Precipitation Partitioning, Tropical Clouds, and Intraseasonal Variability in GFDL AM2

YANLUAN LIN* AND MING ZHAO
University Corporation for Atmospheric Research, Boulder, Colorado, and NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

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

STEPHEN A. KLEIN
Lawrence Livermore National Laboratory, Livermore, California

V. RAMASWAMY
NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

SHAOCHENG XIE
Lawrence Livermore National Laboratory, Livermore, California

(Manuscript received 15 July 2012, in final form 20 January 2013)

ABSTRACT

A set of Geophysical Fluid Dynamics Laboratory (GFDL) Atmospheric Model version 2 (AM2) sensitivity simulations by varying an entrainment threshold rate to control deep convection occurrence are used to investigate how cumulus parameterization impacts tropical cloud and precipitation characteristics. In the tropics, model convective precipitation (CP) is frequent and light, while large-scale precipitation (LSP) is intermittent and strong. With deep convection inhibited, CP decreases significantly over land and LSP increases prominently over ocean. This results in an overall redistribution of precipitation from land to ocean. A composite analysis reveals that cloud fraction (low and middle) and cloud condensate associated with LSP are substantially larger than those associated with CP. With about the same total precipitation and precipitation frequency distribution over the tropics, simulations having greater LSP fraction tend to have larger cloud condensate and low and middle cloud fraction.

Simulations having a greater LSP fraction tend to be drier and colder in the upper troposphere. The induced unstable stratification supports strong transient wind perturbations and LSP. Greater LSP also contributes to greater intraseasonal (20–100 days) precipitation variability. Model LSP has a close connection to the low-level convergence via the resolved grid-scale dynamics and, thus, a close coupling with the surface heat flux. Such wind–evaporation feedback is essential to the development and maintenance of LSP and enhances model precipitation variability. LSP has stronger dependence and sensitivity on column moisture than CP. The moisture–convection feedback, critical to tropical intraseasonal variability, is enhanced in simulations with large LSP. Strong precipitation variability accompanied by a worse mean state implies that an optimal precipitation partitioning is critical to model tropical climate simulation.

1. Introduction

Tropical precipitation, from isolated cumulonimbus to organized mesoscale convective systems and synoptic-scale super clusters, has a wide range of scales. General circulation models (GCMs), with their current resolution (20–200 km), have to parameterize unresolved convective processes via cumulus parameterizations (e.g., Arakawa
and Schubert 1974). On the other hand, GCMs use cloud schemes to handle grid-scale condensation and cloudiness (e.g., Tiedtke 1993). As a result, there is a scale truncation, which artificially separates the continuous convective spectrum in nature into two parts—a parameterized part and a resolved part—in GCMs. Though both aim to represent the vertical transport of heat and moisture, cumulus parameterization achieves it at the subgrid scale, while large-scale cloud scheme represents it at the resolved scale dynamically. Consequently, precipitation in GCMs has two components, a parameterized part from the cumulus parameterization and a resolved part from the large-scale cloud scheme. These two types of precipitation, generated via different paths and mechanisms in the model, have different dependence and effects on model environmental conditions. The model precipitation partitioning (convective versus large scale) is thus closely related to various model characteristics, especially over the tropics. However, such a partitioning is often neglected and the total precipitation is the focus of most studies and analyses.

GCMs have difficulty depicting various features of tropical precipitation. For example, GCMs generally have too light and too frequent precipitation (Wilcox and Donner 2007; Stephens et al. 2010), unrealistic precipitation diurnal cycle (Yang and Slingo 2001), and weak low-frequency precipitation variability (Slingo et al. 1996; Lin et al. 2006). GCMs also simulate substantially different cloud properties, such as ice water content (IWC) and cloud amount (e.g., Zhang et al. 2005; Waliser et al. 2009; Lin et al. 2012). Such cloud discrepancies among the models can be due to the large-scale cloud scheme (e.g., Waliser et al. 2009) or cumulus parameterizations (e.g., Clement and Soden 2005; Held et al. 2007). However, the relationship between model precipitation partitioning and cloud properties and how cumulus parameterizations impact such a linkage have not been extensively explored.

