The Diurnal Cycle of Warm Season Rainfall over West Africa. Part II: Convection-Permitting Simulations

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ABSTRACT

Convection-permitting simulations at 3-km resolution using a regional climate model are analyzed to improve the understanding of the diurnal cycle of rainfall over West Africa and its underlying physical processes. The warm season of 2006 is used for the model simulations. The model produces an accurate representation of the observed seasonal mean rainfall and lower-troposphere circulation and captures the observed westward propagation of rainfall systems. Most of West Africa has a single diurnal peak of rainfall in the simulations, either in the afternoon or at night, in agreement with observations. However, the number of simulated rainfall systems is greater than observed in association with an overestimation of the initiation of afternoon rainfall over topography. The longevity of the simulated propagating systems is about 30% shorter than is observed, and their propagation speed is nearly 20% faster. The model captures the observed afternoon rainfall peaks associated with elevated topography (e.g., the Jos Plateau). Nocturnal rainfall peaks downstream of the topographic afternoon rainfall are also well simulated. However, these nocturnal rainfall peaks are too widespread, and the model fails to reproduce the observed afternoon rainfall peaks over regions removed from topographic influence. This deficiency is related to a planetary boundary layer that is deeper than observed, elevating unstable profiles and inhibiting afternoon convection. This study concludes that increasing model resolution to convection-permitting space scales significantly improves the diurnal cycle of rainfall compared with the models that parameterize convection, but this is not sufficient to fully resolve the issue, perhaps because other parameterizations remain.

1. Introduction

This paper is the second part of a study that aims to improve our understanding of the diurnal cycle of warm season rainfall over West Africa. Here, we follow an observational study (Zhang et al. 2016, hereafter Part I) with an analysis of high-resolution simulations.

Atmospheric models, including both general circulation models (GCMs) and regional climate models (RCMs), are primary tools for predicting rainfall from subsynoptic to multidecadal time scales. The diurnal cycle of precipitation is a critical aspect of the regional climatology and influences rainfall distributions on all time scales. In Part I, we provide an observational analysis of the diurnal cycle of rainfall over West Africa. Previous analyses of satellite-observed precipitation (e.g., Mohr 2004) show a bimodal diurnal cycle as an artifact of spatial averaging. Using state-of-the-art temporally and spatially continuous gridded multisatellite products, such as the Tropical Rainfall Measuring Mission (TRMM 3B42) and the Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN), we conclude that almost all regions have a single diurnal peak, either in the afternoon or at night.

The purpose of this paper is to examine the ability of a regional, convection-permitting atmospheric model to reproduce the diurnal cycle of rainfall over West Africa and capture the underlying physical processes. The performance issues of the current generation of GCMs and RCMs in simulating the diurnal cycle of rainfall over West Africa are reviewed in section 2. Section 3 documents the regional climate model used in this study, including the configuration of the convection-permitting model.
simulation. Observational and reanalysis datasets used to evaluate the model are also described in section 3. Results are presented in section 4, and conclusions are summarized in section 5.

2. Background

Representing the diurnal cycle of rainfall over West Africa remains a challenging issue for the current generation of GCMs and RCMs. GCMs can often produce realistic simulations of the mean precipitation on monthly to annual time scales, but they fail to capture the diurnal cycle of rainfall over West Africa (Cook and Vizy 2006; Dai 2006; Xue et al. 2010). For example, Dai (2006) compares the rainfall simulated by 18 different GCMs to TRMM observations and shows that over West Africa all the models initiate convective rainfall too early in the day (i.e., around local noon compared to late afternoon). In addition, the observed nocturnal rainfall peaks diagnosed in Part I are not captured by the GCMs. Recent efforts to improve convective parameterization in GCMs provide a better representation of the timing of convection (e.g., Rio et al. 2009, 2013; Bechtold et al. 2014), but the nocturnal rainfall peaks are still not represented well. Such misrepresentations undermine our confidence in the models’ ability to properly represent the physical processes of precipitation, including those associated with high-impact extreme events.

