephens 2005).

The lack of coastal stratocumulus is a well-known and robust problem in a number of general circulation models (GCMs) (e.g., Schmidt et al. 2006; Donner et al. 2011; Voldoire et al. 2012) participating in phase 5 of the Coupled Model Intercomparison Project (CMIP5). Because of deficient coastal stratocumulus, an ensemble mean of 20 GCMs from CMIP5 shows striking positive biases in shortwave cloud forcing along the west coasts of North America, South America, and Africa (see

Corresponding author address: Huan Guo, UCAR Visiting Scientist Programs, NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08540.
E-mail: huan.guo@noaa.gov

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Fig. 1d in Hwang and Frierson 2013). The Geophysical Fluid Dynamics Laboratory (GFDL) CMIP5 Atmospheric Model (AM3) improves upon the physical realism of the previous-generation model (AM2; Anderson et al. 2004) by implementing new convective parameterizations, an aerosol activation parameterization, and a comprehensive atmospheric chemistry package. The AM3 climatology is more realistic for most fields against a suite of global observations and reanalyses (Donner et al. 2011). In coupled atmosphere–ocean mode [i.e., the GFDL Coupled Climate Model (CM3)], sea surface temperature climatology in the marine stratocumulus regime off the west coast of South America also improves (Griffies et al. 2011, their Fig. 2). However, deficient stratocumulus persists from AM2/CM2 simulations. This is perhaps not surprising since the planetary boundary layer (PBL) and cloud macrophysical parameterizations remain essentially unchanged. As highlighted by Donner et al. (2011), addressing the coastal stratocumulus bias is a high priority for future model development.

Coastal stratocumulus decks break up as they gradually transition offshore to shallow cumulus with a much lower reflectivity. This transition is rather smooth, and cloud properties vary continuously. However, parameterizations have often been developed for specific cloud regimes (Lock et al. 2000; Bretherton and Park 2009). The categorization of clouds in distinct regimes is more or less artificial. It introduces inconsistencies between different parameterizations and poses challenges when combining the various components to function together. Recently, eddy-diffusivity mass flux (EDMF) schemes have been proposed to unify dry convective, shallow cumulus and stratocumulus-topped boundary layers. However, the criterion to differentiate between regimes (usually referred to as decoupling criterion) is critical for a realistic simulation of stratocumulus (Siebesma et al. 2007; Neggers et al. 2009; Neggers 2009; Köhler et al. 2011). A uniform treatment of low-level clouds, capable of representing a variety of regimes without regime-specific adjustments, would represent a significant advance.

Motivated by these scientific needs, we have incorporated a unified turbulence and cloud parameterization in AM3. This parameterization is known as Cloud Layers Unified by Binormals (CLUBB; http://clubb.larson-group.com; Larson and Golaz 2005; Golaz et al. 2007). CLUBB predicts the evolution of subgrid variations in vertical velocity, temperature, and total water in every model grid box (Larson et al. 2002; Golaz et al. 2002a,b). Probability density functions (PDFs) representing subgrid variations in moisture and/or temperature have been used for parameterizing cloudiness since Mellor (1977). Although the inclusion of vertical velocity in the PDFs was proposed by Randall et al. (1992) and Lappen and Randall (2001), application of these PDFs using binormals in climate models is novel. It is well known that aerosol activation depends on local supersaturation and hence vertical velocity at scales far below those resolvable by climate models with horizontal spacing of approximately 100 km. Because of the significant subgrid variability in vertical velocity (Donner et al. 1999) and the nonlinear dependence of aerosol activation on vertical velocity, using average fields from coarse-resolution climate models for the purpose of aerosol activation would be highly problematic. The subgrid vertical velocity predicted by CLUBB can be used for aerosol activation (Guo et al. 2010). Subgrid cloud water variations are also important because many microphysical processes depend nonlinearly on cloud water (Pincus and Klein 2000; Larson et al. 2001b). The Morrison and Gettelman (2008, hereafter MG) two-moment microphysics scheme accounts for critical subgrid cloud water variations. However, their treatment of subgrid cloud water variations is highly simplified by assuming a constant relative variance of cloud water. CLUBB, as a PDF-based scheme, is able to provide these subgrid variations explicitly (Golaz et al. 2002a,b). In so doing, CLUBB is able to couple and interact with other process parameterizations in a more physically sound manner.

CLUBB is a partial third-order turbulence closure scheme coupled with an assumed PDF (Larson et al. 2002; Golaz et al. 2002a,b). It predicts 8 second-order moments and 1 third-order moment. These moments are in turn used to select a particular PDF member from the assumed-PDF family for every grid point and time step. Higher-order moments and buoyancy terms are closed through integration over the particular PDF. The assumed-PDF family takes the form of a double Gaussian for several reasons. First, a double-Gaussian PDF agrees well with observations in the marine boundary layer and large eddy simulations (Larson et al. 2001a; Bogenschutz et al. 2010; Perraud et al. 2011). Second, a Gaussian PDF allows for an analytical diagnosis of cloud fraction and cloud condensate (Mellor 1977). Third, and perhaps most importantly, it is able to represent both symmetric and skewed distributions. A symmetric distribution is appropriate for stratocumulus clouds with little skewness, but cumulus layers are typically highly skewed (Bechtold et al. 1995). A double-Gaussian PDF can accommodate positively, negatively, and neutrally skewed cloud regimes and thereby provide a uniform treatment of a variety of cloud regimes.

Single-column simulations with CLUBB incorporated in AM3 (AM3–CLUBB) have been described in Guo et al. (2010, 2011). CLUBB has recently also been implemented in the National Science Foundation–U.S. Department of Energy–National Center for Atmospheric
Research (NSF–DOE–NCAR) Community Atmosphere Model (CAM–CLUBB; Bogenschutz et al. 2012, 2013). This paper documents the performance of AM3–CLUBB for global simulations and is organized as follows: Section 2 describes the base model and its configuration. Section 3 evaluates base model results. Section 4 investigates the sensitivity to horizontal resolution. Section 5 presents additional sensitivity tests to CLUBB, adjustable CLUBB parameters, and subgrid cloud water variations. We summarize our findings in section 6.

2. Model description and configuration

a. Brief description of the GFDL AM3

The GFDL AM3 (Donner et al. 2011) has been developed based on the GFDL AM2 (Anderson et al. 2004) and includes a number of new features and treatments. AM3 uses a finite-volume dynamical core based on a cubed-sphere grid (Putman and Lin 2007). AM3’s top is near 1 Pa with 48 vertical levels.

Table 1 summarizes the moist convection and cloud parameterizations in AM3. The deep convection parameterization employs a mass flux scheme (Donner scheme; Donner 1993; Donner et al. 2001), which considers deep updraft cells, meso-scale updrafts, and mesoscale downdrafts. The shallow convection parameterization is based on Bretherton et al. (2004), developed at the University of Washington (UW), with modifications as described in Zhao et al. (2009). The PBL treatment follows Lock et al. (2000) for convective PBLs and stratocumulus layers. The cloud macrophysics is parameterized according to Tiedtke (1993). The cloud microphysical parameterization is a one-moment scheme, except for cloud water. It follows Rotstayn (1997) with updated treatment of mixed-phase stratiform clouds (Rotstayn et al. 2000) and also includes some important changes as discussed in Anderson et al. (2004). AM3 microphysics, referred to as Rotstayn–Klein, also includes a prognostic equation for cloud droplet number to allow for interactions between aerosols and clouds (Ming et al. 2006, 2007; Golaz et al. 2011).

b. Base configuration of AM3–CLUBB

CLUBB is a unified turbulence and cloud parameterization. In AM3–CLUBB, the shallow convection, PBL, and cloud macrophysical parameterizations are all replaced by CLUBB (Table 1). In our implementation, the moist process parameterizations in AM3–CLUBB are called in the order of Donner deep convection, CLUBB, and finally MG microphysics.

