Published in final edited form as:

Mon Weather Rev. 2016 January ; 145(No 1): 215–233. doi:10.1175/MWR-D-15-0294.1.

The sensitivity of WRF daily summertime simulations over West Africa to alternative parameterizations. Part 2: Precipitation

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Abstract

This paper evaluates the performance of the Weather and Research Forecasting (WRF) model as a regional-atmospheric model over West Africa. It tests WRF sensitivity to 64 configurations of alternative parameterizations in a series of 104 twelve-day September simulations during eleven consecutive years, 2000–2010. The 64 configurations combine WRF parameterizations of cumulus convection, radiation, surface-hydrology, and PBL. Simulated daily and total precipitation results are validated against Global Precipitation Climatology Project (GPCP) and Tropical Rainfall Measuring Mission (TRMM) data. Particular attention is given to westward-propagating precipitation maxima associated with African Easterly Waves (AEWs). A wide range of daily precipitation validation scores demonstrates the influence of alternative parameterizations. The best WRF performers achieve time-longitude correlations (against GPCP) of between 0.35–0.42 and spatiotemporal variability amplitudes only slightly higher than observed estimates. A parallel simulation by the benchmark Regional Model-v.3 achieves a higher correlation (0.52) and realistic spatiotemporal variability amplitudes. The largest favorable impact on WRF precipitation validation is achieved by selecting the Grell-Devenyi convection scheme, resulting in higher correlations against observations than using the Kain-Fritsch convection scheme. Other parameterizations have less obvious impact. Validation statistics for optimized WRF configurations simulating the parallel period during 2000–2010 are more favorable for 2005, 2006, and 2008 than for other years. The selection of some of the same WRF configurations as high scorers in both circulation and precipitation validations supports the notion that simulations of West African daily precipitation benefit from skillful simulations of associated AEW vorticity centers and that simulations of AEWs would benefit from skillful simulations of convective precipitation.

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Introduction

This paper is a sequel to Noble et al. (2014), which analyzes the sensitivity of the National Center for Atmospheric Research (NCAR) Weather and Research Forecasting (WRF) model daily circulation over West Africa to alternative model parameterizations. The WRF is a numerical weather prediction (NWP) model used for atmospheric-science research. WRF incorporates a community model infrastructure that facilitates scientific collaboration, whereby the operational and research communities work jointly toward the development of next-generation NWP capabilities by giving the research community better access to operational codes for investigating modeling successes and failures (Bernardet et al. 2008). The infrastructure has also allowed rapid adaptation of the WRF for regional climate model (RCM) applications (Liang et al. 2012). An RCM includes coding to compute atmospheric processes plus soil hydrology, and accounts for the boundary forcing of high-resolution terrain, land-sea contrasts, surface characteristics, and other components of the Earth-system. RCMs are driven by time-variable conditions along their lateral atmospheric boundaries and are thus used to downscale global retrospective analysis (or reanalysis) or multi-decadal global climate models (GCMs) to provide information for climate, climate variability and change with regional refinements (Giorgi and Mearns 1991).

Despite the WRF model's worldwide popularity, the model was designed for short-range weather prediction over North America and not intended for long-term climate simulations (Dudhia 2014). Recent studies have investigated its capabilities for North American RCM applications (Caldwell et al. 2009; Liang et al. 2012). WRF RCM applications in tropical regions have encountered numerous problems, including deficient rainfall at the Equator and precipitation overestimation over West Africa (Druyan et al. 2009). To remedy unsatisfactory simulation skill for West African, East African, South African precipitation, several studies test model sensitivities to different physics parameterizations (Flaounas et al. 2010; Pohl et al. 2011; Crétat et al. 2012). This paper focuses on WRF simulation skill for West Africa, and takes the optimization-step emphasized by Flaounas et al. (2011) further, by analyzing the multiple combinations of five parameterizations; in effect considering 64 different model configurations.

West Africa includes the Sahel, a semi-arid transition-zone at 10°N to 20°N bounded by the Sahara Desert to the north and a rainy region to the south that includes Senegal, Mali, Mauritania, Niger, Burkina Faso, Chad, and Sudan. The rainy season occurs during boreal summer when the West African Monsoon (WAM) brings the largest portion of the annual rainfall to the Sahel. The Sahel remains dry during the winter and spring months until rains arrive in late June from a northward inland surge of moist monsoon air from the Gulf of Guinea, marking the onset of the WAM (Sultan and Janicot 2000). Scientific attention has focused on the Sahel because the area suffered a series of severe droughts during the late 1960s to the 1980s. To better understand its weather and climate variability, the Sahel has been the site of major field experiments, including the JET2000 Experiment (Thorncroft et al. 2003) and the African Monsoon Multidisciplinary Analysis (AMMA), which included comprehensive field measurements during the 2006 boreal summer (Redelsperger et al.

2006). This paper evaluates WRF precipitation simulations during the AMMA Special Observing Period 3 (SOP3).

Although model-based climate studies relate to monthly or seasonal mean fields, confidence in simulations of the seasonal climate improves if the model realistically captures the characteristics of relevant daily weather phenomena. The current study aims to examine the sensitivity of WRF skill for downscaling reanalysis at daily timescales, a first step in evaluating its performance for monthly to seasonal timescales. In particular, the current study evaluates its WRF simulations of spatial precipitation patterns associated with African Easterly Waves (AEWs). AEWs are westward propagating synoptic atmospheric waves, best monitored at 850, 700 or 600-hPa, with wavelengths of 3000–5000 km and two distinct period bands: 2–6 and 6–9 days. AEWs are a major source of synoptic-scale precipitation variability over West Africa. (Diedhiou et al. 1999; Druyan et al. 2008; Burpee 1972). Accordingly, WRF performance should be evaluated in terms of how well AEW-associated circulation and precipitation are represented.

There is considerable literature that relates precipitation to AEWs. Several studies find that convection and precipitation are more prevalent within and ahead of the trough. Composites of AEWs show rainfall maxima southwest of the 700-hPa wave apex (Reed et al. 1977; Druyan et al. 2008). Satellite infrared imagery shows that a preferred location for convective rainfall over West Africa is ahead of AEW troughs (Payne and McGarry 1977). Rain gauge investigations note positive rainfall anomalies in and ahead of AEW troughs (Diedhiou et al. 1999).

Other studies found that some convection occurred east of the trough, in the southerly flow. AEWs over the northern Sahel (17.5°N) are more likely to have moist mesoscale convection east of troughs, while AEWs at more southerly latitudes (7.5°N) seem to be rainy more often at and west of troughs (Fink and Reiner 2003), linked to convection and rainfall over the Sahel region (Ruti 2010). Rainfall totals can be greatest just prior to AEW trough passage within AEW troughs, or east of troughs within the strongest 700-hPa southerlies (Druyan et al. 2008). In a study based on TRMM precipitation radar and ERA-I, Janiga and Thorncroft (2016) determine that high summertime precipitation rates over the Sahel favor the northerly phase of AEWs (west of troughs), while AEW related rainfall over the western coast of Africa and the east Atlantic shifts toward the trough where the air is moist. They also suggest that climate simulation models with parameterized convection tend to underestimate rain rates west of the troughs and overestimate rain rates within the troughs and to their east. The most frequent preference for heavy precipitation southwest of the apex relates to the broad area of lower tropospheric convergence created by AEWs west of the 700-hPa trough (Druyan et al. 1996).