Simply increasing a GCM’s resolution is not sufficient for correcting inaccuracies in the simulation of the diurnal cycle of rainfall if the resolution is not fine enough to explicitly allow convective rainfall without the use of cumulus parameterization (Lee et al. 2007; Ploshay and Lau 2010; Dirmeyer et al. 2012). He et al. (2015) also find that their regional climate model simulations at 20- and 10-km resolutions have similar issues with the diurnal cycle as the GCMs, and altering cumulus parameterization schemes does not help to capture the nocturnal rainfall peaks. This inability suggests that the errors are at least partially associated with the parameterized physical processes that control rainfall production in the models.

One approach to avoiding the use of cumulus parameterization in models is to conduct convection-permitting simulations using spatial resolutions on the order of 4 km or finer. Sato et al. (2009) examine the dependence of the diurnal cycle of rainfall on spatial resolution in simulations with a global, convection-permitting model with 14-, 7-, and 3.5-km grid spacing. Over the tropical continents, the 3.5-km run produces realistic diurnal rainfall peaks in the afternoon and night, in both timing and magnitude, when compared with the TRMM observations. The 7- and 14-km simulations produce 1.5- and 4.5-h delays in the afternoon peak, respectively. Noda et al. (2012) suggest that these delays are associated with inaccuracies in the model’s simulation of organized convective systems with radii less than 100 km. Dirmeyer et al. (2012) also show that a global convection-permitting model produces a more realistic diurnal cycle of rainfall than global models with parameterized convection or an embedded two-dimensional convection-permitting model.

Convection-permitting simulations with GCMs are computationally expensive, especially for simulating seasonal or longer time scales. Regional climate modeling provides an efficient alternative. RCMs use the same set of governing equations as GCMs and lateral boundary conditions from GCMs, but the use of a limited domain makes high-resolution simulation practical, and the constraint of requiring hydrostatic balance used in GCMs can be relaxed. In addition, the focus on a particular region can produce more accurate simulations when surface features such as topography are more accurately represented, and physical parameterizations (e.g., radiation calculations and land surface models) that are more suitable for the analysis region are selected (e.g., Cook and Vizy 2012; Vizy et al. 2013).

Pearson et al. (2014) and Birch et al. (2014) examine the diurnal cycle of rainfall in regional model simulations with 4- and 1.5-km resolution and explicit convection. These high-resolution simulations reproduce the two types of rainfall peaks observed over many regions of West Africa, which are associated with afternoon convection and nocturnal propagating features. In the regional average, the diurnal cycles are similar in the 1.5- and 4-km simulations. The primary differences are that the 1.5-km simulation has an afternoon peak that is one hour earlier, and it has less nocturnal rainfall than the 4-km simulation. A version of the same model with 12-km resolution and parameterized convection fails to produce nighttime peaks. The difference in the accuracy of the diurnal cycle of rainfall between the higher- and lower-resolution simulations is attributed to the treatment of convection (explicit vs parameterized) and not directly to the resolution differences.

With preliminary testing to select physical parameterizations that work well in the region, the regional Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008) accurately reproduces West African rainfall on seasonal to interannual time scales (e.g., Hagos and Cook 2007; Cook and Vizy 2012; Vizy et al. 2013; Crédat et al. 2014). Working on the synoptic time scale, Laing et al. (2012) conduct 4-km-resolution WRF convection-permitting simulations over tropical northern Africa for 12.5 days during the summer of 2006.
The model captures the diurnal cycle and other statistical properties of precipitation systems in the lee of the Ethiopian Highlands.

In Part I, an observational analysis shows that most regions of West Africa (98% in the climatology and 72% in a case study for 2006) have a single diurnal peak of rainfall either in the afternoon (i.e., 1500 and 1800 UTC) or at night (i.e., 2100, 0000, and 0300 UTC). Two types of regions experience afternoon rainfall peaks. One type is regions with topographic features, and the other is regions far removed from upstream topography. Coherent regions with nocturnal rainfall peaks are located 3°–10° of longitude downstream (i.e., to the west) of regions with afternoon rainfall maxima. These nocturnal rainfall maxima are associated with the westward propagation of rainfall systems and not with local convective instability.

This paper builds on the observational analysis to further advance our understanding of the diurnal cycle of rainfall by examining convection-permitting simulations over West Africa. These simulations cover the entire warm season of West Africa, which provides more confidence than in the case studies of previous convection-permitting simulations (e.g., Pearson et al. 2014; Birch et al. 2014). More importantly, the analysis of the diurnal cycle of rainfall in our simulations is guided by the observational findings in Part I. This analysis provides an opportunity to understand the extent to which the critical physical processes that control the diurnal cycle are represented accurately in the model.