Donner deep convection yields convective fraction and vertical velocity. The product of the convective fraction and vertical velocity is subtracted from the grid-mean vertical velocity, so only the environmental vertical velocity (outside convection) is “seen” by CLUBB. CLUBB produces total condensate concentrations (i.e., the sum of liquid and ice): the cloudy-area average of which is fed into the MG microphysics. The MG microphysics is responsible for the conversion from liquid to ice via the Wegener–Bergeron–Findeisen, freezing, riming, and other processes; MG also converts condensate to precipitation (i.e., rain and snow). As the shallow convection parameterization is removed and replaced by CLUBB, the MG microphysics is responsible for both shallow convective and large-scale stratiform precipitation. It is noted that the subgrid variations of temperature and moisture, except cloud water variations (as discussed in section 2b), are not fed into MG. The full application of CLUBB subgrid variations to the MG microphysics will be considered for future work. With the incorporation of the MG two-moment microphysics in AM3–CLUBB, both liquid droplet and ice particle number concentrations are prognostic.

The treatment of turbulent transport of tracers (e.g., aerosols and chemical species) is similar to that in AM3, except that eddy-diffusion coefficients are based on CLUBB’s turbulence kinetic energy and length scale.

1) AEROSOL ACTIVATION AND DROPLET AND ICE NUMBER

One advantage of CLUBB is its subgrid PDF of vertical velocity, which offers a natural link to aerosol activation. In AM3–CLUBB, a mechanistic aerosol activation scheme is employed (Ming et al. 2006), which diagnoses
the activated droplet number concentration as a function of vertical velocity and aerosol characteristics and concentrations. The subgrid vertical velocity from CLUBB is sampled by the Ming et al. (2006) algorithm to calculate aerosol activation. Then, a numerical integration over the vertical-velocity PDF is performed to obtain a grid-averaged activated droplet number concentration, using a 196-point Gauss–Hermite quadrature.

The aerosol activation scheme provides a preliminary estimate for cloud droplet number concentration. Cloud droplets are also subject to large-scale transport, turbulence mixing, evaporation, collision, and coalescence. A budget equation, which takes these processes into account, is used to prognose cloud droplet number concentration. A detailed description of the treatment of droplet number is presented in Guo et al. (2010).

The ice particle number concentration is predicted following Salzmann et al. (2010). However, ice particle sizes are not linked to ice number concentration. Ice optical properties remain as functions of temperature and convective-system properties as in AM3 [see section 3a(2) in Donner et al. (2011)]. Including the ice particle size in the radiation, as well as rain and snow, will be reserved for future work.

2) CLOUD MICROPHYSICS

To explore aerosol–cloud interactions, MG two-moment microphysics has been adopted in AM3–CLUBB (MG; Salzmann et al. 2010). The MG microphysics scheme explicitly treats the cloud water subgrid variability for computing microphysical process rates for autoconversion, accretion, and immersion freezing. These process rates decrease with $\nu$, where $\nu$ is the inverse of relative variance for in-cloud cloud water $\nu = q_{c,\text{in,cld}}^2/\text{Var}(q_{c,\text{in,cld}})$, and $q_{c,\text{in,cld}}$ and Var$(q_{c,\text{in,cld}})$ are the mean and variance of cloud water mixing ratio in cloudy areas, respectively. In the MG microphysics, $\nu$ is assumed to be a constant. Observationally, $\nu$ can vary substantially; for example, Barker et al. (1996) report cloud optical depth variances normalized by mean optical depths to range over a factor of 10 or more. Furthermore, MG showed that the autoconversion rate can be enhanced by a factor of more than 6 by changing the value of $\nu$. As a result, global simulations are very sensitive to $\nu$ (Gettelman et al. 2008).

Instead of setting $\nu$ to be a constant, we relate $\nu$ to the subgrid variation of cloud water in a model grid box using the following expression:

$$\nu = \frac{q_c^2}{CF \times \text{Var}(q_c) - (1 - CF)q_c^2},$$

where $q_c$ and Var$(q_c)$ are mean and variance of cloud water mixing ratio in a model grid box $q_c$, respectively, and CF is cloud fraction. The terms $\overline{q_c}$, Var$(q_c)$, and CF are analytically diagnosed from CLUBB. A detailed derivation of Eq. (1) is presented in appendix A. Noting that $\nu$ becomes unbounded when Var$(q_{c,\text{in,cld}}^2)$ becomes small and Eq. (1) becomes unphysically negative when CF becomes small, we have bounded $\nu$ in AM3–CLUBB between 0.01 and 2.0. More detailed discussions on these bounds are presented in section 5.

CLUBB and MG microphysics assume different subgrid distribution forms. CLUBB uses a double-Gaussian form, while MG microphysics adopts a gamma distribution, so the CLUBB cloud water subgrid variations are not directly applicable to the MG microphysics. This discrepancy notwithstanding, using Eq. (1) instead of a constant value for $\nu$ allows temporal and spatial variations in the subgrid structure of cloud water associated with different cloud regimes to impact cloud microphysics. Most of the $\nu$ values for cumulus range from 1 to 1.5, and most of the stratocumulus values range from 2 to 5 in the single-column model CLUBB simulations reported in Guo et al. (2010). Barker et al. (1996) report that inverse normalized optical depths are generally less than 1 for cumulus and from 1 to 8 for stratocumulus, so, in agreement with Barker et al. (1996), CLUBB values of $\nu$ are generally smaller for cumulus than for stratocumulus.

MG’s subgrid enhancements of microphysical process rates are a result of variability in cloud water, while the effects of the correlations between cloud water and other hydrometeors are ignored. Rain production depends on cloud water amount, and therefore rain and cloud water are likely to be correlated. Based on satellite retrievals, Lebsock et al. (2013) show that the average accretion rate may be enhanced by a factor of 1.6 when the correlation between cloud water and rainwater is considered. Therefore, the accretion rate has been enhanced by a factor of 1.1 globally, in addition to the enhancement resulting from cloud water variability.