GCM-simulated tropical intraseasonal variability (ISV) is strongly impacted by cumulus parameterizations (e.g., Tokioka et al. 1988; Lin et al. 2008; Bechtold et al. 2008; Hannah and Maloney 2011; Kim et al. 2011, 2012; Hirons et al. 2013a,b). For example, GCMs with a cumulus parameterization tending to inhibit deep convection generally have increased tropical variability (Tokioka et al. 1988; Wang and Schlesinger 1999; Zhang and Mu 2005). Using greater entrainment rate in cumulus parameterizations also benefits tropical ISV (Bechtold et al. 2008; Neale et al. 2008; Jung et al. 2010; Kim et al. 2012), but such improvement is generally accompanied by worsened mean state bias in a number of different models (Kim et al. 2011) and is termed as “entrainment dilemma” in Mapes and Neale (2011). Note that some cumulus parameterization modifications can improve both variability and mean state without significantly modulated precipitation partitioning (Bechtold et al. 2008; Jung et al. 2010). Precipitation partitioning and its connection to the tropical cloud, ISV, and the mean state warrant further investigation.

In this study, we attempt to reveal possible connections between model precipitation partitioning, cloud properties, ISV, and the mean state over the tropics using one particular model, Geophysical Fluid Dynamics Laboratory (GFDL) Atmospheric Model version 2 (AM2) (Anderson et al. 2004). Note that ISV in this study specifically refers to intraseasonal precipitation variance. Various model sensitivity simulations are described in section 2, followed by a description of the large-scale and convective precipitation characteristics in section 3. The relationship between precipitation partitioning and cloud properties using a composite method is presented in section 4. Precipitation partitioning, ISV, and the mean state are analyzed in section 5. Summary and conclusions are given in section 6.

2. Model experiments

The model used in this study is the GFDL AM2 (Anderson et al. 2004). The relaxed Arakawa–Schubert scheme (RAS) (Moorthi and Suarez 1992) in AM2 uses a spectrum of entraining plumes with a closure that relaxes the cloud work function back to a critical value over a time scale varying from 2 h for shallow convection to ∼12 h for deep convection. Following Tokioka et al. (1988), deep convection is inhibited in plumes with a lateral entrainment rate lower than a critical value determined by the depth of the subcloud layer ($\theta_0 = \alpha/Z_m$), in which $\alpha$ is the Tokioka (TK) limiter constant and $Z_m$ is the subcloud layer depth. Assuming a subcloud layer depth of 1 km, a Tokioka limiter constant of 0.025 used in AM2 gives an equivalent fractional entrainment rate of 0.025 km$^{-1}$. As the Tokioka limiter constant increases, the threshold entrainment rate increases and deep plumes with smaller entrainment rate are prevented from occurring, especially in the dry environment. This inhibits the deep convection occurrence and modifies model tropical environmental conditions. Effectively, Tokioka limiter experiments are approximately equivalent to the increased entrainment rate simulations.

To investigate the impact of entrainment specification on tropical cloud, precipitation, and ISV, a set of AM2 sensitivity simulations using varying Tokioka limiter constants ($\alpha = 0, 0.025, 0.05, 0.1, \text{and} 0.2$, called TK0, AM2, TK2, TK4, and TK8, respectively) for deep convection are conducted (Table 1). These are 5-yr atmosphere-only simulations with a resolution of
2.0° latitude × 2.5° longitude using prescribed seasonal climatology (no interannual variation) of SST and sea ice. Previous studies have shown 5 years of this type of simulation is enough to capture some basic model characteristics (e.g., Golaz et al. 2011). The goal of these sensitivity simulations is not to determine their resemblance to observations, but to better understand how cumulus parameterization impacts cloud, precipitation fields, and tropical ISV. Model microphysics and resolution will also impact precipitation and ISV (e.g., Kim et al. 2012), but we focus on cumulus parameterization in this study.