3. Methodology

a. Description of the regional climate model simulations

The Advanced Research version of WRF, version 3.4.1 (ARW; Skamarock et al. 2008), is used to conduct convection-permitting simulations over West Africa. We use 3-km horizontal resolution to explicitly resolve moist convection without the use of cumulus parameterization. A model domain encompassing the region bounded by 7°–17°N and 7°W–20°E (371 latitude × 985 longitude grid points) is used, shown as the thick black box in Fig. 1. This domain covers the study region used in the observational analysis of Part I. The domain is chosen to avoid coastal rainfall effects over the West African monsoon region. Such a large domain is useful for reducing the impacts of the lateral boundary conditions on the model solution in the domain interior.

Because of the high computational demands of running a 3-km-resolution simulation over a domain with 365,435 grid points, one summer, 2006, is selected for a case study. The simulation is initialized at 0000 UTC 1 March 2006 and run through 0000 UTC 1 October 2006, and the warm season (June–September) is analyzed. The summer of 2006 is chosen because it is representative of a typical summer season over West Africa, and it has been extensively studied as part of the African Monsoon Multidisciplinary Analyses (AMMA) special observing period (Lebel et al. 2010). This year is also evaluated in the observational analysis conducted in Part I. The model integration time step is 15 s, and hourly model output is archived for analysis.

Initial and boundary conditions are taken from the 6-hourly National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR; Saha et al. 2010), which has a horizontal resolution of 0.5° for atmospheric fields and 0.31° for surface fields. CFSR is chosen because of its high spatial resolution.

Physical parameterizations selected for use in the simulation include the Lin et al. microphysics scheme (Lin et al. 1983; Rutledge and Hobbs 1984; Chen and Sun 2002), the RRTM longwave radiation scheme (Mlawer et al. 1997), the Dudhia shortwave radiation scheme (Dudhia 1989), the Yonsei University boundary layer scheme (Hong et al. 2006), the MM5 Monin–Obukhov surface layer scheme (Skamarock et al. 2008), and the Noah land surface model (Chen and Dudhia 2001). This combination of parameterizations has been shown to reproduce the West African climate realistically at various spatial resolutions greater than 10-km (Cook and Vizy 2012; Vizy et al. 2013). The cumulus convection parameterization is disabled.

The above simulation is the default simulation used in this study, and its results are presented in the next section. To verify that the diurnal cycle of rainfall produced in this simulation is due to the internal model physics rather than being injected into the model domain through the lateral boundaries, an additional simulation was run with the diurnal cycle filtered out of the lateral boundary conditions. The diurnal cycle of rainfall throughout the model domain is insensitive to this filtering.

Analysis of the output from the default simulation raised concern about a dependence on the atmospheric boundary layer and cloud microphysics parameterizations. Therefore, two additional 3-km-resolution simulations are conducted. Both sensitivity simulations are identical to the default except that in one the Mellor–Yamada–Janjić (MYJ; Janjić 1994) atmospheric boundary layer scheme is used instead of the Yonsei University boundary layer scheme. The second sensitivity simulation uses the Thompson microphysics scheme (Thompson et al. 2004) instead of the Lin et al. microphysics scheme. The results of these sensitivity simulations are discussed in the results section.
b. Description of the observational/reanalysis datasets

Several observational/reanalysis datasets are used to evaluate the modeled diurnal cycle of rainfall and various atmospheric fields. For rainfall, we use the 3-hourly TRMM 3B42V7 product (Huffman et al. 2007) and the 3-hourly PERSIANN data (Sorooshian et al. 2000). Both have a spatial resolution of 0.25°.

The 3-hourly Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2011) is used for evaluating the atmospheric fields on diurnal time scales. At the time of this study, MERRA is the only reanalysis product that supplies atmospheric fields on 3-hourly intervals over West Africa. Other reanalyses are also used for model evaluation on longer time scales, including the NCEP CFSR and the ERA-Interim (Dee et al. 2011). These products are available at 6-hourly intervals for 0000, 0600, 1200, and 1800 UTC.