3) CLOUD MACROPHYSICS

The CF is analytically diagnosed by integrating the joint PDF over saturated portions: that is,

$$\text{CF} = \int_w \int_{q_s} \text{PDF}
\left(q_v \geq q_{\text{sat}} \right) dw d\theta_t dq_v,$$

where $q_v$ is specific humidity, $q_{\text{sat}}$ is saturated specific humidity, $w$ is vertical velocity, $\theta_t$ is liquid water potential temperature, and $q_v$ is total water specific humidity. For warm clouds, the treatment of $q_{\text{sat}}$ is straightforward, but ice clouds or mixed-phase clouds are more complex. Unlike droplet activation, ice nucleation needs supersaturation with respect to ice; for example, 40% supersaturation
Table 2. Configurations of AM3–CLUBB base and sensitivity tests in this study. Tests are with CLUBB on or off (AM3–MG); horizontal resolution of 0.5°, 1°, or 2°; physical and CLUBB time steps (Δt_{phys}/Δt_{CLUBB}) of either 20 and 2 min or 30 and 3 min; inverse of relative variance for in-cloud cloud water v of 1 or based on Eq. (1) with spatial and temporal variability; tuned CLUBB parameters Y or not (N); enhancement factor (E_{acc}) of accretion rate (related to the correlation of rain and cloud water); and analysis period of either from 1981 to 2000 or from 1981 to 1985.

<table>
<thead>
<tr>
<th>Name</th>
<th>CLUBB Resolution</th>
<th>Δt_{phys}/Δt_{CLUBB} (min)</th>
<th>v</th>
<th>Tuned</th>
<th>E_{acc}</th>
<th>Analysis period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>on</td>
<td>1°</td>
<td>20/2</td>
<td>variable</td>
<td>Y</td>
<td>1.1</td>
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<tr>
<td>Sensitivity tests</td>
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<tr>
<td>Resolution</td>
<td>on</td>
<td>0.5°</td>
<td>20/2</td>
<td>variable</td>
<td>Y</td>
<td>1.1</td>
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<tr>
<td>Tuning and cloud water variability</td>
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<tr>
<td>AM3–MG (no CLUBB)</td>
<td>off</td>
<td>1°</td>
<td>20/—</td>
<td>1</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>No tune, v = 1, and no Enhance_Accr</td>
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<tr>
<td>Tune only</td>
<td>on</td>
<td>1°</td>
<td>20/2</td>
<td>1</td>
<td>N</td>
<td>1</td>
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<tr>
<td>Variable v only</td>
<td>on</td>
<td>1°</td>
<td>20/2</td>
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<tr>
<td>Tuning + variable v + Enhance_Accr</td>
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<td>variable</td>
<td>Y</td>
<td>1</td>
</tr>
</tbody>
</table>

For homogeneous ice nucleation. Therefore, the treatment of q_{sat} should allow for ice supersaturation.

To apply Eq. (2) for both liquid and ice clouds, we treat q_{sat} as follows: For air temperature T = 0°C, q_{sat} is the saturation specific humidity with respect to liquid water q_{sl}. To allow ice supersaturation when T < 0°C and allow ice nucleation to occur when T < −5°C and also in order to obtain a smoother transition of q_{sat} from liquid to ice when −5°C ≤ T < 0°C (Liu et al. 2007; Salzmann et al. 2010), we take q_{sat} to be a linear combination of saturation with respect to liquid q_{sl} and ice q_{si}. Note that q_{si} and q_{sl} are functions of temperature. Below −35°C, q_{sat} is the saturation specific humidity with respect to ice but multiplied by a critical relative humidity RH_{c} that is required for ice nucleation (Liu and Penner 2005; Salzmann et al. 2010). In the range between −35°C and −5°C, q_{sat} depends on q_{si} and a linear combination of the critical relative humidity at −35°C and the 100% relative humidity at −5°C. Therefore, q_{sat} can be written as

\[
q_{sat} = \begin{cases} 
q_{sl}, & \text{if } T \geq 0°C; \\
q_{sl} \left(1 + \frac{|T|}{5}\right), & \text{if } 0°C > T \geq −5°C; \\
q_{si} \left(T + \frac{35}{30} + RH_{c} \frac{|T| − 5}{30}\right), & \text{if } −5°C > T \geq −35°C; \\
q_{si} RH_{c}, & \text{if } T < −35°C.
\end{cases}
\tag{3}
\]

Combining Eqs. (2) and (3) yields a unified treatment for warm and ice cloud fraction. The value of q_{sat} varies continuously with temperature and accommodates ice supersaturation. Because of our limited physical understanding of ice cloud processes, there are significant uncertainties associated with this treatment when T is below 0°C. For example, RH_{c} varies over a wide range depending on aerosol composition, aerosol number concentration, updrafts, and temperature (Liu and Penner 2005). More physically based treatments of supersaturation that depend explicitly on vertical velocity (e.g., Phillips et al. 2007) should be explored within the CLUBB framework.

3. Global model results

The base results in this study are from 20-yr global simulations where sea surface temperature (SST) and sea ice are prescribed following the Atmospheric Model Intercomparison Project (AMIP) (Gates 1992; Gates et al. 1999). The cubed-sphere grids in both AM3–CLUBB and AM3 simulations have 90 × 90 points on each face (c90; corresponding to a horizontal resolution of approximately 1° or 100 km). The time steps are 2 and 20 min for CLUBB and other physical parameterizations, respectively. The simulation period is from 1 January 1980 to 31 December 2000. The first year is considered as a spinup, and the climatology for the period 1981–2000 is analyzed in this section (Table 2).
a. Shortwave cloud forcing

Metrics based on cloud radiative forcing provide discriminating evaluations of global simulations of cloud and radiation fields (Pincus et al. 2008), so we first present the annual-mean shortwave cloud forcing (SWCF) at the top of the atmosphere in Fig. 1. The agreement between AM3–CLUBB and the Clouds and the Earth’s Radiant Energy System—Energy Balanced and Filled climatology (CERES–EBAF; Loeb et al. 2009) for the period 2000–10 is generally good. AM3–CLUBB is able to simulate the spatial distributions of major cloud systems. There are negative biases over the tropical Indian Ocean, western Pacific, Southern Ocean, and Atlantic in both AM3–CLUBB and AM3, indicating excessive cloudiness there. Compared to AM3, coastal stratocumulus cloud biases are significantly reduced, especially near Africa and South America, although they are still underestimated as illustrated by positive biases. The reduction of the positive biases suggests that the representation of the PBL and cloud macrophysics is improved in AM3–CLUBB in the major marine stratocumulus regions. This is encouraging especially because the lack of coastal stratocumulus has been a robust bias in GFDL climate models, persisting in both AM2 and AM3. Additionally, this bias is also a common problem in other state-of-the-art climate models (Schmidt et al. 2006; Voldoire et al. 2012).

The seasonal cycles of subtropical stratocumulus are also important. The strongest (most negative) SWCF tends to occur around local summer or autumn season, and the weakest occurs around local winter or spring. These seasonal cycles are closely related to insolation (Klein and Hartmann 1993). We examine the seasonal variations of SWCF over three prevalent subtropical marine stratiform regions in Fig. 2: Peru (80°–90°W, 10°–20°S), Namibia (0°–10°E, 10°–20°S), and California (120°–130°W, 20°–30°N), as analyzed by Klein and Hartmann (1993). In the Peruvian region, the SWCF magnitude peaks around −100 W m$^{-2}$ during austral spring and is weakest (about −45 W m$^{-2}$) during austral late summer and fall in CERES–EBAF. AM3–CLUBB has the strongest (most negative) SWCF of about −83 W m$^{-2}$ in November and the weakest SWCF of about −59 W m$^{-2}$ during June and July. However, AM3 behaves quite differently, with dual peaks during May and November and the weakest SWCF during February and August. The magnitude of SWCF in AM3 is generally smaller than CERES–EBAF or AM3–CLUBB.