3. Characteristics of large-scale and convective precipitation

In AM2, precipitation can be generated via the grid-scale condensation [large-scale precipitation (LSP)] and cumulus parameterization [convective precipitation (CP)]. LSP can be also produced by the convective detrainment, but this is generally relatively small (<1 mm day⁻¹). The two types of precipitation have contrasting characteristics. Figure 1 shows a snapshot of LSP and CP distribution in the tropics from TK8. First, LSP is episodic, infrequent, and generally has its own life cycle. Most of the strong LSP develops from tropical disturbances in a favorable environment gradually moistened by parameterized convection. In contrast, CP is widespread, frequent, and spontaneously responds to favorable environmental conditions. Second, the maximum intensity of LSP is about one order of magnitude larger than that of CP (Fig. 1). Corresponding to the much stronger intensity, LSP is related to stronger large-scale vertical motion and larger latent heat release than CP (not shown). Because of mass continuity, the strong vertical motion is accompanied by intense low-level convergence (Fig. 1a). As a result, LSP is able to sustain itself and has a long lifetime (a few days) if the environment is favorable (e.g., high SST and humidity). In contrast, CP has much smaller heating and vertical motion over a small area, their accumulative effect averaged over a model grid box as represented by the cumulus scheme is small. Finally, LSP generates a huge amount of IWC (up to several grams per kilogram) as the moist boundary layer air is lifted up by the grid-scale vertical motion. Cloud fraction associated with LSP is also much larger (~90%; not shown). In contrast, CP has smaller IWC and cloud fraction, especially at the lower and middle troposphere. Each convective plume can have intense vertical motion and large IWC but, because of its small spatial scale, its average over a model grid box is small. The contrasting cloud properties and low-level wind fields associated with LSP and CP indicate that model tropical cloud and climate are closely related to the precipitation partitioning between LSP and CP.

The partitioning of LSP and CP is strongly impacted by cumulus parameterization. A larger TK constant

![Figure 1](image-url)
tends to inhibit deep convection occurrence frequency and reduce CP. To compensate, LSP increases to achieve approximately the same total precipitation in the tropics (Table 1). This is because latent heating associated with precipitation needs to balance the radiative cooling in the tropics. For example, in the tropics, LSP increases from 0.10 mm day$^{-1}$ in AM2 to 1.92 mm day$^{-1}$ in TK8 with nearly the same total precipitation (Table 1). The robust nature of the compensating relationship between CP and LSP was also noted in other models (Scinocca and McFarlane 2004; Lin et al. 2008).

Spatial distribution of total precipitation differs among the simulations (Fig. 2). First, total precipitation decreases over land areas (South America and Africa) as TK constant increases. Strong precipitation (>$13$ mm day$^{-1}$) over the main islands in the Maritime Continent in TK0 decreases significantly in TK8. Second, precipitation within the warm pool area shifts eastward as TK constant increases. For example, maximum precipitation is near 150°E in AM2 and shifts to the east in Pacific intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ) in TK8. Another prominent

![Fig. 2. Mean precipitation (mm day$^{-1}$) for (a) TK0, (b) AM2, (c) TK4, and (d) TK8 simulations.](image)
change is the increase of precipitation in the tropical Indian Ocean (IO) with large TK constant. Some analysis in the tropical IO box (9°S–9°N, 60°–90°E) is described later. Further analysis shows that precipitation decrease over land is mainly from the reduction of CP (not shown), while precipitation increase over ocean, including tropical IO, is mainly from the increase of LSP (Fig. 3). The larger decrease of CP over land than over ocean is because of the relatively drier atmosphere over land, which has a larger impact on convection occurrence as TK constant is varied. The significantly reduced CP over land is only partially (30%–50%) compensated by increased LSP (Fig. 3). This results in an overall reduction of total precipitation over land, especially in tropical Africa and the Amazon (Fig. 2). As TK constant increases, deep convection is inhibited, especially over the dry regions (land). This is helpful for moisture buildup and a more unstable atmosphere because of the reduced vertical transport by convection. Both benefit the increased frequency of transient perturbation and LSP as shown in Fig. 1b. Corresponding to the increased LSP, evaporation over the tropics also
increases. For example, evaporation increases slightly from 3.94 mm day$^{-1}$ in TK0 to 4.16 mm day$^{-1}$ in TK8 (Table 1). Note that precipitation and evaporation are in balance globally. The slightly increased tropical evaporation is due to the strengthened tropical circulation (not shown) and increased transient wind perturbations (Fig. 1a). Figure 3 indicates that the spatial distribution of evaporation also changes among these simulations.