4. Results

a. Evaluation of the simulated seasonal mean climate

The model’s ability to simulate the seasonal mean circulation and rainfall fields is first examined. Figure 2 compares the model-simulated 925-hPa wind and specific humidity with three reanalyses over the full simulation domain (7°–17°N and 7°W–20°E; Fig. 1). The southwesterly monsoon flow is captured well in the model. The modeled specific humidity agrees well with CFSR, which supplies boundary conditions for the simulation, and these two are drier than MERRA and ERA-Interim over the southern part of the domain. The differences in the atmospheric humidity among the reanalyses suggest uncertainty in these datasets.

Figure 3 displays the 650-hPa wind and specific humidity from the model simulation and the reanalyses. The easterly flow of the African easterly jet is accurately simulated by the model, and the zonal structure of specific humidity in the model is close to the reanalyses, especially for CFSR, as expected. Other levels in the lower troposphere are also examined (not shown) to conclude that the WRF convection-permitting simulation provides a reasonable simulation of the 2006 warm season mean.

Figures 4a–c display the June–September (JJAS) 2006 mean rainfall rate from TRMM, PERSIANN, and the default WRF convection-permitting simulation, respectively. TRMM and PERSIANN have similar seasonal mean rainfall distributions. The model captures the meridional gradient of the seasonal rainfall reasonably well. South of 13°N, the
The model also reproduces the observed zonal structure, with drier conditions west of the Greenwich meridian and wetter conditions to the east. The rainfall maxima located near the Jos Plateau is also reproduced in the convection-permitting simulation. However, the model produces stronger rainfall than observation over most of the southern part of the domain (7°–12°N, 2°W–19°E) and weaker rainfall in the north (15°–17°N).
The model also does not capture the observed rainfall maximum over western Burkina Faso and its associated gradient. In addition to the seasonal mean, 3-hourly snapshots of WRF-simulated rainfall are compared with TRMM images (not shown). Most of the rainfall in the WRF simulation is in the form of mesoscale convective systems (MCSs), in agreement with TRMM.

b. Diurnal cycle of rainfall in the simulation

Figure 5 displays the percentage of daily rainfall distributed into 3-hourly intervals in the simulation for JJAS 2006. As in the observational analysis discussed in Part I, UTC is used as local time for this domain. Anomalously high afternoon rainfall near the eastern boundary (not shown) is neglected because it is spurious, being related to matching the model’s interior solution to the lateral boundary forcing. Over West Africa (west of 10°E), afternoon rainfall starts in the vicinity of the Jos Plateau (9°–11.5°N, 7°–10°E) at 1300–1600 UTC and in other regions at 1900–2200 UTC. The percentage of rainfall then decreases at 2200–0100 and 0100–0400 UTC, and there is little rainfall during the late morning and noon/early afternoon times. The afternoon maxima observed in TRMM (Fig. 1 in Part I) are delayed to the evening in the model. The nocturnal rainfall after midnight is weaker in the model than the observations.

Figure 6 shows distributions of the observed and simulated peak hour of rainfall in the mean diurnal cycle for JJAS 2006. To compare with TRMM (Fig. 6a), the model-simulated hour of maximum rainfall is first evaluated using 1-hourly output and then rounded to the closest 3-hourly interval at the TRMM reporting times (Fig. 6b). In contrast to TRMM, nocturnal peaks dominate West Africa in the simulation, with the exception of some isolated areas (e.g., the Jos Plateau).

We use the regions defined in Part I for case studies and then generalize the findings. The afternoon (AF; 9°–11.5°N, 3°W–0°), southern nocturnal (SN; 9°–11.5°N, 2°–5°E), and northern nocturnal (NN; 13.5°–16.5°N, 2°–5°E) domains are indicated by the three western boxes in Fig. 1 and Figs. 6a and 6b. To further explore the role of topography in shaping the diurnal cycle of rainfall, an additional domain is added to the east in the vicinity of the Jos Plateau (9°–11.5°N, 7°–10°E).