AEWs are not always accompanied by precipitation as found by Taleb and Druyan (2003). Analysis of observations suggests that only about one-third of seasonal precipitation totals is recorded on days affected by statistically significant wavelet amplitudes of 700-hPa meridional wind in the 3–5 day period band.

GCM simulations show westward propagating rainfall “footprints” presumed to be associated with AEWs on time-longitude Hovmöller plots (Xue and Shukla 1993). However, squall lines and MCSs can often propagate at different speeds relative to their associated AEWs (Fortune 1980). Westward propagating precipitation bands, many, presumably, embedded within AEWs, appear as diagonal swaths on time longitude (Hovmöller) diagrams of TRMM daily observations over West Africa (Druryan et al. 2006).

Mesoscale convective systems (MCSs), which produce most of the precipitation during the summer monsoon in West Africa, move more quickly than AEWs on average and less than a half are associated with AEWs (Lebel et al. 2003). Radar-based studies of the same period as this study found that MCS precipitation in West Africa is more influenced by conditional stability and vertical wind shear than on AEW phase (Guy et al. 2011). Berry and Thorncroft (2012) show in WRF simulations that organized deep convection embedded within an AEW makes a large contribution to the synoptic-scale mean potential vorticity and therefore to the energetics of the AEW. Their WRF experiment demonstrates that convection is vital for the maintenance of the AEW over West Africa and suggests that AEWs require active convection to persist for an extended length of time.

Multiple alternative WRF parameterizations are available to represent physical processes: convection parameterization schemes (CPS), PBL schemes, land-surface models (LSM), microphysics parameterization schemes (MPS), and radiation-transfer (RAD) schemes. A configuration of WRF parameterizations must be selected for each application and perhaps for each geographic region. Testing and validating WRF parameterizations is especially important because time mean precipitation simulations are sensitive to model configuration (Lynn et al. 2008). Thus, the motivation here is to test the sensitivity of WRF simulations of West Africa weather and climate to model configuration. Suggestions of skillful WRF configurations resulting from this evaluation should benefit other investigators planning WRF applications over West Africa. Part 1 (2014) reports on configurations for circulation simulations— while this paper discusses WRF skill in simulating precipitation.

Summary of WRF circulation performance

Noble et al. (2014) compare 12-day simulations of circulation and 700-hPa vorticity over West Africa from 64 alternative WRF configurations to MERRA, NCP2 and radiosonde soundings at two locations. The largest favorable impact on WRF vorticity simulation is realized by selecting the Grell-Devenyi (GD) cumulus convection scheme (Grell and Dévényi 2002). This preference may reflect the more versatile skill of that scheme’s ensemble approach to computing the two-way interaction between convection and large-scale circulation within the very complex WAM regime. Vorticity simulations using GD achieve higher correlations with reanalysis than the remaining simulations using the Kain-Fritsch (KF) convection scheme (Kain 2004). Impacts of other model parameterizations are more ambiguous. Selected WRF configurations have skill in simulating vorticity attributed to AEWs up to nine days into the simulation for 2006, but skill drops sharply thereafter.

Berry’s (2009) analysis of selected WRF simulations over West Africa on a 125 km grid for September 2004 is relevant. He tests the sensitivity of simulations to three cumulus parameterization schemes: Betts-Miller-Janjic (Vaidya and Singh 2000), KF, and GD. Berry

finds that GD simulates the most realistic representation of the westward propagating AEWs that cross the African coast on Sept 2, 4, 7 and 9, 2004. Moreover, using GD also produces the most realistic representation of precipitation. Of the three schemes, only GD simulates all four AEWs since the KF and BMJ schemes dissipate one of the AEWs and propagate another one too slowly. Premature dissipation of AEWs can result from underestimates of deep convection that inhibit the generation of potential vorticity. This, in turn, limits the dynamics that strengthen AEWs (Berry and Thorncroft 2012).

Validation statistics from Noble et al. (2014) for selected WRF configurations simulating the parallel period during ten additional years indicate that results for 2006 are much more favorable than for other years. In fact, during most years, even the best WRF configurations fail to produce 700-hPa vorticity distributions with any correlation to reanalysis after only a day or two. Discrepancies between simulated and observed trajectories of AEW vorticity centers negatively impact model simulation of precipitation variability since significant precipitation maxima during the summer are associated with AEWs.

Methods And Data

a. Simulation Period

The current study examines simulations for 2–13 September 2006, the same 12-day period analyzed by Noble et al. (2014). This period had four well-defined AEW troughs with embedded growing and decaying convective activity of various sizes, durations, and intensities, including the development of the pre-Helene tropical storm at the end of the period (Franklin and Brown 2008; Cifelli et al. 2010). The selected time period also occurs during the combined AMMA and NASA AMMA (NAMMA) field campaigns (Redelsperger et al. 2006; Zipser et al. 2009) during August and September, 2006. Previous WRF modeling studies have examined this period (2011; Druyan et al. 2009; Chiao and Jenkins 2010; Janicot et al. 2011; Flaounas et al. 2012; Cook and Vizu 2010) but none examined the sensitivity of WRF simulations to the wide variety of parameterization schemes available for WRF, save for Noble et al. (2014). The short evaluation period allows the analysis to be based on some 104 simulations.

b. WRF configurations

This paper evaluates the Advanced Research WRF version 3.2.1 (Skamarock et al. 2008), (WRF-ARW, henceforth WRF), which employs the ARW dynamics solver, or “Eulerian mass” solver. The WRF is a modular, non-hydrostatic, and fully compressible model that uses the sigma vertical-coordinate to better simulate airflow over complex terrain. WRF in these experiments uses a 20-km horizontal grid at 30 terrain-following sigma layers between the Earth’s surface and the 50-hPa model top.

Fig. 1 shows the model domain and topographic features used for simulations. Elevations are derived from the Global 30 arc second elevation dataset from United States Geological Survey. The red box designates the region for which validation scores are compiled- an area noted for AEWs and precipitating deep convection. The initial conditions and lateral boundary conditions (LBC), including sea surface temperatures, for all simulations in this

study were specified from the National Centers for Environmental Prediction-U.S. Department of Energy Atmospheric Model Intercomparison Project Reanalysis II NCEP-DOE II (hereafter referred to as NCEP2) (Kanamitsu et al. 2002). The NCEP2 data are interpolated from pressure levels on a 2.5° Gaussian-grid and 6-hourly temporal availability to the WRF grid using the WRF pre-processing system. Reanalysis over sparse data regions like West Africa provides LBC and validation data that are not always a perfect representation of actual conditions, but the gridded interpolation is nevertheless anchored to and consistent with the observed meteorology. Therefore, initializing and driving the WRF with NCEP2 should represent a high level of potential skill of WRF simulations. No nudging or interactive nesting was used in any of the experiments.