GCM precipitation is too frequent and too light (Stephens et al. 2010, and references therein). Figure 1 suggests this may be related to CP, which is too frequent and too light. CP, LSP, and total precipitation distribution (precipitation intensity times frequency) are shown in Fig. 4 for various simulations. To be consistent with Stephens et al. (2010), only precipitation $> 0.01$ mm day$^{-1}$ is included in Fig. 4 with the total occurrence frequency labeled. CP has a much larger total occurrence frequency ($\sim 80\%$) than LSP (20$\%$–33$\%$), and its frequency decreases slightly as LSP increases. CP rarely exceeds 40 mm day$^{-1}$, which is probably because of the mass flux limiter for computational stability used in RAS. As more deep convection is inhibited, CP decreases, with the dominant precipitation intensity shifting to smaller values (Fig. 4a). To compensate, LSP with much larger intensities ($\sim 200$ mm day$^{-1}$) increases (Fig. 4b). LSP frequency increases from 20$\%$ in AM2 to 33$\%$ in TK8. Since convective detrainment is a source of LSP in AM2, light (<1 mm day$^{-1}$) LSP generally occurs simultaneously with CP and does not necessarily stem totally from the large-scale cloud scheme. As a result, the total precipitation frequency is dominated by CP and does not deviate significantly from the CP frequency, except for a few percent from intense LSP (>1 mm day$^{-1}$). For example, CP occurrence frequency is 0.82 and total precipitation occurrence frequency is 0.84 for AM2. One year (1999) of 3-hourly $\frac{1}{4}^\circ$ Tropical Rainfall Measuring Mission (TRMM) 3B42 (Huffman et al. 2007) data are averaged to the model resolution to compute the distribution comparable to the model. The TRMM total precipitation occurrence estimate is much smaller (35$\%$), with the peak intensity near 40 mm day$^{-1}$.

In contrast, because of the contrasting intensity of CP and LSP in the model, model precipitation distribution has two peaks with prevalent light precipitation (Fig. 4c). There are some observational estimates of stratiform and convective precipitation from satellite (TRMM) and radar measurements over the tropics (e.g., Schumacher et al. 2008). However, such observational separation of precipitation conceptually is not the same as the separation of CP and LSP in models (Mapes et al. 2009).

4. The linkage between precipitation partitioning and cloud properties

LSP produces much larger cloud condensate and cloud fraction than CP (not shown). As LSP increases with increased TK constant, we also expect various cloud properties to change. Figure 5 shows the zonal mean IWC from the simulations and CloudSat retrievals. CloudSat IWC retrieval includes all solid phase cloud and precipitation particles (Waliser et al. 2009). IWC in AM2 also includes both ice and snow since ice that falls out of a cloud layer is a source of ice for the layer below (Rotstyna 1997). IWC over the tropics is nearly doubled from AM2 to TK4 and nearly quadrupled...
in TK8. TK8 has zonal mean IWC distribution similar to CloudSat with a smaller value. Note that IWC in AM2 does not include that directly associated with convective plumes. Liquid water content (LWC) and low and middle cloud fraction also increase as LSP increases (not shown). For a brief summary, Table 1 lists the tropical mean liquid water path (LWP), ice water path (IWP), low cloud fraction, and top-of-atmosphere (TOA) radiation from various TK simulations. Compared to AM2, IWP is nearly tripled, while LWP is doubled in TK8 (Table 1). The variation in cloud properties has direct impact on radiation. For example, TOA shortwave absorption reduces from 307 W m\(^{-2}\) in AM2 to 293 W m\(^{-2}\) in TK8, but outgoing longwave radiation (OLR) has only about 1 W m\(^{-2}\) change. How does the TK parameter in the cumulus parameterization impact cloud and radiation in the model?