In the simulation (Fig. 6b), the rainfall peaks are mainly nocturnal in the AF region, which has afternoon peaks in the observations (Fig. 6a). The SN domain has realistically simulated nocturnal rainfall peaks. The transition of the peak hour of rainfall from 1800 UTC over the Jos Plateau to 0300 UTC over the SN domain suggests a westward propagation of rainfall systems, in agreement with the observational results in Part I. The NN domain in the model contains nocturnal peaks in the southern half and afternoon peaks in the northern half, where the model has a dry bias with rainfall rates below 1 mm day\(^{-1}\) (Fig. 4).

While the simulation with 3-km resolution avoids using a cumulus parameterization, a number of other parameterizations remain in the model. Most relevant to the production of rainfall, these parameterizations include schemes for determining heat, moisture, and momentum transport from the planetary boundary layer (PBL) and calculations of the cloud microphysics. As described in section 3, two sensitivity simulations using different PBL and cloud microphysics schemes are used to evaluate the dependence of the default simulation on these parameterizations. Here we note that results shown in Fig. 6b are not sensitive to these selections of parameterizations; altering them is not sufficient to improve the model simulation of the diurnal cycle of rainfall.

In summary, the convection-permitting simulation captures the observed afternoon rainfall peaks associated with elevated topography around the Jos Plateau. Nocturnal rainfall peaks downstream of the topographic afternoon rainfall are also well simulated. However, the regional model generates nocturnal rainfall peaks that are too widespread over the
domain and fails to reproduce the observed afternoon rainfall peaks over regions that are more than a few hundred kilometers downstream of elevated topography.

To explore the spatial distribution of the diurnal cycle of rainfall in more detail, Fig. 7 displays the simulated diurnal cycle of rainfall averaged over 1° x 1° grid boxes from 7° to 17°N and from 7°W to 20°E. A peak is defined when it is at least 1 mm day\(^{-1}\) higher than its neighbor. Of the regions, 59% have a single peak, while 29% exhibit double peaks. This is roughly consistent with the conclusion from the observational analysis (Fig. 5 in Part I) that 72% of the regions experience a single diurnal peak of rainfall in 2006. Note that, because the model has a dry bias north of 14°N, the multiple peaks close to the northern boundary are related to unrealistically small rainfall amounts.

Figure 8 shows the JJAS 2006 mean diurnal cycle of rainfall area averaged over the Jos Plateau, SN, and AF domains from the TRMM observations and the default convection-permitting simulation. Note that the TRMM data have 3-hourly intervals, while the model output is archived at 1-hourly intervals. Therefore, if the difference of the peak hour between the observations and the simulation is less than 3 h, the model is judged to be in agreement with the observation. For the Jos Plateau (Fig. 8a), the observed rainfall peak at 1800 UTC is represented accurately by the model at 1700 UTC. However, the amplitude of the diurnal cycle is much larger in the model, with a maximum rainfall rate that is twice the observed rate.
Over the SN domain (Fig. 8b), the model produces a nocturnal rainfall peak around midnight (at 0200 UTC), which is close to the 0000 UTC peak in the observations. However, similar to the Jos Plateau region, the magnitude of the rainfall peak in the model is twice the observed value. In the AF domain (Fig. 8c), the observed afternoon rainfall peak at 1800 UTC is not reproduced by the model. Instead, peak rainfall rates in the model occur at 2300 UTC, with rainfall persisting through the early morning hours. Rainfall rates in this region are similar to observed values.

c. Physical processes

In this section, the physical processes associated with the diurnal cycle of rainfall are analyzed. We follow the observational analysis in Part I to examine the extent to which the diurnal cycle of rainfall in the model is controlled in the same way as in the observations.

Figures 9 and 10 display Hovmöller diagrams of the JJAS 2006 rainfall averaged over 9°–11.5°N (the latitude range of the three southern analysis boxes; Fig. 6) from TRMM and the convection-permitting simulation, respectively. The propagating rainfall systems are identified through Hovmöller diagrams (Figs. 9 and 10) using a 1 mm day$^{-1}$ threshold. The duration and speed of each system are calculated, and the statistics of the propagating rainfall systems are summarized in Table 1. One prominent similarity is that both the observed and simulated rainfall distributions are dominated by westward-propagating systems. This is also the case for the two sensitivity simulations with different physical parameterizations (not shown). As discussed in section 2, GCMs and coarser-resolution RCMs with parameterized convection produce mostly static afternoon rainfall without propagation, which results in missing the nocturnal rainfall peaks. Here, the well-simulated westward propagation

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**Fig. 6.** Hour of maximum rainfall from JJAS 2006 in (a) TRMM and (b) the WRF convection-permitting simulation. Boxes denote the four domains defined in Fig. 1.