In the Namibian region, SWCF is the strongest (most negative) during September–November (SON) and the weakest during May according to CERES–EBAF. SWCF in AM3–CLUBB and AM3 have similar seasonal cycles,

![Fig. 1. Annual-mean SWCF (W m$^{-2}$) for (a) AM3–CLUBB, (b) CERES–EBAF, (c) AM3–CLUBB model error, and (d) AM3 model error. The boxes indicate subtropical stratocumulus regions, Peru (80°–90°W, 10°–20°S), Namibia (0°–10°E, 10°–20°S), and California (120°–130°W, 20°–30°N), analyzed by Klein and Hartmann (1993).]
except that the magnitude in AM3–CLUBB is larger and more realistic than that in AM3 by about 20 W m$^{-2}$.

The magnitude of SWCF in the Californian region reaches its maximum during boreal summer and its minimum during boreal winter in CERES–EBAF. Both AM3 and AM3–CLUBB underestimate the amplitude of the seasonal cycle, but AM3–CLUBB is more realistic than AM3 in both phase and amplitude.

b. Longwave cloud forcing

Figure 3 shows the annual-mean longwave cloud forcing (LWCF). AM3–CLUBB captures the major characteristics of the LWCF field. LWCF is biased low in the midlatitudes in both AM3 and AM3–CLUBB, implying that ice clouds are underestimated. The negative bias in AM3–CLUBB is larger than AM3, but it is comparable to the bias in AM3 using a similar MG implementation reported in Salzmann et al. (2010, their Fig. 3d), especially in the Southern Hemisphere. We suspect that the negative bias in Fig. 3 might be associated with the ice nucleation parameterization and supersaturation approach in Eq. (3), as the simulated ice clouds are sensitive to nucleated ice number concentrations in the midlatitudes. Over the tropical Indian Ocean and western tropical Pacific, there are negative biases in AM3–CLUBB but positive biases in AM3. These negative biases are related to the fraction of ice detrained from convective anvils to large-scale stratiform clouds in the deep convection parameterization, which was tuned from 5% to 1% in order to reduce outgoing longwave radiation bias in the tropics after CLUBB and MG microphysics are incorporated in AM3, similarly to Salzmann et al. (2010). The fraction of ice detrained from convective anvils to large-scale stratiform clouds is defined as the ratio of the vertical integral of ice transfer from convective anvils into large-scale stratiform clouds to the sum of the vertical integrals of lateral transfer of condensate from convective updraft cells into convective anvils and condensation and deposition in convective anvils. Full details are available in Donner et al. (2011, section 3e) and Donner (1993). While an intermediate tuning of the convective detrainment fraction would likely reduce the LWCF biases in deep convection regions, the global-mean outgoing longwave radiation would be negatively impacted.

c. Precipitation

Annual-mean precipitation is displayed in Fig. 4. With respect to the precipitation reported by version 2 of the Global Precipitation Climatology Project (GPCP v.2; Adler et al. 2003), positive (wet) model biases prevail. Regarding these apparent biases in both AM3 and AM3–CLUBB relative to GPCP, Kato et al. (2011) showed that net surface irradiances imply global-mean precipitation about 15%–20% higher than GPCP. An analysis of recent satellite observations by Stephens et al. (2012) indicates the global-mean precipitation is likely between the GPCP estimates and 25% higher.

Both AM3 and AM3–CLUBB biases mainly occur in the tropics. There are wet biases in the tropical Pacific and Indian Oceans. The partitioning of precipitation in both AM3 and AM3–CLUBB shows that precipitation in the tropics mainly originates from deep convection while large-scale precipitation dominates in the midlatitudes (Figs. 5a,b). AM3–CLUBB also overestimates precipitation over the Amazon basin and tropical Africa (Fig. 4c). These wet biases might be associated with the deep convection parameterization, with the differing South American and African biases in AM3 and AM3–CLUBB indicating differing behavior of deep convection.
FIG. 3. Annual-mean LWCF (W m\(^{-2}\)) for (a) AM3–CLUBB, (b) CERES–EBAF, (c) AM3–CLUBB model error, and (d) AM3 model error.

FIG. 4. Annual-mean precipitation (mm day\(^{-1}\)) for (a) AM3–CLUBB, (b) GPCP v.2, (c) AM3–CLUBB model error, and (d) AM3 model error.
when CLUBB replaces the corresponding AM3 parameterizations.

In AM3–CLUBB, the shallow convection parameterization is turned off and replaced by CLUBB (Table 1). As a result, the shallow convective precipitation is included in the precipitation associated with CLUBB. The CLUBB-associated precipitation in AM3–CLUBB is higher than the large-scale (stratiform) precipitation (Figs. 5a,b) but less than the sum of stratiform and shallow convective precipitation, in AM3 (Fig. 5c). Meanwhile, the deep convective precipitation is higher in AM3–CLUBB than in AM3 (Fig. 5d).

More deep convective precipitation but less shallow precipitation in AM3–CLUBB might suggest that some deep convective plumes act like shallow plumes. This is corroborated by temperature tendencies from the relevant parameterizations (Fig. 6). From 15°S to 15°N, AM3 has stronger heating from the shallow convection and large-scale parameterizations than CLUBB, especially near the equator and in the Southern Hemisphere (Figs. 6a,b). The heating from the deep convection parameterization in AM3 peaks around 400–500 hPa, but in AM3–CLUBB, the maximum heating (>2 K day⁻¹) extends to a lower altitude of approximately 800 hPa (Figs. 6c,d). With and without CLUBB, the deep convective parameterization behaves quite differently. It is more active and partly takes over shallow convection and thus produces more precipitation in AM3–CLUBB.

Moist adiabatic adjustment (Manabe et al. 1965) is turned off in AM3–CLUBB but remains in AM3 in order to hinder the development of unstable and/or over-saturated conditions in saturated atmosphere. Nevertheless, in AM3 it only contributes a small amount of precipitation (Fig. 5a), suggesting that most instabilities are largely removed by convection and large-scale parameterizations.

**d. Aerosol optical depth**

To better address aerosol–cloud interactions, aerosol mass concentrations and optical properties are calculated online in AM3 and AM3–CLUBB. Aerosols are...
mostly emitted or chemically produced in the boundary layer where their lifetime is a few days because of efficient dry deposition by turbulent mixing and washout by precipitating clouds. By modifying turbulence and cloud parameterizations, it could be expected that aerosol lifetime, aerosol distributions, and optical depths could differ in AM3 and AM3–CLUBB.

Figure 7 compares annual-mean aerosol optical depth (AOD) around 550 nm simulated by AM3 and AM3–CLUBB with retrievals from the Multiangle Imaging Spectroradiometer (MISR) data (Diner et al. 1998; Kahn et al. 2005). The distribution of AOD for AM3–CLUBB is closer to MISR than AM3 in most places, as illustrated in Figs. 7c and 7d, and further corroborated by a smaller global-mean bias, a smaller root-mean-square error (rmse), and a higher correlation. The largest differences are in arid regions (West Africa and Arabian Peninsula). On the other hand, in midlatitude polluted regions such as in eastern Europe, AOD decreases in AM3–CLUBB with values closer to MISR. We also notice a better agreement in the Indo-Gangetic basin with an increased AOD in AM3–CLUBB. When compared with the Aerosol Robotic Network (AERONET) (Holben et al. 1998), AM3–CLUBB also shows a slightly improved global correlation relative to AM3 (0.75 versus 0.73).

e. Climatological skill

A summary view of the performance of AM3–CLUBB is given by target diagrams (Jolliff et al. 2009) in Fig. 8. The differences between model simulations and global observations are displayed in terms of normalized model bias and unbiased root-mean-square difference (RMSD). An overview of various global annual-mean diagnostics is also available in Table 3.