To reveal the connection between clouds and precipitation partitioning, we composite model clouds based on LSP and CP, respectively. The same surface precipitation in a box similar to a GCM grid box can be associated with different cloud types and microphysical and macrophysical properties in nature. Though not all clouds precipitate, precipitation is always associated with some types of cloud. Considering that most GCM simulations with prescribed SST have a reasonable tropical mean precipitation and TOA radiation balance (Randall et al. 2007), it is informative to see how GCM cloud and radiation change with surface precipitation, especially separately for LSP and CP. Three-hourly model outputs from a 1-yr period are used for the composite. Model radiation time step is 3 h and the results using model time step (half hour) outputs are similar. Since LSP and CP may occur simultaneously in the model (e.g., Fig. 1), we need to minimize the contamination by only compositing those times dominated by one type of precipitation. Only those times with CP larger than 10 times of LSP are included in the composite of CP, and vice versa. On the basis of this criterion, roughly 95% of CP and 70% of LSP are included in these composites.

Figure 6 shows the cloud fraction, relative humidity (RH), LWP, IWP, OLR, and TOA shortwave absorption all as a function of LSP and CP intensity for AM2. The composites using other simulations are similar. We note much larger cloud fraction, LWP, and IWP associated with LSP than with CP. For example, cloud fraction is less than 10% in the lower and middle troposphere for CP less than 20 mm day\(^{-1}\). In contrast, it reaches 60%–100% in a deep air column for LSP greater than 10 mm day\(^{-1}\). IWP for the LSP composite is roughly 10 times larger than that for the CP composite. LSP also occurs in a much moister environment than CP. Radiation also differs significantly between the two composites. TOA shortwave absorption and OLR approximately cancel out for the LSP composite >2 mm day\(^{-1}\). In contrast, TOA shortwave absorption is ~200 W m\(^{-2}\) larger than OLR for the CP composite.

![Fig. 5. Latitude–pressure plot of zonal mean IWC for (a) CloudSat retrieval, (b) AM2, (c) TK4, and (d) TK8.](image-url)
This is related to a strong diurnal cycle of convective precipitation around noon in AM2 (not shown). Such contrasting radiative differences between LSP and CP may impact tropical ISV via the radiation instability (e.g., Raymond 2001), as discussed later. Because of significantly larger cloud condensate with LSP than CP, simulation with larger LSP tends to have larger cloud condensate if precipitation occurrence frequency is about the same (Fig. 4). Different cloud properties (e.g., cloud fraction and IWP) and radiation are thus closely linked to the different precipitation partitioning in these simulations. The increased IWP and LWP in simulations with greater LSP (Table 1), to the first order, is because cloud condensate associated with LSP is much larger than that associated with CP, as shown in Fig. 6.

Several specific features may be identified from these composites. For example, LSP has two distinct regimes. One is the drizzle-type precipitation (<1 mm day\(^{-1}\)) from shallow boundary layer clouds with cloud top below 800 hPa (shallow regime). The other is dominated by intense precipitation (>20 mm day\(^{-1}\)) with the whole air column close to saturation (deep regime). For the CP composite, there are also two regimes (shallow and deep) indicated by different cloud fraction, RH, and convective mass flux (not shown). The shallow regime (<1 mm day\(^{-1}\)) has a shallow moist layer below 850 hPa. The deep regime (>10 mm day\(^{-1}\)) has a moist upper troposphere with cloud fraction up to 60%–70% there.

In summary, cloud and radiation differences among these simulations are closely related to the modulation of precipitation partitioning and intensity distribution by cumulus parameterization. The composite method may be useful for contrasting different large-scale cloud schemes and cumulus parameterizations.