Over the SN domain (Fig. 8b), the model produces a nocturnal rainfall peak around midnight (at 0200 UTC), which is close to the 0000 UTC peak in the observations. However, similar to the Jos Plateau region, the magnitude of the rainfall peak in the model is twice the observed value. In the AF domain (Fig. 8c), the observed afternoon rainfall peak at 1800 UTC is not reproduced by the model. Instead, peak rainfall rates in the model occur at 2300 UTC, with rainfall persisting through the early morning hours. Rainfall rates in this region are similar to observed values.

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**Fig. 7.** Diurnal cycle of WRF-simulated JJAS 2006 rainfall (mm day$^{-1}$) area averaged for 1° × 1° grid boxes within the region of 7°–17°N, 7°W–20°E. The boxes are identical to those in Figs. 4 and 6 in Part I. Grid boxes with multiple diurnal peaks of rainfall are shaded in blue. The x axis of each panel ranges from 0000 to 2400 UTC at 1-h intervals. A peak is defined when it is at least 1 mm day$^{-1}$ higher than its neighbor times.
of rainfall is a promising improvement in the representation the diurnal cycle of rainfall in climate models.

The westward-propagating systems are frequently initiated in the afternoon near 9°–10°E, indicating that the model realistically simulates the afternoon rainfall related to the topography of the Jos Plateau. In the simulation, these systems propagate westward into the SN region, similar to TRMM, resulting in a realistic timing of rainfall peaks in the SN domain (Figs. 6, 8b). However, the model initiates afternoon rainfall too frequently around the Jos Plateau; the total number of propagating rainfall systems in the model is more than twice that in the observation (Table 1). This overestimation corresponds to the wet bias in the seasonal mean rainfall over the Jos Plateau and downstream regions to the west (Fig. 4).

In the model, rainfall systems propagate through the AF domain during the evening and night, causing the misrepresentation of the diurnal cycle of rainfall in that region (Fig. 6). There is no secondary afternoon peak in the AF domain that is comparable to the observations (Fig. 8c). A similar Hovmoller diagram for simulated rainfall at the NN domain latitudes (13.5°–16.5°N, not shown) exhibits few events and a low rainfall rate, corresponding to the dry bias in seasonal mean (Fig. 4).

Because of this dry bias, the model fails to reproduce the diurnal cycle of rainfall over the northern part of the domain.

Generally, the number of rainfall systems generated in the model is more than twice that in the observations because of an overestimation of the initiation of afternoon rainfall around the Jos Plateau (Table 1). In addition to the doubled frequency of rainfall events, the modeled systems have lifetimes that are about 30% shorter than observed in TRMM and propagation speeds that are nearly 20% faster. Here we give an estimated time of propagation. Consider the propagation of a convective system from the center of the JP domain (10.25°N, 8.5°E) to the center of the SN domain (10.25°N, 3.0°E); the distance is 601.8 km. Using a mean speed of 12.4 and 14.7 m s⁻¹ for TRMM and the WRF simulation, respectively, the estimated time is 13.5 h for TRMM and 11.4 h for WRF. These numbers agree with the peak hour maps.

To understand the overestimated initiation of afternoon rainfall around the Jos Plateau, the low-level circulation is examined for this region. Figure 11 shows 925-hPa winds and specific humidity in the vicinity of the Jos Plateau region in the three reanalyses and the default simulation. The simulated low-level flow matches well with the reanalyses, indicating that the overestimation of afternoon rainfall initiation is not caused by a bias in the large-scale low-level flow.