Although AM3–CLUBB and AM3 have comparable biases and root-mean-square differences for shortwave absorbed radiation (SWABS) and outgoing longwave radiation (OLR), AM3–CLUBB shows slightly larger magnitude biases and differences in SWCF and LWCF than AM3. AM3–CLUBB shows less spatial variability in LWCF than observation, while AM3 shows larger variability.

For most fields, AM3–CLUBB has slightly larger magnitude biases and root-mean-square differences than AM3.
Among the 11 fields evaluated in Fig. 8, LWCF and sea level pressure (SLP) have the largest difference between AM3–CLUBB and AM3. Most fields do not exhibit large differences in skill between AM3 and AM3–CLUBB. For SWCF, LWCF, and precipitation, key fields related to clouds, AM3–CLUBB performs similarly to CAM–CLUBB (Bogenschutz et al. 2013). For example,
SWCF biases and root-mean-square errors are $-2.8$ and $10.3 \text{ W m}^{-2}$ in AM3–CLUBB and $-1.8$ and 12.45 W m$^{-2}$ in CAM–CLUBB. For LWCF, the corresponding errors are $-3.6$ and 7.2 W m$^{-2}$ in AM3–CLUBB and $-4.7$ and 7.61 W m$^{-2}$ in CAM–CLUBB. Root-mean-square errors for precipitation are 1.15 and 0.97 mm day$^{-1}$ in AM3–CLUBB and CAM–CLUBB, respectively. Over the continental United States, AM3–CLUBB exhibits a positive SWCF bias. The reason is unclear. However, such bias is not present in CAM–CLUBB. Over the Southern Ocean, CAM–CLUBB shows a positive bias, while AM3–CLUBB does not (our Fig. 1c and Fig. 4 in Bogenschutz et al. 2013).

When compared to the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) or the Moderate Resolution Imaging Spectroradiometer (MODIS) (King et al. 2003), both AM3–CLUBB and CAM–CLUBB significantly underestimate liquid water path (LWP) (our Table 3 and Table 3 in Bogenschutz et al. 2013). However, there are large uncertainties associated with satellite retrievals; for example, the LWP retrievals from AMSR-E differ appreciably from MODIS. A comprehensive comparison between AM3–CLUBB and CAM–CLUBB is beyond the scope of this paper.

### 4. Sensitivity to resolution

In addition to the base simulations discussed in section 3, we have performed sensitivity tests at different horizontal resolutions of $180 \times 180$ points (c180; approximately 0.5° or 50 km) and $48 \times 48$ points (c48; approximately 2° or 200 km) with an unchanged vertical grid. In 2° resolution tests, physical and CLUBB time steps are adjusted to be 30 and 3 min, respectively. The positive SWCF biases of coastal stratocumulus near Peru, Namibia, and California are smaller in AM3–CLUBB than AM3 at all resolutions and become smaller in AM3–CLUBB at higher resolution (Figs. 1, 9, and 10a). In contrast, these biases are less sensitive to resolution in AM3 (Fig. 10a). Unlike marine stratocumulus, AM3–CLUBB SWCF global metrics are fairly insensitive to resolution (Figs. 1 and 9a,b).

Figure 10b presents the seasonal cycles of SWCF at different resolutions near Peru, where the largest subtropical stratocumulus persists (Wood 2012). Although the seasonal variations in AM3–CLUBB differ from those in AM3, they illustrate similarities at different resolutions, especially at 0.5° and 1°. In AM3–CLUBB, at higher resolution, the monthly-mean SWCF tends to become more negative (a smaller positive annual-mean bias; Fig. 10a) and larger cloud fraction and liquid water content (Figs. 11a,b).

As compared to the reference vertical profiles from European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) dataset (Dee et al. 2011), AM3–CLUBB underestimates cloud water at 0.5°, 1°, and 2° but overestimates cloud fraction at 0.5° and 1°. Meanwhile, AM3 underestimates both cloud fraction and cloud water at all resolutions, leading to a more positive SWCF bias (Fig. 10a). Both cloud fraction and liquid water content tend to increase with resolution (Figs. 11a,b), partly because the temperature and moisture gradients near inversion layers are better resolved, and this compares more favorably with ERA-Interim in higher-resolution simulations (Fig. 11c,d). Also note that higher resolution better resolves coastal topography, such as the Andes and coastal mountains of California and Namibia, which is conducive to the better representations of vertical profiles and more realistic simulations of coastal stratocumulus.
We notice that differences of vertical profiles between 2° and 1° are larger than those between 1° and 0.5° (Fig. 11). This is consistent with more significant improvements in AM3–CLUBB coastal stratocumulus from 2° to 1° than from 1° to 0.5° (Figs. 1c and 9a,b).

AM3–CLUBB generally displays similar spatial patterns for longwave cloud forcing at all resolutions. An exception is a larger negative bias in tropical western Pacific, at higher resolution (Figs. 3 and 12a,b). This larger negative bias may be related to the ice fraction detrained from convective anvil as discussed in section 3b. AM3 exhibits a substantial reduction in the positive bias over the western Pacific and Indian Oceans as the resolution is increased from 2° to 0.5° (Figs. 12c,d). In both AM3 and AM3–CLUBB, LWCF decreases in the western Pacific at higher resolution.

For precipitation, AM3’s global metrics decline somewhat more at higher resolution than AM3–CLUBB’s, and there are some regional changes. For example, AM3–CLUBB shows more excess precipitation in South America and Africa at higher resolution (Figs. 4 and 13a,b). In AM3, the precipitation over the Andes becomes excessive as resolution increases, but wet bias over Indian Ocean is reduced slightly (Figs. 4 and 13c,d). Note that CLUBB or deep convection parameters have not been retuned in the resolution sensitivity experiments.

Table 4 shows some global metrics (e.g., root-mean-square error of SWABS) exhibit reduced sensitivity to model horizontal resolution in AM3–CLUBB. The reduced sensitivity to horizontal grid spacing $\Delta x$ has been reported by Larson et al. (2012) and Bogenschutz and Krueger (2013). The reduced sensitivity is partly a result of the dependence of turbulent length scale $L$ on $\Delta x$ (Larson et al. 2012). As grid spacing becomes smaller, $L$ and CLUBB’s contribution to the flow evolution become smaller but model dissipation becomes stronger. Subgrid variance is smaller, so that CLUBB’s impacts become weaker and cloud circulations are more governed by model dynamics. The dependence of $L$ on $\Delta x$ makes CLUBB become “scale aware” (Ringler et al. 2011; Larson et al. 2012) and thus adjust its impacts according to $\Delta x$. A significant benefit from CLUBB’s internal dependence of $L$ on $\Delta x$ is that less tuning is required.