5. Precipitation partitioning and ISV

Previous studies noted that ISV increases as the LSP fraction increases in GCM simulations (Tompkins and Jung 2004; Lin et al. 2008; Kim et al. 2011). Simulations using RAS with varying TK constants have been found to have varying equatorial wave activities and ISV (Tokioka et al. 1988; Lin et al. 2008; Maloney 2009; Hannah and Maloney 2011; Frierson et al. 2011; Kim et al. 2011). It is also noted that such improved variability was generally accompanied by increased mean state bias (Kim et al. 2011; Mapes and Neale 2011). TK constant controls the convection occurrence and LSP fraction as shown before, but how are they related to ISV and the mean state? We attempt to reveal some possible connections by investigating the contrasting environmental dependence and impacts of LSP and CP using these TK simulations. Because of the contrasting representation of precipitation processes by cumulus parameterization and large-scale cloud scheme, such a transfer of precipitation from CP to LSP will impact various model features including the tropical mean state and precipitation variability.

To investigate the intraseasonal precipitation variability, we compute the 20–100-day bandpass-filtered precipitation variance separately for LSP, CP, and total precipitation using daily precipitation as Kim et al. (2011). It is clear that LSP has much larger (~10 times)
variance than CP (Fig. 7). Other simulations also show much larger variability of LSP than CP (not shown). This may be related to the overall much larger intensity of LSP than CP (Figs. 1, 4). The spatial distribution of the variability is similar between LSP and CP. The maximum variability is over the Indian Ocean, Pacific Ocean ITCZ and SPCZ, and east of the Philippines. In contrast, the variability over the Maritime Continent is small. This is consistent with Sobel et al. (2008), who found stronger intraseasonal rainfall variance over ocean than over land and emphasized the importance of surface flux on tropical ISV.

Because of the much larger ISV of LSP, simulations with larger LSP fraction also have larger total precipitation ISV (Fig. 8). ISV doubles from TK0 (2 mm day$^{-1}$) to TK8 (4 mm day$^{-1}$) and almost linearly increases with LSP. This is consistent with Kim et al. (2011), who found increased ISV for simulations with larger TK constant. The analysis here suggests that the larger ISV in TK8 is dominated by the part from LSP, while for AM2, ISV is mostly contributed by CP. It should be noted that only the power of ISV is affected by the LSP fraction, similar to Tompkins and Jung (2004). The dominant frequency of the precipitation variation does not appear to be significantly different among these simulations.

Next we discuss some potential linkages between the precipitation partitioning and ISV. As TK constant increases, more deep convection is inhibited and results in an overall drier and colder upper troposphere (Figs. 9a,b). This is related to the different heating profile of CP and LSP. Figure 9c shows the composite of precipitation normalized heating profiles over the tropical IO box for CP and LSP >10 mm day$^{-1}$. Though the magnitudes of normalized convective and large-scale heating are similar, CP heating is larger in the upper troposphere (above 350 hPa), and so is the moistening (not shown). The right interaction of heating structure with large-scale waves is critical for ISV. In this sense, when the vertical heating structures are modulated by the precipitation partitioning, ISV will change accordingly. It should be pointed out that these simulations are not
expected to produce various realistic heating profiles associated with the suppressed, disturbed, and mature convective conditions as shown in Mapes et al. (2006). For the same total precipitation and, thus, the same latent heat release, a model with a larger fraction of LSP tends to be colder and drier in the tropical upper troposphere. This is consistent with other studies (Kim et al. 2011; Zhao et al. 2012). The unstable stratification tends to support more active disturbances. The dry and cold upper troposphere reduces the moist static energy (MSE) in the middle and upper troposphere with the minimum MSE altitude slightly lifted up (Fig. 10a). On the other hand, vertical motion increases for runs with larger LSP, especially at the upper troposphere over the ascending branch of the tropical circulation (Fig. 10b). For example, TK8 has maximum vertical motion ~30% larger than AM2 near 400 hPa over the tropical IO box. This implies a larger divergence in TK8 than AM2. Both of these effects contribute to a smaller gross moist stability (GMS) (Neelin and Held 1987), which leads to slower propagation of waves and favors ISV, as expected from theoretical studies. The equatorial wave speed is proportional to the square root of the GMS based on the first baroclinic mode theory (Neelin and Zeng 2000). These results are consistent with Lin et al. (2008) and Frierson et al. (2011), who found smaller GMS for simulations using increased TK constant. Overall, because of the different impact of LSP and CP on model temperature and moisture fields, precipitation partitioning regulates the tropical mean thermodynamic state, such as stability, which subsequently influences tropical wave properties and ISV.