Numerical experiments are designed to evaluate WRF performance for different combinations of the WRF parameterizations that are identified in Table 1. This study tests 64 configurations for simulation using the following parameterizations: CPS from KF and GD, PBL physics from Yonsei University (YU), Mellor-Yamada-Janjic (MJ), and Mellor-Yamada-Nakanishi-Niino (MN) schemes, surface physics from the 5-Layer Thermal Diffusion LSM (5L), the NOAH (NO) LSM, the Rapid Update Cycle (RU) LSM, and the Pleim-Xue (PX) LSM, radiation physics from the Rapid Radiative Transfer Model (Rt), the Community Atmosphere Model (CM), and microphysics from the (W5). Of course, given the multiplicity of parameterizations available for WRF, it is impossible to test every possible combination (Liang et al. 2012).

Table 2 shows the 64 numerical experiments tested using data from 2006, configured by changing one parameterization at a time, starting with the first option and its acronym listed in Table 1. Experiments are labeled consecutively, 1–64. Although numerous, the combinations tested here represent a small subset of testable possibilities. Note that WRF Experiment 2 is the recommended WRF reference configuration for WRF v.3.2.1 NWP, (Wolff 2011; Harrold 2012) and for tropical simulations (personal communication, Jimmy Dudhia, 2008). Hereafter, WRF Experiment 2 is referred to as the WRF2 and each WRF experiment is referred to in parallel fashion (e.g. WRF Experiment 27=WRF27). It is possible that no single WRF configuration is optimal under all circumstances (location, times of day, season, etc.) The reader is referred to Skamarock (Skamarock et al. 2008) for further details of all parameterizations in Tables 1 and 2.

The MPS explicitly resolves water vapor, cloud, and precipitation processes. Pohl et al. (2011) and Crétat et al. (2012) find that MPS exert a minor influence on the location, intensity, and number of rainy events over East and Southern Africa. A number of Single-Moment MPS schemes can be used in WRF: 3-Class (WSM3), 5-Class (WSM5), and 6-Class (WSM6) (Hong et al. 2004). Both the WSM5 and WSM6 are suitable for domain resolutions less than 25 km (Hong et al. 2006). This study adapts the computationally less-expensive WSM5. Table 2 does not show MPS since the WSM5 is used in all WRF configurations. However, the discussion refers to a sensitivity test for the impact of alternative MPSs.

d. Validation Data Sets

To assess the skill of the simulations, model results are compared to satellite rainfall estimation products (SREPs) described in Table 3. The conventional rain gauge network in West Africa is inadequate for validating spatial and temporal details of the precipitation simulations. SREPs are useful alternatives to gauge measurements because of their better spatial and temporal coverage. Several independently derived SREP—albeit based on similar measurements—are also referenced.

Differences among SREPs reflect the degree of confidence that we can place in the verification analysis. The TRMM Algorithm 3B42 product is one of the best sources for merged high-quality precipitation estimates, particularly because it provides 3-hourly high-spatial resolution (0.25°) estimates (Huffman et al. 2007). TRMM does not include any ground-validation in its sub-monthly products. However, the alternative NASA Global Precipitation Climatology Project 1-Degree Daily (GPCP 1DD) “final” analysis SREP is calibrated with rain-gauge data, and is, perhaps, the best historical precipitation product available for this purpose (Huffman et al. 2009). Results are also compared with the Climate Prediction Center Morphing (CMORPH) (Xie 2004) and Precipitation Estimation from Remote Sensing Information using Artificial Neural Network (PERSIANN) (Behrangi et al. 2009). Modeled precipitation data are also compared to MERRA and NCEP2 reanalysis, which provide independent estimates at $x, y = 1.25^\circ$ and 2.5° , respectively.

To better assess WRF potential to characterize West African weather patterns, results from another model are presented as a benchmark. The NASA and Center for Climate-Systems Research Regional Model-v.3 (NASA-GISS/CCSR-RM3; hereafter RM3) is run over the same domain on a 0.5° grid for the same 12-day period and forced by the same LBC. The RM3 has previously been used to study AEWs (Druryan et al. 2006; 2009; 2010a) and longer-term climate simulations in the West African Monsoon Modeling Evaluation (WAMME) initiative (Druryan et al. 2010b). Druryan et al. (2010b) summarize WAMME results from five RCMs simulating the WAM with both reanalysis and GCM forcing, but that study does not include the WRF model.

Results

a. Total-Accumulated Precipitation

Distributions of accumulated precipitation (p_{tot}) for 2–13 September 2006 are constructed for each of the 64 WRF experiments in Table 2 and then compared to SREP observations. All modeled and observed SREP p_{tot} are compared on a $0.25^\circ \times 0.25^\circ$ grid by interpolation with the first-order-conservative-remapping method (Jones 1999). Figs. 2a–2j show the 12-day p_{tot} for GPCP, TRMM, WRF2, WRF27, WRF32, WRF59, WRF60, WRF64, and RM3, respectively. WRF2 is the default configuration, while the other WRF configurations validate best against 2006 SREP p_{tot} as explained in section 3c. Furthermore, WRF27 and WRF32 12-day simulations of circulation and 700-hPa vorticity over West Africa validate best against reanalysis (Noble et al. 2014). The GPCP p_{tot} (Fig. 2a) shows two sub-regions: the southern box outlines the tropical rain-belt region that includes most p_{tot} (5°N – 15°N , 25°W – 10°E), while the northern box (10°N – 20°N , 25°W – 10°E) outlines the Sahel region

(Nicholson 2013). The combined sub-regions make up the region shown in Fig. 1, for which all results are validated.

Differences between GPCP and TRMM p_{tot} (Figs. 2a–2b) mean that WRF-validation scores against GPCP will differ from scores validated against TRMM. Moreover, the differences are a humble reminder that the actual precipitation characteristics may be elusive. The GPCP shows slightly more p_{tot} maxima than TRMM over central Nigeria (8°N–12°N, 4°E–10°E), over the central savanna-plains, and on the West-African coast (10°N–13°N, 16°W–12°W), as well as a slightly wetter Sahel region. The WRF configurations produce too much rain, especially WRF2 in Fig. 2c., whereas WRF27, WRF32, WRF59, WRF60, and WRF64 in Figs. 2d–2i show less exaggerated rain than the default. All WRF experiments show a very wet rain-band region and a drier Sahel region compared with observations, implying excessive simulated low-level moisture convergence along the West African coast. The RM3 in Fig. 2h produces p_{tot} maxima similar to GPCP and TRMM over all regions (resulting in correspondingly favorable RM3-validation scores, discussed below in section 3c.) None of the WRF experiments produces the observed orographic precipitation maxima over the Cameroon Highlands. WRF32 and WRF64 are the best WRF simulations in representing the maximum values in the east, the relative minima near zero longitude and east of the Guinea Highlands; and the secondary peak along and offshore the west coast. Both WRF versions use the GD convective scheme, MN PBL and the PX surface model. Differences resulting from the different parameterizations are explored in Section 3c.