Nevertheless, this reduced sensitivity does not necessarily mean that AM3–CLUBB model results may not be further improved with higher resolution. Coastal stratocumulus clouds and their profiles are simulated more realistically at 1° or higher (Figs. 10, 11). Although the dependence of $L$ on $\Delta x$ built into CLUBB may reduce the need for tuning at different resolutions and provide scale awareness, improvements with increasing
resolution of the host model can still be expected. As the explicitly represented dynamics and physics of the host model are more sharply represented at higher resolution, the role of the subgrid parameterization, which inevitably is an approximate representation of the unresolved flow, lessens.

5. Sensitivity to microphysics, CLUBB parameters, and subgrid cloud water variability

In addition to the incorporation of CLUBB, AM3–CLUBB differs from AM3 in its cloud microphysics parameterization (Table 1). AM3–CLUBB adopts the MG two-moment scheme, while AM3 employs the Rotstayn–Klein one-moment scheme (Donner et al. 2011). Therefore, the differences between AM3–CLUBB and AM3 model results are partly due to microphysical schemes, as well as CLUBB. To explore the impacts of the microphysics schemes, we conduct a sensitivity test, which is the same as AM3, except that the Rotstayn–Klein one-moment scheme has been replaced by the MG two-moment scheme (Salzmann et al. 2010), referred to as AM3–MG (Table 1). The major difference between AM3–MG and AM3–CLUBB is whether CLUBB is active (Table 2).

Cloud and turbulence processes are often subgrid scale and interact with each other. Their parameterizations in GCMs often contain approximations and adjustable parameters. Some parameters cannot be derived theoretically or from observations, and thus tuning is often unavoidable in global applications (Anderson et al. 2004; Schmidt et al. 2006; Donner et al. 2011; Voldoire et al. 2012; Bogenschutz et al. 2013; Golaz et al. 2013). With the incorporation of CLUBB into AM3, some CLUBB parameters were adjusted in order to achieve energy balance and increase realism of global simulations. These adjusted parameters are mainly associated with dissipation, mixing length scale, pressure terms, and skewness for wind moments and scalar fluxes. The adjustment details are presented in appendix B.

Gettelman et al. (2008) pointed out that the MG microphysics scheme is sensitive to in-cloud cloud water variability. With and without such variability, the global-mean LWP and droplet effective radius can differ by 20%. We conduct sensitivity tests where the inverse of relative variance for in-cloud cloud water \( y \) is set to be a constant value of 1 or varies spatially and temporally based on the cloud water variability provided by CLUBB [see Eq. (1)]. As noted in section 2b, \( y \) is bounded between 0.01 and 2 in the AM3–CLUBB base configuration. Values less than 0.01 produced poor SWCF simulations. Larger values of \( y \) (smaller relative cloud water variance) correspond to slower autoconversion and more cloudiness. A sensitivity test with an upper bound of \( y \) of 10 has been conducted with AM3–CLUBB. Results show little sensitivity to larger values of \( y \) (not shown here). However, a wider range of [0.01, 10] imposes a weaker artificial constraint on \( y \), and would be more physically appealing. The implementation of MG microphysics uses a constant \( y \) value of 2 in the Community Atmosphere Model, version 5 (CAM5), and a variable \( y \) bounded between 0.001 and 1 in CAM–CLUBB (Bogenschutz et al. 2013).

Table 2 lists configurations of the sensitivity tests without and with CLUBB, with CLUBB parameters, and inverse relative variance \( y \). The horizontal resolution is approximately 1° and the analysis period is from 1981 to 1985. Five-year simulations are adequate to reliably estimate the sensitivities of cloud microphysics,
CLUBB parameters, and \( \nu \) on the fields of interest, as also noted by Park and Bretherton (2009) for their implementation of UW shallow convection scheme in CAM3.5.

Figure 14a shows the SWCF bias for AM3–MG with \( \nu = 1 \), no CLUBB, and no enhancement for accretion rate. Coastal stratocumulus clouds are improved relative to AM3 (Fig. 1d), especially near South America, where the transition from stratocumulus to trade wind cumulus is somewhat abrupt. Globally, the SWCF is biased low (\( \sim -5 \text{ W m}^{-2} \)). Additionally, the radiation at the top of the atmosphere is problematic; for example, both the absorbed shortwave and outgoing longwave radiation are approximately \( -8 \text{ W m}^{-2} \) lower than the corresponding CERES–EBAF observations. In this sensitivity test the microphysical, radiation, dynamical, and other configurations of AM3–MG are as close as possible to those of AM3–CLUBB in order to facilitate the comparison with AM3–CLUBB. More realistic simulations could probably be obtained after further tuning AM3–MG. However, a detailed discussion on optimizing AM3–MG is beyond the scope of this paper.

In Fig. 14b1, where CLUBB is active, CLUBB parameters are not tuned (appendix B), and \( \nu \) is 1, the radiation is significantly out of balance, with a net radiation at the top of the atmosphere of approximately \( -12 \text{ W m}^{-2} \). A strong negative bias of SWCF prevails with a global value of approximately \( -17 \text{ W m}^{-2} \). Furthermore, the positive bias of SWCF of coastal stratocumulus near California and Peru produces an unrealistic gradient between stratocumulus along the coasts and cumulus well offshore. After CLUBB parameters are tuned (Fig. 14b2), the negative bias gets smaller in shallow cumulus regimes and the positive bias of coastal stratocumulus almost disappears, leading to a higher correlation and an improved transition from stratocumulus to cumulus (Fig. 14b2). This increase of coastal stratocumulus is partly a result of the reduction of entrainment drying of stratocumulus layer (Köhler et al. 2011). Tuning the pressure-term coefficients for scalar fluxes and mixing length in CLUBB decreases the turbulence mixing of moisture and heat, thus preventing stratocumulus layers from being dried out by entraining drier air from the free atmosphere.

With spatially and temporally variable \( \nu \) [Eq. (1)], the negative bias and root-mean-square error are reduced substantially (Fig. 14b3). This bias reduction suggests that the removal of cloud water (or cloudiness) resulting from precipitation is more efficient for variable \( \nu \). More importantly with variable \( \nu \), depending on the subgrid variations of cloud water provided by CLUBB [see Eq. (1)], the simulation tends to have smaller values of \( \nu \) in cumulus regions than stratocumulus areas, as illustrated by a larger reduction of the negative bias in cumulus
regions (Fig. 14b3). This is physically reasonable and agrees with satellite observations (Barker et al. 1996). Combining the tuned CLUBB parameters with variable $v$ further improves the SWCF field (Fig. 14b4). Moreover, enhancing the accretion rate by a factor of 1.1 ($\text{Enhance\_Accr}$) slightly reduces the bias and root-mean-square error (Fig. 14b5). The configuration denoted “tune + variable $v$ + Enhance\_Accr” is the AM3–CLUBB base configuration described in section 2b (Table 2).

The impacts of the tuned CLUBB parameters and $v$ on LWCF and precipitation are weaker than on SWCF. The adjusted CLUBB parameters reduce the root-mean-square errors and increase the correlations somewhat, and the variable $v$ reduces the global cloudiness (not shown here).