Suppressed deep convection occurrence also helps the moisture buildup and benefits LSP activity. LSP
increases more significantly over ocean than over land (Fig. 3). The enhanced evaporation with strong winds (wind–evaporation feedback) (Neelin et al. 1987; Emanuel 1987) is essential for the development and maintenance of LSP. As shown before, LSP is associated with large vertical motion and low-level convergence. Strong low-level winds increase the surface evaporation if other conditions are the same in the model. As a result, LSP has a close coupling to the surface flux. Accompanying the increased LSP, evaporation also increases east of the Maritime Continent and tropical Indian Ocean. This is clearly shown in the precipitation and surface evaporation difference between TK8 and AM2 (Fig. 11b). Compared with AM2, precipitation in TK8 decreases by up to 5 mm day\(^{-1}\) over most areas of the Maritime Continent, while it increases significantly over the east flank of the Maritime Continent, Indian Ocean, and east Pacific ITCZ. The increased precipitation over the ocean is generally located downstream of the increased evaporation (Fig. 11a). Surface wind magnitude of TK8 is about 2 m s\(^{-1}\) larger than AM2 in the tropics (not shown), and the larger surface winds correspond well with the larger surface evaporation in TK8. The increased surface wind in TK8 is due in part to a strengthened tropical circulation and in part to local enhanced winds associated with LSP. Overall, with increased TK constant, the model tends to produce larger LSP, which is related to the larger surface wind and evaporation. As a result, the coupling between precipitation and the surface flux is enhanced, and this is beneficial to model tropical ISV.

Convection moistens the surrounding air as moisture is transported upward to the middle and upper troposphere. Moist low and middle troposphere also help convection initiation and maintenance. The strong dependence of convection on moisture and convective moistening is a key to ISV (Raymond and Fuchs 2009). This is termed as moisture–convection feedback (Woolnough et al. 2001; Grabowski and Moncrieff 2004). A relationship between column water vapor path (WVP) and precipitation over the tropical oceanic area has been noted (Bretherton et al. 2004). Figure 12 shows the composite of LSP, CP, and total precipitation on WVP over the tropical IO box. Similar to Bretherton et al. (2004), LSP depends strongly on WVP and increases exponentially with WVP. However, CP occurs at low WVP (\(<25\) mm) and increases slowly with WVP. This implies the sensitivity of CP to WVP is relatively weak in AM2. This is because convection trigger in RAS is solely based on a threshold cloud work function (similar to CAPE). Such triggering does not take into account the moisture effect, especially at high altitudes. Note that plumes do entrain, so there is a moisture effect, but this is much weaker than LSP. The weak dependence of CP on WVP suggests a weak moisture–convection feedback when CP dominates a model’s total precipitation. The moisture–convection feedback is enhanced when LSP increases. In this sense, a GCM with greater LSP tends to have larger tropical ISV. Of course, convection schemes sensitive to humidity (Bechtold et al. 2008; Hannah and Maloney 2011; Hirons et al. 2013a,b) or superparameterization (Benedict and Randall 2009; Thayer-Calder and Randall 2009) will also increase tropical ISV following the same moisture–convection argument.

Finally, we briefly mention the cloud–radiation feedback. Figure 6 suggests much larger radiative heating for CP than LSP. As TK constant increases, both CP and associated cloud–radiative heating decrease (e.g., Table 1). The reduced radiative heating can contribute to enhancement of tropical wave variance (e.g., Lin et al. 2007). To summarize, our results of enhanced ISV for the large LSP cases are consistent with various tropical
ISV feedback mechanisms. However, a detailed exploration of the various mechanisms is beyond the scope of the present study.