Fig. 3 shows the 2–13 September 2006 p_{tot} ratios (WRF/observed, area-averaged over each of three regions shown in Fig. 2a) for each of the 64 WRF experiments, relative to GPCP (green bars) and TRMM (red bars). Fig. 3a shows the ratios for the Sahel sub-region, Fig. 3b for the rain-band sub-region and Fig. 3c for the combined region. The x-axis shows each WRF version from Table 2 along with the RM3 (labeled R3). The plots show that the WRF wet-biases are common to all configurations and are slightly smaller in the comparisons to TRMM. Note that ratios for the rain-band region (Fig. 3b) are similar to ratios for the combined regions (Fig. 3c), whereas the ratios for the Sahel region (Fig. 3a) are generally higher. The combined sub-regional domain represented in Fig. 3c (see Fig. 1) is chosen to monitor WRF precipitation performance in subsequent discussions.

A Taylor-diagram provides a visual framework for a statistical summary of how well patterns match each other in terms of their correlation (r), a normalized standard deviation (σ_n) normalized by dividing by the corresponding SREP σ value, and a normalized rmse centered difference between each point concurrently on one plot (Taylor 2001). Fig. 4 graphically summarizes the skill scores between the modeled and SREP p_{tot} distributions between 5°N–20°N in a Taylor diagram. The radial distance from the origin measures the magnitude of each σ_n , normalized by dividing each WRF σ by the corresponding TRMM σ value. The normalized $rmse$ centered difference between each point and TRMM is measured by the values of the dashed semi-circles. The spatial r , WRF versus TRMM, is given by the azimuthal position of each point, labeled along the outer arc. Fig. 4b makes the same comparison against GPCP p_{tot} . Figs. 4a–4b include the statistical scores achieved by each of the 64 WRF configurations, and secondary reference-points of the other SREP, MERRA and NCEP2, and RM3. The positions of WRF default and the five WRF-configurations from Fig.

2 are labeled. Fig. 4a shows that the majority of WRF p_{tot} distributions achieve r -scores between 0.25–0.45 versus TRMM, while Fig. 4b shows that they get somewhat higher r -scores versus GPCP ($r=0.40$ – 0.70 .) In fact, WRF64 p_{tot} (also shown in Fig. 2g) scores the highest r versus GPCP (0.70.) RM3 outperforms all the WRF configurations by achieving the most favorable r and σ_n versus TRMM and GPCP ($r=0.78$ and 0.90 , $\sigma_n=1.10$ and 1.13 , respectively), consistent with the p_{tot} shown in Fig. 2i.

b. Simulation of meridional moisture flux

Modeled moisture advection in the lower troposphere is crucial because the flux of summertime moisture into West Africa regulates precipitation rates. Druyan et al. (2010b) analyze the strength of the 950-hPa meridional moisture advection (qv) for June–September as a diagnostic of model performance. Here, we consider qv at the standard atmospheric-level of 925-hPa as a lower troposphere diagnostic of the water cycle over West Africa during the period of this study. Fig. 5a shows MERRA 925-hPa mean vector winds (V_{925}) for 2–13 September 2006, superimposed over the 12-day mean qv . Figs. 5b–5e show four versions of the spatial distribution of WRF minus MERRA V_{925} superimposed over WRF qv -bias for each configuration relative to MERRA.

There is no objective way to determine whether the WRF configurations have collectively produced a more realistic representation of lower-tropospheric moisture advection than MERRA since it is also model dependent. WRF2, WRF32, WRF60 show a reduction in qv in the lee of the Guinean Highlands. The three non-default WRF configurations in Figs. 5c–5e reproduce monsoonal circulation and qv patterns similar to MERRA over the Atlantic Ocean and Gulf of Guinea. However, they include a sizeable positive qv bias relative to reanalysis in the Guinean region near 5° – 10° N and 10° W– 10° E and over the southeastern North Atlantic. These differences indicate that WRF imports excess moisture into WA in the lower troposphere. The exaggerated northward and eastward moisture transports across the Guinean coast region are consistent with high precipitation accumulations discussed Section 3a and Fig. 2. Negative WRF qv biases over the eastern Gulf of Guinea may contribute to the aforementioned negative precipitation biases near the observed Cameroon orographic precipitation maximum.

Further analysis shows that WRF simulated q validate well against reanalysis while WRF simulated v are too strong (in the area of positive qv bias). All the WRF configurations (not shown) show similar V_{925} and qv features to those shown in Figs. 5b–5e. In summary, WRF produces enhanced near-surface circulation toward WA. Similar deficiencies in MM5 seasonal simulations are reported by Druyan et al (2010b), attributed to edge effects from the western boundary of their model domain at 35° W, the same western domain boundary of the domain used in this study. The impact on WRF simulations of moving the western boundary westward is not explored here.

c. Daily-Accumulated Precipitation

Time-longitude Hovmöller distributions (Martius et al. 2006; Hovmöller 1949) of daily precipitation (p_{daily}) for the boxed region in Fig. 1a are constructed for each of the 64 WRF experiments in Table 2 and then compared to the corresponding GPCP observations. The

validation of Hovmöller time-longitude distributions of simulated versus observed p_{daily} provides statistics that evaluate temporal and longitudinal variability. Fig. 6 shows nine time-longitude Hovmöller diagrams of p_{daily} for 2–13 September 2006, in addition to three Hovmöller diagrams of 700-mb relative vorticity (RV). The x-axis indicates longitude, and the y-axis indicates elapsed-time. The data represent averages over latitudes 5°N–20°N, plotted against each longitude, 20°W–10°E. Fig. 6a shows the GPCP Hovmöller. Figs. 6b–6c show TRMM and CMORPH, Figs. 6d–6h show WRF27, WRF32, WRF59, WRF60 and WRF64 respectively, and Fig. 6i does the same for RM3. Figs. 6d–6h show each WRF configuration generating four westward-moving p_{daily} maxima-tracks roughly corresponding to GPCP. The p_{daily} tracks are related to transient AEWs and therefore to the tracks on Hovmöller distributions of meridional wind and vorticity discussed in Noble et al. (2014). To observe if the parameterized convection has a tendency to occur in the areas of a 700-mb trough (Noble et al. 2014), time-longitude Hovmöller distributions of 700-mb RV are shown for NCEP2 (Fig. 6j), WRF27 (Fig. 6k), and WRF32 (Fig. 6l).