6. Summary

A unified turbulence and cloud parameterization based on multivariate PDFs, CLUBB, has been incorporated into the GFDL AM3 GCM (AM3–CLUBB). CLUBB is a higher-order turbulence closure scheme coupled with a PDF approach. It uses a double-Gaussian functional PDF that is able to represent both highly skewed cumulus and unskewed stratocumulus regimes. CLUBB predicts the subgrid variations in vertical velocity, temperature, and total water. CLUBB subgrid vertical velocity and cloud water variations are used for aerosol activation and cloud microphysical parameterizations.

AM3–CLUBB global simulations compare favorably with a suite of global observations and reanalyses. There is a significant improvement in coastal stratocumulus clouds, which are severely underestimated in GFDL AM2 and AM3. The representation of coastal stratocumulus also improves with higher horizontal resolution. At higher resolution, AM3–CLUBB better represents the sharp temperature and moisture gradients near inversion layers. Also, the coastal mountains and abrupt transitions from mountains to ocean are better resolved. AM3–CLUBB produces more realistic cloud fraction and cloud water content. It also better captures the seasonal variability of stratocumulus than AM3. Moreover, AM3–CLUBB also simulates the aerosol optical depth more realistically.

The improved simulations of coastal stratocumulus could potentially have significant implications. A lack of coastal stratocumulus clouds would allow too much shortwave radiation to reach the ocean, develop large warm SST biases throughout the eastern tropical Pacific (Mechoso et al. 1995; Ma et al. 1996) and influence seasonal SST cycles (Gordon et al. 2000). Such SST biases
could impose nonlocal impacts on tropical circulations and phenomena, including El Niño–Southern Oscillation (ENSO) and intertropical convergence zone (ITCZ). A 20% reduction in low cloud fraction is able to affect seasonal ENSO forecasts (Gordon et al. 2000). Large and Danabasoglu (2006) show that SST biases are partially responsible for excess precipitation in the Southern Hemisphere tropics: that is, “double” ITCZ, perhaps one of the most longstanding and significant biases in the coupled atmosphere–ocean simulations.

Outside regions dominated by marine stratocumulus, cloud radiative forcing and precipitation are slightly inferior to those in AM3. With some slight variations among fields, AM3–CLUBB and CAM–CLUBB (Bogenschutz et al. 2013) are comparably skillful in their simulations of SWCF, LWCF, and precipitation.

Except for coastal stratocumulus, SWCF in AM3–CLUBB seems to be fairly insensitive to model horizontal resolution. This contrasts with AM3, in which SWCF global scores improve at higher resolution, while its poor simulation of coastal stratocumulus is insensitive to resolution.

Tuning CLUBB parameters improves the spatial patterns of cloudiness: for example, the transition from coastal stratocumulus to shallow cumulus, SWCF in subtropics and midlatitudes, and the correlations between model fields and observations. Allowing microphysical process rates to depend on the CLUBB subgrid cloud liquid variations reduces the global cloudiness and energy imbalance.

![Figure 13](image)

**FIG. 13.** As in Fig. 9, but for annual-mean error of precipitation (mm day$^{-1}$).

<table>
<thead>
<tr>
<th>Variable</th>
<th>AM3 resolution</th>
<th>AM3–CLUBB resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5°</td>
<td>1°</td>
</tr>
<tr>
<td></td>
<td>0.5°</td>
<td>1°</td>
</tr>
<tr>
<td>LCA (%)</td>
<td>12.1</td>
<td>13.6</td>
</tr>
<tr>
<td>MCA (%)</td>
<td>18.0</td>
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</tr>
<tr>
<td>HCA (%)</td>
<td>6.7</td>
<td>6.7</td>
</tr>
<tr>
<td>TCA (%)</td>
<td>7.0</td>
<td>7.4</td>
</tr>
<tr>
<td>SWABS (W m$^{-2}$)</td>
<td>9.4</td>
<td>10.3</td>
</tr>
<tr>
<td>OLR (W m$^{-2}$)</td>
<td>6.4</td>
<td>7.0</td>
</tr>
<tr>
<td>TOA albedo</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>LWP ocean (g m$^{-2}$)</td>
<td>48.3</td>
<td>50.1</td>
</tr>
<tr>
<td>IWP (g m$^{-2}$)</td>
<td>39.7</td>
<td>45.4</td>
</tr>
<tr>
<td>$r_{\text{eff}}$ in January (µm)</td>
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<td>3.9</td>
</tr>
<tr>
<td>$r_{\text{eff}}$ in July (µm)</td>
<td>4.4</td>
<td>4.6</td>
</tr>
<tr>
<td>SLP (hPa)</td>
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<td>4.0</td>
</tr>
<tr>
<td>T200 (K)</td>
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<td>0.9</td>
</tr>
<tr>
<td>T850 (K)</td>
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<td>0.6</td>
</tr>
<tr>
<td>U200 (m s$^{-1}$)</td>
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<td>2.0</td>
</tr>
<tr>
<td>$T_{\text{ref}}$ (°C)</td>
<td>2.4</td>
<td>2.1</td>
</tr>
</tbody>
</table>

**Table 4.** Root-mean-square errors of AM3–CLUBB and AM3 at 0.5°, 1°, and 2° horizontal resolution for 1981–2000 with respect to observations in Table 3.
CLUBB is more expensive than traditional mass flux, eddy diffusivity, or eddy-diffusivity mass flux schemes, because it prognoses nine high-order moments and requires substeps. In the current configuration, there are 10 substeps for CLUBB in each host physical time step. Relative to AM3, AM3–CLUBB costs about 20%–30% more computationally. CLUBB and MG microphysics use approximately 25% and 1% of the total model runtime, respectively. One possible alternative would be to reduce the number of prognosed turbulent moments with diagnostics relationships: for example, a simplified turbulence closure (Bogenschutz and Krueger 2013).

Among key areas for future work is the treatment of ice and mixed-phase clouds in AM3–CLUBB. AM3–CLUBB, as currently formulated (similar to AM3), does not include interactions between aerosols and ice particle size. The simplified treatment of ice saturation [Eq. (3)] is problematic and should be replaced by a treatment that allows for its dependencies on vertical velocity, atmospheric composition, and the masses and particle sizes of liquid and ice (e.g., Phillips et al. 2007). Consequently, the current treatment of ice clouds (e.g., ice nucleation and ice cloud fraction) is subject to major uncertainties. These deficiencies may be partly responsible

---

**FIG. 14** Annual-mean error of SWCF (W m$^{-2}$) for (a) AM3–MG (no CLUBB) where tuning is not applicable; (b1) AM3–CLUBB without CLUBB parameter tuning (appendix B), with $v = 1$, and without enhanced accretion; (b2) AM3–CLUBB with tuning only; (b3) AM3–CLUBB with variable $v$ only; (b4) AM3–CLUBB with tuning and variable $v$; and (b5) AM3–CLUBB with tuning, variable $v$, and enhanced accretion. The detailed configurations are described in Table 2.
for negative biases in SWCF and LWCF, rather than CLUBB’s intrinsic formulation.