In addition to the promising results of tropical ISV in superparameterization simulations (e.g., Thayer-Calder and Randall 2009), there have been extensive studies about how to improve tropical variability in GCM simulations. For example, enhancing the convection dependence on moisture generally increases ISV (Neale et al. 2008; Bechtold et al. 2008). This does not necessarily increase LSP, but CP becomes more sensitive to the column moisture and increases the moisture–convection feedback. Using an environmental humidity-dependent entrainment rate greatly improves the simulation of Madden–Julian oscillation (MJO) in the European Centre for Medium-Range Weather Forecasts (ECMWF) model (Bechtold et al. 2008). By suppressing premature development of deep convection, more moisture is able to build up and effectively preconditions the development of deep convection (Del Genio 2012; Hirons et al. 2013b). A well-simulated transition from shallow to deep convection is key to the simulated evolution of MJO, including its suppressed phase (Hirons et al. 2013a,b). Modification of trigger and entrainment in convection schemes impacts LSP fraction and ISV (Tompkins and Jung 2004; Kim et al. 2011). Increasing shallow heating also benefits ISV (Benedict et al. 2013) since it is more effective in inducing low-level convergence (note heating is directly related to vertical motion) and surface wind and flux. The present study may be useful for a better understanding of the relationship between precipitation partitioning and tropical mean state and transient activities.

6. Summary and conclusions

A set of GFDL AM2 sensitivity simulations by varying the amount of deep convection occurrence are conducted to investigate how cumulus parameterization impacts tropical cloud and precipitation characteristics. In the tropics, model CP is frequent (~80%) and light (a few mm day$^{-1}$), while LSP is episodic and heavy (up to several hundreds of mm day$^{-1}$). Simulations with a larger Tokioka limiter constant tend to have a greater LSP fraction as more deep convection is inhibited. CP is
significantly reduced over land and only partially compensated by increased LSP as TK constant increases. In contrast, LSP significantly increases and dominates the overall increase of precipitation over ocean. As a result, inhibition of deep convection induces a transfer of precipitation from land to ocean. Such redistribution of precipitation over land and ocean may impact the tropical circulation in the model.

Total precipitation occurrence frequency is similar among these simulations. A composite analysis reveals that cloud fraction (low and middle) and cloud condensate associated with LSP is substantially larger than that associated with CP. As a result, simulations having greater LSP also have larger cloud condensate and low and middle cloud fraction. The analysis suggests that the model cloud properties are closely related to the precipitation partitioning between LSP and CP. The cloud differences (cloud fraction and cloud condensate) among these simulations can be explained by the different precipitation partitioning, which is strongly impacted by the TK constant. We note enhanced intraseasonal precipitation variability as LSP increases in these simulations. Because of the different vertical heating profiles of CP and LSP, simulations with greater LSP tend to be colder and drier in the upper troposphere. The induced unstable stratification and low-level moisture buildup due to deep convection inhibition benefit LSP production. Model LSP has a close connection to the low-level convergence and, thus, a close coupling with the surface heat flux. Wind–evaporation feedback is essential to the development and maintenance of LSP. In addition, LSP has a stronger dependence and sensitivity on the column moisture than CP. The moisture–convection feedback is thus enhanced in simulations with larger LSP.

Overall, because of the contrasting dependence and impacts of LSP and CP on model environmental conditions, precipitation partitioning, which is mainly controlled by cumulus parameterization in these simulations, is critical for model tropical climate simulation and understanding. Finally, this result is only based on a single model, and it remains to be verified for other models. However, analysis based on CP and LSP separately may be a useful step toward a better understanding of the complex model world.

**Acknowledgments.** This research is supported by the Office of Science (BER), U.S. Department of Energy (Lin). Support for S. A. Klein and S. Xie was provided by the Atmospheric System Research and Regional and Global Climate Modeling Programs of the Office of Science at the U.S. Department of Energy. Their contribution to this work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. We are grateful to Dr. Waliser for providing us with the ice retrievals from CloudSat. We thank Hiram Levy II and Huan Guo for their comments on the manuscript. We also acknowledge the three anonymous reviewers for their constructive comments, which significantly improved the organization and clarity of the paper.

**REFERENCES**


Wang, W. Q., and M. E. Schlesinger, 1999: The dependence on convection parameterization of the tropical intraseasonal oscillation simulated by the UIUC 11-layer atmospheric GCM. *J. Climate*, 12, 1423–1457.