The comparison of GPCP to NCEP2 RV tracks present in Fig. 6j show that precipitation maxima occur in areas of significant RV (orange.) The comparison to GPCP indicates exaggerated WRF p_{daily} maxima, several position displacements, and time lags. For example, Figs. 6d–6h show each WRF configuration simulating tracks in rather straight lines, implying constant propagation speeds, unlike GPCP, TRMM, and CMORPH that show tracks jumping from one maximum to another. The largest noticeable discrepancy between the WRF models and SREP observations occurs with track #2 during 3–8 September. All of the WRF configurations miss the appearance of track #2 on 3–4 September 2006, because of a propagation time lag. Only WRF32 and WRF60 (Figs. 6e and 6g) show the track correctly reaching 20°W on 8 September. Perhaps this difference is related to the trajectories of two AEW circulations merging during these days (Noble et al. 2014). The comparison of GPCP to NCEP2 RV tracks present in Fig. 6j show that precipitation maxima occur in areas of substantial RV (orange.) However, the RV track #2 in NCEP2 shows a trough occurring over 7°W on 5–6 September; the GPCP and the TRMM show p_{daily} maxima occurring earlier. All the WRF simulations show p_{daily} maxima occurring within the 700 mb RV trough. Both WRF27 and WRF32 p_{daily} maxima (Fig. 6d and 6e) occur over 7°W on 5–6 September at the same time as substantial 700mb-RV (Fig. 6k and 6l) and then proceed to 10°W–15°W on 7–8 September. WRF simulations in Figs. 6d–6h simulate a distinct track #3, which is almost in spatiotemporal agreement with GPCP, TRMM, and CMORPH, except that the SREP do not show p_{daily} maxima for 9 September at 3°W, whereas the WRF shows continuous p_{daily} maxima from 3°–5°W for that day. Schwendike and Jones (2010) attribute the interruptions of the rainfall events to the growth and decay of MCSs ahead of the AEW. The MCSs underwent stages of decay and regeneration, formed into a mesoscale convective vortex that enhanced the AEW vorticity, and interacted with another vortex generated by the topography near the coast; the WRF simulations do not capture these complex interactions. These WRF model p_{daily} simulation errors help explain some of the low skill score described below. WRF27 and WRF32 p_{daily} maxima for track #3 occur in the presence of modeled 700 mb RV troughs. Janiga and Thorncroft (2016) suggest that models need to appropriately partition between convective versus stratiform precipitation in order to successfully simulate spatial precipitation patterns

organized by AEWs. For example, placing the peak precipitation mainly in the AEW troughs and underestimating rainfall ahead of troughs may indicate that dynamically-forced ascent plays too great a role in the model (Crtat et al. 2012). Crtat et al. (2012) find that WRF can exaggerate the magnitude of AEW related rainfall events and overestimate their longitudinal extent due to excessive coupling between wave activity and convection.

Although the RM3 barely captures the movement of track #1 and track #2, it correctly simulates the positions of the other p_{daily} maxima in GPCP. These results confirm that the RM3 requires an adjustment period of several days for the model physics to accommodate the initial moisture distribution, before it shows skill in simulating daily variability of precipitation, as noted by Druryan et al. (2006). The concept of considering a similar adjustment period in the WRF simulations is further explored in Section 3d.

Fig. 7 graphically summarizes the skill scores of the modeled WRF Hovmller p_{daily} distributions against GPCP in Taylor diagrams. Figs. 7a–7d not only allow us to evaluate model performance by characterizing the statistical relationship between modeled and observed p_{daily} , but they also help us investigate modeled p_{daily} sensitivity to alternative WRF components. The Taylor distribution of statistics is shown four times: in each panel a different WRF parameterization from Tables 1–2 is highlighted to examine its influence on the scores. Fig. 7a does this for CPS, Fig. 7b does this for RAD, Fig. 7c does this for PBL, and Fig. 7d does this for LSM. First, the Taylor diagram shows that the TRMM scores the best r ($r=0.86$) and σ_n ($\sigma_n=0.98$), implying that comparisons between the WRF configurations and GPCP should show some similarities to comparisons with TRMM. Next, the diagrams show that MERRA scores a significant r ($r=0.43$) but low σ_n ($\sigma_n=0.43$) and NCEP2 scores poorly ($r=0.05$), illustrating its significant difference from observational evidence of p_{daily} based on SREP. Third, the RM3 scores the highest r among all the regional models ($r=0.60$). WRF experiments validate with a range of scores, several experiments achieving statistically significant r between $r=0.30$ and $r=0.40$ and a σ_n close to unity. The five WRF configurations that score some of the most favorable σ_n ($\sigma_n < 1.25$) and with high r against GPCP are labeled in each diagram (WRF27, WRF32, WRF59, WRF 60, and WRF64). Changing the CPS parameterization from KF to GD (Fig. 7a) produces an unambiguous improvement in the scores of many WRF configurations, achieving most of the highest r and best σ_n . This is the same conclusion reached in Noble et al. (2014) for the validation of simulated vorticity. In addition, three out of the four best scorers use the Rt RAD rather than the CM (Fig. 7b). Otherwise, some high scoring configurations incorporate alternative parameterizations of RAD, PBL and LSM, implying that their influence is ambiguous. However, no version with the MJ PBL (Fig. 7c) and neither the 5L nor NO LSMs (Fig. 7d) are found in the five selected WRF configurations. In fact, all configurations with MJ PBL and NO-5L LSM give poor performance. Five WRF experiments are shown as promising and notated in Figs. 7a–7d. Note that all of five WRF experiments share the same GD CPS in Fig. 7a and that they use paired-selection of A2-MN PBL in Fig. 7c, and PX-RU LSM in Fig. 7d.

To investigate the causes of the low performance scores, Fig. 8 examines the daily changes in validation scores of five WRF configurations selected as promising from Fig. 7 and the RM3. It shows daily cumulative- r , validating modeled p_{daily} up-to-and-including the day

indicated, versus GPCP and TRMM, for WRF27, WRF32, WRF59, WRF60, WRF64 and RM3. It also shows daily- r , validating the longitudinal variability of $5^{\circ}\text{N} - 20^{\circ}\text{N}$ p_{daily} means for each day for the same WRF configurations versus GPCP and TRMM. The daily- r specific to each day shows whether the simulation for an individual day was skillful or not, which cannot be deduced from the cumulative- r . Each WRF configuration panel in Fig. 8 shows a high cumulative- r at initialization that drops rapidly during the first 2 days and then proceeds with a rather low cumulative- r for the rest of the simulation. The daily- r trends show that the low cumulative- r scores occur for two reasons. First, the SREP indicate p_{daily} maxima between $7^{\circ}\text{W} - 13^{\circ}\text{W}$ on 4 September 2006 (Figs. 8a–8c) while the WRF configurations miss this event. Second, the SREP indicate a disruption of p_{daily} associated with AEW3 on 9 September 2006 near 3°W , while the WRF models show more continuity. The daily- r also show that the WRF models get relatively higher scores against GPCP. WRF model simulation skill of p_{daily} is strongly influenced by temporal error. The peaks and the minimums for each WRF configuration do occur on the same day, indicating that the configurations have similar performance characteristics. Significant, positive daily- r imply that the WRF configurations use information from the LBC to create precipitation events with similar timing and trajectories as SREP. However, the performance of WRF may be sensitive to the synoptic-scale configuration of a particular day and its representation by the forcing data, in addition to model physics. Fig. 8f shows that the RM3 vs. GPCP (or TRMM) cumulative- r is higher than for any of the WRF models, and that the scores improve after the fifth day into the simulation, confirming RM3 model skill improvement after a 5-day spin-up.

d. Spin-up and Multi-Year Validation

Druyan et al. (2006) report that RM3 p_{daily} simulations undergo an initial five-day adjustment period before results compare well with TRMM-observed variability. The benefit of a spin-up is clearly visible in the RM3 Hovmöller of p_{daily} in Fig. 6b and in the correlation scores in Fig. 8f. The five WRF configurations, WRF27, WRF32, WRF59, WRF60, and WRF64, are additionally integrated from initial conditions on August 27 and validated against GPCP for the 2–13 September study period. The six-day spin-up does not, however, improve their precipitation validation scores (not shown).