In Fig. 12, we examine the instability of the lower troposphere as indicated by afternoon moist static energy (MSE) anomaly profiles averaged over the region (9.5°–10°N, 8.3°–8.8°E) downstream (i.e., west) of the Jos Plateau. MSE is the sum of the sensible, latent, and geopotential heat contents of a parcel:

\[
MSE = c_p T + L q + g z, \tag{1}
\]

where \(c_p\) is the specific heat of air at constant pressure, \(T\) is the air temperature, \(L\) is the latent heat of water vaporization, \(q\) is the specific humidity, \(g\) is the acceleration due to gravity, and \(z\) is the geopotential height. MSE increasing with altitude indicates a stable atmosphere. The MSE anomalies are obtained by removing the daily mean from the MSE. To better characterize the diurnal cycle, here we use MERRA because it is available at 3-hourly intervals while the other reanalyses are provided at 6-hourly intervals. MERRA produces an unstable MSE anomaly profile at and above 875 hPa (Fig. 12a). The simulated MSE anomaly profile (Fig. 12b) is neutral from the surface to 850 hPa and then becomes unstable above 850 hPa. The simulated MSE anomaly profile is more unstable than the reanalysis at and above 800 hPa. Similar to MERRA, the thermal contribution to the anomalous MSE profile...
(i.e., $c_p T$) is greatest near the surface, and the moisture contribution (i.e., $L_q$) dominates above 900 hPa.

Figure 13 displays a cross section of cloud fraction simulated by the model, which is a proxy for convection, at 10°N averaged at 1500 UTC through JIAS 2006. The disturbances generated over the Jos Plateau are initiated above 850 hPa and then propagate westward into the analysis region (9.5°–10°N, 8.3°–8.8°E), as suggested by

Fig. 9. Hovmöller diagram of TRMM 3-hourly rainfall (mm day$^{-1}$) averaged between 9° and 11.5°N for (left) June–July and (right) August–September 2006. Gray lines denote the boundaries of the AF (3°W and 0°), SN (2° and 5°E), and JP (7° and 10°E) domains.
the Hovmöller diagram. Therefore, these disturbances enter the analysis region at levels with unstable profiles that are favorable for the development of deep convection. The more unstable MSE anomaly profile in the model is consistent with having more frequent initiation of afternoon convection in this region compared with the observations.

In the AF domain, as discussed above, the observed afternoon rainfall peak is not captured in the convection-permitting simulations. Instead, the model
produces nocturnal rainfall peaks. This apparent delay is common to regions not affected by topographic rainfall in the simulation (Fig. 6). Figure 14 displays the MSE anomaly profiles for the AF domain in MERRA and the default simulation. At low levels, from the surface to 850 hPa, the model produces an MSE anomaly profile that is close to neutral, while MERRA shows an unstable profile. Although the model has an unstable profile from 850 to 750 hPa, similar to MERRA, the neutral layers below inhibit the onset of deep convection. This suggests that the afternoon rainfall peaks in the model are not well captured in the convection-permitting simulations because the model produces an unrealistically stable profile below 850 hPa.

By separating the temperature and moisture contributions to the total MSE (indicated by the dashed and dotted–dashed lines, respectively, in Fig. 14), it is clear that the MSE anomaly profile in the simulation is stabilized by the specific humidity maximum at 850 hPa. The diurnal cycle of the low-level specific humidity in the model is compared with MERRA in Fig. 15a. The diurnal cycle of specific humidity in the model simulation at 900 hPa is similar to MERRA, but not at 925 and 950 hPa. At 800 and 850 hPa, the model produces an afternoon peak of specific humidity, while MERRA does not show prominent diurnal variation.

Differences in the low-level moisture between the model simulation and MERRA are associated with the development of the PBL. Using AMMA in situ observations, Lothon et al. (2008) suggest that the daytime development of the PBL generates strong vertical mixing of atmospheric moisture in the lower troposphere and reduces the near-surface moisture, which agrees with the finding in Part I (Fig. 10 in Part I). Figure 15b displays the diurnal cycle of the PBL height simulated by the model (solid black line).