Although CLUBB generates PDFs of vertical velocity, total water mixing ratio, and liquid water potential temperature, which interact nonlinearly with microphysics, AM3–CLUBB in its current formulation uses only their averages over the cloudy portion of the CLUBB PDF to drive the microphysics parameterization. In doing so, this implementation prevents critical macrophysical characteristics from being exploited by the microphysics parameterization. Strategies, such as Latin hypercube sampling (Larson et al. 2005) and subcolumns (Pincus et al. 2006), are available to sample the CLUBB PDFs more effectively for microphysics and radiation and should be explored.

Future research work will also involve aerosol indirect effects and the implementation of a prognostic precipitation scheme. Aerosol indirect effects are likely too large in many GCMs, partly because GCMs overestimate the positive relationship between liquid water path (LWP) and aerosol optical depth (Quaas et al. 2009) and between LWP and cloud condensation nuclei concentrations (Wang et al. 2012). Our AM3 single-column simulations with CLUBB exhibit regime-dependent positive and negative LWP changes with increasing aerosol loadings, because microphysical and dynamic feedbacks to aerosol perturbations, such as sedimentation and entrainment, are well captured (Guo et al. 2011). Recent studies show that a prognostic precipitation treatment decreases the dependence of precipitation production on autoconversion and increases accretion dependence, in better agreement with observations and weakening aerosol effects on LWP (Posselt and Lohmann 2009; Wang et al. 2012).

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APPENDIX A

Relative Variance for In-Cloud Cloud Water

The inverse of relative variance for in-cloud cloud water \( v \) is defined as

\[
v = \frac{q_{c}^{in,cld2}}{\text{Var}(q_{c}^{in,cld})},
\]

where \( q_{c}^{in,cld} \) and \( \text{Var}(q_{c}^{in,cld}) \) are the mean and variance of cloud water mixing ratio in cloudy areas, respectively. Let \( q_{c}^{in} \) denote mean cloud water mixing ratio in a model grid box \( q_{c} \) and \( CF \) denote the cloud fraction. Then, Eq. (A1) can be rewritten as

\[
v = \frac{q_{c}^{2}/CF^{2}}{\text{Var}(q_{c}^{in,cld})},
\]

According to the definition of variance, \( \text{Var}(q_{c}^{in,cld}) \) is expressed as

\[
\text{Var}(q_{c}^{in,cld}) = \int_{\text{cloudy}} \left( q_{c} - \frac{q_{c}^{in,cld}}{\text{CF}} \right)^{2} f_{in,cld}(q_{c}) dq_{c}, \tag{A3}
\]

where \( f_{in,cld} \) denotes the probability density function (PDF) of \( q_{c}^{in,cld} \). It is assumed that the PDF of cloud water in a model grid box \( f(q_{c}) \) is

\[
f(q_{c}) = \text{CF} \times f_{in,cld}(q_{c}), \quad \text{if} \quad q_{c} > 0 \quad \text{or cloudy} \tag{A4}
\]

and

\[
\int_{\text{clear}} f(q_{c}) dq_{c} = 1 - \text{CF}. \tag{A5}
\]

Substituting Eqs. (A4) and (A5) into Eq. (A3), we get

\[
\text{Var}(q_{c}^{in,cld}) = \frac{1}{\text{CF}} \int_{\text{cloudy}} q_{c}^{2} f(q_{c}) dq_{c} - \frac{q_{c}^{2}}{\text{CF}^{2}} = \frac{1}{\text{CF}} \int_{\text{cloudy}+\text{clear}} q_{c}^{2} f(q_{c}) dq_{c} - \frac{1}{\text{CF}} \int_{\text{clear}} q_{c}^{2} f(q_{c}) dq_{c} - \frac{q_{c}^{2}}{\text{CF}^{2}}
\]

\[
= \frac{1}{\text{CF}} \left[ \text{Var}(q_{c}) + \frac{q_{c}^{2}}{\text{CF}^{2}} \right] - \frac{q_{c}^{2}}{\text{CF}^{2}}, \tag{A6}
\]

\[
\text{Var}(q_{c}^{in,cld}) = \frac{1}{\text{CF}} \left[ \text{Var}(q_{c}) + \frac{q_{c}^{2}}{\text{CF}^{2}} \right] - \frac{q_{c}^{2}}{\text{CF}^{2}}, \tag{A6}
\]
Table B1. Tuned and original values of CLUBB parameters and their meanings and/or impacts. Parameters C1, C5, C6, C7, and C11b have been discussed in Golaz et al. (2007), where C7 was generalized to be a function of skewness. Later versions of CLUBB also incorporated a similar skewness dependency on C6. In addition, C6 and C7 damping coefficients are further increased when the mixing length falls below the threshold defined by wpxp_L_thresh. When this happens, the maximum value of C6 and C7 is controlled by C6_Lscale0 and C7_Lscale0. This additional damping only occurs in stable layers and is intended to prevent the generation of spurious turbulence in such layers.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Meanings and/or impacts</th>
<th>Tuned</th>
<th>Original</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Newtonian dissipation for vertical velocity variance</td>
<td>1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>C4</td>
<td>Return-to-isotropy term for wind variances (horizontal and vertical)</td>
<td>1.0</td>
<td>5.2</td>
</tr>
<tr>
<td>C5</td>
<td>Pressure correlation term for wind variances (horizontal and vertical)</td>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>C6</td>
<td>Pressure correlation term in heat- and moisture-flux equations (low skewness limit)</td>
<td>0.5</td>
<td>4.0</td>
</tr>
<tr>
<td>C7</td>
<td>Buoyancy contribution to pressure correlation term in heat- and moisture-flux equations (low skewness limit)</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>C11b</td>
<td>Pressure term in third-moment vertical velocity (high skewness limit)</td>
<td>0.15</td>
<td>0.35</td>
</tr>
<tr>
<td>wpxp_L_thresh</td>
<td>Threshold mixing length below which additional damping is applied to C6 and C7</td>
<td>150</td>
<td>60</td>
</tr>
<tr>
<td>C6_Lscale0</td>
<td>Maximum C6 value when additional damping is applied because the mixing length falls below wpxp_L_thresh</td>
<td>30</td>
<td>14</td>
</tr>
<tr>
<td>C7_Lscale0</td>
<td>Maximum C7 value when additional damping is applied because the mixing length falls below wpxp_L_thresh</td>
<td>0.99</td>
<td>0.85</td>
</tr>
</tbody>
</table>

where we use \( \frac{1}{\langle q^2 \rangle} \frac{d \langle q^2 \rangle}{dq} = 0 \) and \( \frac{\text{cloudy} \cdot \text{clear} \cdot q^2 f(q_c)}{dq_c} = \text{Var}(q_c) + \bar{q}_c^2 \) and \( \text{Var}(q_c) \) is the variance of \( q_c \).

Combining Eq. (A6) with Eq. (A2), we obtain

\[
v = \frac{\bar{q}_c^2}{CF \cdot \text{Var}(q_c) - (1 - CF)\bar{q}_c^2}. \tag{A7}
\]

APPENDIX B

Adjusted CLUBB Parameters

To obtain a desirable energy balance and enhance the realism of AM3–CLUBB simulations, some CLUBB parameters have been tuned as shown in Table B1, which lists the tuned and original values of the CLUBB parameters (for additional details, see http://clubb.larson-group.com). Also shown are the meanings and/or impacts of these tuned parameters.

REFERENCES