WRF27, WRF32, WRF59, WRF60, and WRF64 simulations are repeated with NCEP2 boundary conditions for the remaining years, 2000–2018. Fig. 9 shows cumulative- r vs. elapsed time for the Hovmöller p_{daily} distributions for simulations of all 11 years. Fig. 9a compares TRMM against GPCP and Figs. 9b–9f show the same for the selected WRF configurations. CMORPH observations are excluded here because they only start in 2003. Fig. 9a, shows that the TRMM and GPCP are similar, although there is slight disagreement during the first two days. The largest drop from high to low correlations occurs during the first 48 hours in each WRF simulation, which indicates that NCEP2 forcing data do not greatly influence the precipitation produced in the simulations. The WRF configurations show that 2006 (red filled-circles) does not perform well, although it gives significant scores from 10–13 September. Indeed, the simulations for 2005 and 2008 give the best r -scores and the simulations for 2001, 2002 and 2004 give the worst performing scores. Fig. 9 shows that the validation of 2005 maintains high correlations throughout the period for all WRF

configurations. The interannual differences in correlation scores are greater than the differences between configurations, suggesting that the precipitation variability during some years is more difficult to simulate than during others. These results differ slightly from the prequel Noble et al. (2014) study, which shows that 2006 maintains high correlations throughout the 12-day period and 2005 achieves the best scores for 700-hPa vorticity when validated against reanalysis. The similar correlation scores between the precipitation results of this study and the vorticity results of Noble et al. (2014) support the assumption that skillful simulations of daily precipitation over West Africa require skillful simulations of AEW related vorticity centers.

f. Impacts of alternative microphysics

The foregoing evaluation of WRF performance combines the roster of parameterizations listed in Table 2 with the WRF Single-Moment 5-Class MPS scheme. Impacts of using alternative MPS schemes are now tested by repeating the 12-day simulations of versions WRF32 and WRF27 with each of two alternative microphysics schemes: the new Thompson graupel (2012) and the Goddard cumulus ensemble (Wolff 2011; Harrold 2012). Berry and Thorncroft (2012) also consider these schemes, but favor the new Thompson MPS scheme after testing 32 WRF configurations for AEW simulation. Here, the horizontal distribution of 12-day precipitation accumulations is compared to GPCP data and validation statistics are compared with results based on using the WSM5. Results for 2006, listed in Table 4a, show that substituting the new Thompson MPS in place of the WSM5 in WRF32 increases the spatial correlation of simulated precipitation with GPCP observed 12-day accumulations from 0.54 (Fig. 2) to 0.61, and the correlation with the GPCP observed time-longitude Hovmöller p_{daily} distribution of precipitation (as in Fig. 6) from 0.32 to 0.40 (Table 4b). There are also concomitant improvements in the variance and bias. The Goddard scheme did not improve the performance of WRF32, and neither MPS improved WRF27. This suggests that the new Thompson graupel MPS has some advantages over the WSM5 for selected WRF versions. However, the apparent advantage of using the Thompson graupel MPS for the 2006 Hovmöller p_{daily} distribution was not evident in the simulations for the other years (see Fig. 9).

Discussion and Conclusion

More than 100 12-day WRF simulations, run on a 20-km grid over West Africa in September during eleven consecutive years, are evaluated to examine the sensitivity of WRF daily precipitation simulations over West Africa to model configuration. This study focuses on the simulation of 12-day accumulations and daily precipitation over West Africa during September, where much of the precipitation variability is linked to transient AEWs. Evaluation of the corresponding circulation, mean and daily, is reported in a prequel paper, Noble et al. (2014). Some 64 WRF configurations are tried by using different combinations of available WRF parameterizations: CPS, LSM, PBL and RAD physics. Simulated precipitation data are compared to NASA's GPCP and TRMM satellite precipitation estimates, which provide independent estimates of actual conditions at a relatively high horizontal resolution ($x, y=0.25^\circ$).

The WRF model simulates the summer monsoon precipitation maximum over West Africa, but with somewhat higher values than observed. Precipitation simulations are analyzed for 2–13 September 2006, a period that coincides with the NAMMA field campaign, where four major precipitation events associated with transient AEWs occur within the zonal belt 5°N–20°N. Six WRF configurations, including five of the better performing configurations, produce 12-day accumulations that range from 110%–186% (105%–180%) of GPCP (TRMM) values, and show the south to north gradients from rainy to dry conditions over the Sahel. The most excessive accumulation is simulated by the WRF model's default configuration (2014), 180% (175%) of GPCP (TRMM) values. Excessive WRF accumulations are consistent with the WRF exaggerated northward and eastward moisture flux across the West African and Guinean coast regions in these simulations. The best WRF performers in this analysis are WRF27, WRF32 and WRF64, which all share GD CPS. WRF32 and WRF64 share the MN PBL and the PX surface model but differ in their radiation parameterization. Compared to other regional model performance over West Africa though, the discrepancies in the mean state are serious deficiencies. Excessive precipitation accumulations are consistent with the WRF exaggerated northward and eastward moisture transports across the West African and Guinean coast regions in these simulations.

Propagation of rain maxima associated with the four westward-propagating AEWs appears as diagonal swaths on time-longitude Hovmöller charts of daily precipitation. Corresponding tracks of 700-hPa meridional wind and vorticity on Hovmöller distributions are discussed in Noble et al. (2014). Time-longitude Hovmöller distributions of daily accumulated precipitation from WRF were objectively validated against GPCP, TRMM, and CMORPH. WRF-generated tracks favor rather constant propagation speeds whereas the observations show irregular swaths. Alternative parameterizations influence the simulation of precipitation maxima and tracks, borne out by the range of validation scores for the 64 WRF configurations summarized on Taylor-Diagrams. The best WRF performers achieve correlations (against GPCP) of between 0.35–0.42 and spatiotemporal variability amplitudes only slightly higher than SREP. A parallel simulation by the benchmark RM3 achieves a higher correlation ($r=0.52$) and realistic spatiotemporal variability amplitudes against GPCP. It should be noted that none of the RCMs show the propagating precipitation maxima shifting with the formation of MCSs and subsequent regeneration of convection along a new phase line in the Hovmöller diagram that eventually became Tropical Cyclone Helene (Schwendike and Jones 2010). The WRF simulations in this study were unable to capture those complex interactions, which are best attempted using higher resolution models with explicit convection.