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<th>TABLE 1. Statistics of the propagating rainfall systems in TRMM (Fig. 9) and the WRF convection-permitting simulation (Fig. 10).</th>
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<td>TRMM</td>
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<td>Total number of propagating systems</td>
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<td>Mean duration of propagation (h)</td>
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<td>Mean propagation speed (m s(^{-1}))</td>
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Fig. 11. JJAS 2006 mean 925-hPa wind (vectors; m s\(^{-1}\)) and specific humidity (shaded; g kg\(^{-1}\)) over JP in (a) MERRA, (b) CFSR, (c) ERA-Interim, and (d) the WRF convection-permitting simulation. White denotes regions where the surface pressure is lower than 925 hPa, and the differences between each dataset are due to spatial resolution.
Compared with MERRA (dashed black line), the model produces a PBL that is 50% deeper. As a result, vertical mixing in the model is stronger at 900 and 850 hPa. This enhanced vertical mixing is associated with the unobserved moistening of these levels (Fig. 15a). In the sensitivity simulation using the MYJ PBL scheme, the diurnal cycle of low-level specific humidity is similar to the default simulation, and the PBL is even deeper than the default simulation (not shown).

5. Conclusions

Based on the characterization and physical understanding of the diurnal cycle of rainfall over West Africa developed in Part I, in this paper we evaluate convection-permitting regional model simulations for the warm season of 2006 to further understand the physical processes that control the diurnal cycle of rainfall over West Africa and a model’s ability to capture these processes. The simulations cover a West African domain (7°–17°N and 7°W–20°E) at 3-km resolution, with initial and lateral boundary conditions supplied from the CFSR. In addition to a default simulation, two sensitivity simulations are conducted by altering the PBL and cloud microphysics schemes.

FIG. 12. (a) Profiles of MERRA total MSE (solid lines; $10^3$ m$^2$ s$^{-2}$), $A_p T$ (dashed lines), and $Lq$ (dotted-dashed lines) anomalies at 1500 UTC averaged over the domain (9.5°–10°N, 8.3°–8.8°E) to the west of the top of JP. (b) As in (a), but for the WRF simulation. Anomalies of the geopotential term $gz$ are negligible and not shown.

FIG. 13. Cross section of simulated cloud fraction (%) at 10°N. White area denotes the topography of the Jos Plateau.
The results are summarized as follows:

- The model realistically simulates the seasonal mean rainfall and lower-troposphere circulation. Moreover, the westward-propagating nature of the region’s rainfall is well captured, producing a distinct advantage compared to the rainfall simulated in GCMs or RCMs at coarser resolutions with convective parameterization activated.

- The model produces a single diurnal peak of rainfall over most of West Africa, either in the afternoon or at night, in agreement with TRMM satellite-derived rainfall observations. The number of simulated rainfall systems is roughly twice that in the observations, in association with too-frequent initiation of afternoon rainfall in the vicinity of the Jos Plateau. The model also produces rainfall systems that are shorter lived, by about 30%, with propagation speeds nearly 20% faster than those observed in TRMM.

- The model captures the afternoon rainfall peaks associated with elevated topography (i.e., around the Jos Plateau). Nocturnal rainfall peaks downstream of the topographic afternoon rainfall are also well simulated.

- The model fails to reproduce observed afternoon rainfall peaks over regions not associated with topography. Nocturnal rainfall is too widespread, and this model inaccuracy is the same with alternate choices in PBL and cloud microphysics parameterizations. The reason is that the model has a PBL that is deeper in the afternoon than is observed, as represented in MERRA. The result is that the simulated unstable region of the afternoon MSE anomaly profile is located at a higher altitude than in MERRA, and the low-level MSE anomaly profile is nearly neutral. This vertical structure inhibits the low-level development of afternoon convection over most regions with no topographic features. In contrast, downstream (i.e., west) of the mountains, this MSE profile is favorable for the initiation of afternoon convection because the disturbances propagate from an elevated surface that is above the neutral levels and located at the unstable levels.

An improved understanding of the diurnal cycle of rainfall, including its processes and representation in models, is important for advancing weather and climate prediction over West Africa. This study demonstrates that atmospheric models running at convection-permitting resolutions significantly improve the representation of the diurnal cycle of rainfall compared to GCMs and coarser-resolution RCMs with parameterized convection (Cook and Vizy 2006; Dai 2006;
However, increasing the model resolution to a convection-permitting resolution (e.g., 3 km) may not produce completely realistic simulations because other parameterization-dependent issues can arise. For example, rainfall in convection-permitting simulations can still be sensitive to parameterized cloud microphysics processes. In this study, the overproduction of nocturnal rainfall was related to the height of the planetary boundary layer and, therefore, the parameterization of boundary layer processes.

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