The largest favorable impact on WRF precipitation simulation is realized by selecting the GD CPS. Noble et al. (2014) reports a similar success for the simulation of 700-hPa vorticity variability. This preference may reflect the more versatile skill of that scheme's ensemble approach to computing the two-way interaction between convection and large-scale circulation (Grell and Dévényi 2002). Simulations using this scheme achieve higher correlations with SREP than the remaining simulations using the KF CP (Kain 2004), and GD also simulates less extreme daily precipitation maxima than KF CPS (not shown.) As in the current study, Berry (2009) finds that using GD CPS in WRF produces the most realistic representation of the precipitation field and the most realistic representation of the westward

propagating AEWs that cross the African coast. Rather than using a single closure criterion to determine how the cumulus parameterization scheme feeds back on the model atmosphere, GD employs the ensemble mean of multiple closure schemes using CAPE removal, destabilization effects, moisture convergence and low-level vertical velocity. The trigger is a measure of buoyancy that can be modified by the low-level moisture convergence or active convection. The closure schemes are also perturbed by variations of sensitive parameters related to strength of convection and feedback on the model atmosphere. The current study and that of Berry (2009) suggest that this ensemble approach is particularly suited to the complex summer WAM conditions that generate precipitation within MCSs, AEWs and along the inter-tropical discontinuity rain band. Berry (2009) suggests that the presence of dry Sahara air overlying the moist monsoon layer keeps mean layer humidity below the triggering threshold used by the Betts-Miller-Janjic scheme, which requires a moist vertical profile. Moreover, in Berry's experiments, KF produces broad areas of light precipitation for propagating systems instead of the observed narrow swaths of substantial rainfall, which may be a result of deep saturated layers in post-convective soundings that produce unrealistic stratiform rainfall, and GD produces the most realistic propagating precipitation maxima and the most realistic orographic maximums.

Impacts of other model parameterizations are more ambiguous. More consistently favorable results are obtained using the RU and PX LSM. Configurations incorporating the NO LSM did not perform well, but there are no unambiguous impacts attributed to using the remaining RAD, PBL and LSM schemes.

Examination of the cumulative and non-cumulative daily correlation scores versus elapsed-time for the selected WRF configurations for 2006 shows some WRF skill in simulating precipitation during the first two days, and for days 9–11 September, while the rest of daily scores were more disappointing. Our comparison of each SREP to data from 20 NAMMA rain gauge stations confirms that GPCP and TRMM are consistent with ground truth.

The WRF limitations for simulating daily meteorological fields do not preclude the model producing realistic seasonal mean climate fields, especially if many of the high frequency errors are random. While 64 model configurations cover a wide range of configurations, the testing reported here is not exhaustive. Results in this study favor WRF27, WRF32, WRF60, and WRF64 as the model configurations to consider; yet WRF27 (see Table 2) is the configuration that achieves the best overall performance. This is sustained by the circulation validation reported in a prequel paper (Noble et al. 2014), which describes the evaluation of WRF-AEW circulation variability for the same 64 configurations. Future work should explore the performance of new WRF parameterizations for simulating West African weather and climate.

Acknowledgments

The authors gratefully acknowledge the inspiration and encouragement for this project of the late Professor Thomas Warner. EUN was supported by NASA cooperative agreement NNX11AR61G. LMD and MF were supported by US National Science Foundation grant AGS-1000874 and NASA cooperative agreement NNX11AR63A. MERRA data were obtained from NASA's GMAO web site at <http://gmao.gsfc.nasa.gov/merra>, NCEP Reanalysis-2 data were provided by the NOAA-ESRL Physical Sciences Division, Boulder, CO from their web site at <http://www.esrl.noaa.gov/psd>.

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Fig. 1.

a) WRF model computational-domain with terrain elevation contours at 250 m intervals. The red box outlines the region validated for precipitation variability.

Fig. 2. Precipitation totals (p_{tot}), for the 2–13 September 2006 period, (a) GPCP (b) TRMM (c) WRF2, the default configuration (d) WRF27 (e) WRF32 (f) WRF59 (g) WRF60 (h) WRF64 and (i) RM3. The plot for GPCP shows the Sahel region in red, and the tropical rain-band region in black.

Fig. 3. Ratios of total precipitation between WRF to GPCP (red bar) and TRMM (green bar) for (a) the Sahel region, 10°N to 20°N, 20°W to 10°E, (b) the rain-band region, 5°N to 15°N, 20°W to 10°E and (c) both regions combined, 5°N to 20°N, 20°W to 10°E

Fig. 4.

Taylor diagrams displaying validation scores of 64 WRF simulations of 12-day precipitation accumulations over the area outlined in Fig. 1a. The corresponding scores of other data sets and of the RM3 simulation are also shown. Selected WRF configurations are identified. Spatial correlation coefficients are designated along radial spokes while values of concentric arcs marked along the x and y-axes indicate σ , normalized by the reference data standard deviation, thus σ_n . The dashed semi-circles measure the normalized rmse-centered differences between each point and the reference data a) against TRMM reference data and b) against GPCP reference data.

Fig. 5.

a) MERRA 925-hPa resultant vector winds (v_9) for 2–13 September 2006 and mean meridional moisture flux (qv) ($g\ kg^{-1}$) ($m\ s^{-1}$). b) WRF2 minus MERRA v_9 and qv , c) WRF27 minus MERRA v_9 and qv , d) WRF32 minus MERRA v_9 and qv , and e) WRF60 minus MERRA v_9 and qv .

Fig. 6.

Time vs. longitude Hovmöller distributions of daily-accumulated precipitation, pdaily, (mm day⁻¹). Precipitation is plotted at 0000 UTC on the designated day (y-axis), 2–13 September, and averaged over 5°N–20°N. (a) GPCP, (b) TRMM, (c) CMORPH, (d) WRF27 (e) WRF32 (f) WRF59 (g) WRF60 (h) WRF64 and (i) RM. Time vs. longitude Hovmöller distributions of Relative Vorticity (m²s⁻² x10⁵) at 700-mb are shown for j) NCEP2, k) WRF27, and l) WRF32.

Fig. 7.

Validation scores for the time vs. longitude Hovmöller distributions of pdaily (as in Fig. 5), for each of 64 WRF experiments compared to GPCP. In these Taylor-diagrams, values along radial spokes indicate r and values of concentric arcs indicate σ , normalized by GPCP standard deviations, thus σ_n . The dashed semi-circles measure the normalized rmse-centered differences between each point and GPCP. Colors (see legends) differentiate between major WRF model parameterizations used in each experiment (see Table 2): a) CPS, b) RAD, c) PBL, and d) LSM. The best WRF scores are highlighted with their version-number listed in Table 2. (NCEP2 reanalysis is labeled as R2.)

Fig. 8.

Time series showing two aspects of correlation (r) of the WRF modeled pdaily against the GPCP and TRMM pdaily valid at 0000 UTC. The cumulative- r between the models and GPCP (solid blue line) and TRMM (solid green line) validates results up-to-and-including-the-day indicated. The daily- r between the models and GPCP (dashed red line) and TRMM (dashed orange line) validates results specific-to-that-day.

Fig. 9.

An 11-year comparison of correlations (cumulative- r) vs. elapsed time for modeled Hovmöller p_{daily} distributions vs. GPCP for 2–13 September 2000 through 2010 valid at 0000 UTC: a) TRMM b) WRF27, c) WRF32, d) WRF59, e) WRF60, f) WRF64

Table 1

WRF Parameterizations considered for all experiments, with abbreviated code used throughout this study and source citation.

WRF Model Parameterization	Abbreviation	Source
Planetary Boundary Layer (PBL) Model		
Asymmetrical Convective Model-v.2	A2	(Pleim 2007)
Mellor-Yamada-Janjic	MJ	(Janji 2002)
Mellor-Yamada-Nakanishi-Niino	MN	(Nakanishi and Niino 2006)
Yonsei-University	YU	(Hong et al. 2006)
Microphysics Scheme (MPS)		
WRF Single-Moment 5-Class	W5	(Lim and Hong 2005)
Land Surface Model (LSM)		
5-Layer Thermal-Diffusion	5L	(Skamarock et al. 2008)
Pleim-Xiu	PX	(Pleim et al. 2003)
Rapid-Update-Cycle	RU	(Benjamin et al.)
Unified-Noah	NO	(Chen and Dudhia 2001)
Cumulus Convection Scheme (CPS)		
Grell-Devenyi Ensemble	GD	(Grell and Dévényi 2002)
Kain-Fritsch scheme	KF	(Kain 2004)
Radiation (RAD) Scheme		
Community Atmospheric Model	CM	(Collins et al. 2004)
Rapid Radiation Transfer Model	Rt	(Iacono et al. 2008)

Table 2

64 different WRF model combinations of parameterizations included in the sensitivity analysis

WRF Version	CPS	PBL	LSM	RAD	WRF Version	CPS	PBL	LSM	RAD
WRF1	KF	YU	5L	Rt	WRF33	KF	YU	5L	CM
WRF 2	KF	YU	NO	Rt	WRF34	KF	YU	NO	CM
WRF 3	KF	YU	RU	Rt	WRF35	KF	YU	RU	CM
WRF4	KF	YU	PX	Rt	WRF36	KF	YU	PX	CM
WRF 5	KF	MJ	5L	Rt	WRF37	KF	MJ	5L	CM
WRF6	KF	MJ	NO	Rt	WRF38	KF	MJ	NO	CM
WRF 7	KF	MJ	RU	Rt	WRF39	KF	MJ	RU	CM
WRF 8	KF	MJ	PX	Rt	WRF40	KF	MJ	PX	CM
WRF 9	KF	A2	5L	Rt	WRF41	KF	A2	5L	CM
WRF10	KF	A2	NO	Rt	WRF42	KF	A2	NO	CM
WRF11	KF	A2	RU	Rt	WRF43	KF	A2	RU	CM
WRF12	KF	A2	PX	Rt	WRF44	KF	A2	PX	CM
WRF13	KF	MN	5L	Rt	WRF45	KF	MN	5L	CM
WRF14	KF	MN	NO	Rt	WRF46	KF	MN	NO	CM
WRF15	KF	MN	RU	Rt	WRF47	KF	MN	RU	CM
WRF16	KF	MN	PX	Rt	WRF48	KF	MN	PX	CM
WRF17	GD	YU	5L	Rt	WRF49	GD	YU	5L	CM
WRF18	GD	YU	NO	Rt	WRF50	GD	YU	NO	CM
WRF19	GD	YU	RU	Rt	WRF51	GD	YU	RU	CM
WRF 20	GD	YU	PX	Rt	WRF52	GD	YU	PX	CM
WRF21	GD	MJ	5L	Rt	WRF53	GD	MJ	5L	CM
WRF 22	GD	MJ	NO	Rt	WRF54	GD	MJ	NO	CM
WRF 23	GD	MJ	RU	Rt	WRF55	GD	MJ	RU	CM
WRF 24	GD	MJ	PX	Rt	WRF56	GD	MJ	PX	CM
WRF25	GD	A2	5L	Rt	WRF57	GD	A2	5L	CM
WRF26	GD	A2	NO	Rt	WRF58	GD	A2	NO	CM
WRF 27	GD	A2	RU	Rt	WRF59	GD	A2	RU	CM
WRF28	GD	A2	PX	Rt	WRF60	GD	A2	PX	CM

WRF Version	CPS	PBL	LSM	RAD	WRF Version	CPS	PBL	LSM	RAD
WRF 29	GD	MN	5L	Rt	WRF61	GD	MN	5L	CM
WRF30	GD	MN	NO	Rt	WRF62	GD	MN	NO	CM
WRF31	GD	MN	RU	Rt	WRF63	GD	MN	RU	CM
WRF32	GD	MN	PX	Rt	WRF64	GD	MN	PX	CM

Table 3

Validation data

Source	Diagnostic	Spatial Resolution	Temporal resolution	Period of Record	Reference (http://)
GPCP	Precipitation (Pr)	0.25°	Daily	09/02/2006 to 09/14/2010	precip.gsfc.nasa.gov/rain_pages/daily_choice.html
TRMM 3B42	Precipitation (Pr)	0.25°	3-hourly	09/02/2006 to 09/14/2011	trmm.gsfc.nasa.gov/data_dir/data.html
CMORPH	Precipitation (Pr)	0.25°	3-hourly	09/02/2006 to 09/14/2012	www.cpc.ncep.noaa.gov/products/janowiak/cmorph_description.html
PERSIANN	Precipitation (Pr)	0.25°	3-hourly	09/02/2006 to 09/14/2013	chrs.web.uci.edu/persiann
MERRA	Zonal Wind (U) and Meridional Wind (V)	1.25°	6-hourly	09/02/2006 to 09/14/2006	gmao.gsfc.nasa.gov/merra
NCPR2	Zonal Wind (U) and Meridional Wind (V)	2.5°	6-hourly	09/02/2006 to 09/14/2008	www.esrl.noaa.gov/psd/data/gridded/data.ncep_reanalysis2.html
RM3 RCM	Zonal Wind (U) and Meridional Wind (V)	0.5°	6-hourly	09/02/2006 to 09/13/2006	Druyan et al. (2006)
	Precipitation (Pr)	0.5°	6-hourly	09/02/2006 to 09/13/2006	

Table 4

Correlation scores from the comparison of WRF modeled precipitation estimates to NASA GPCP estimates. The WRF models utilize the new Thompson graupel (Th) and the Goddard cumulus ensemble (Gd) microphysics. a) shows 12-day accumulations and b) shows the time-longitude Hovmöller distribution of p_{daily} precipitation.

a) Total Accumulation				
DATA	R	RMS	RATIO-SD	BIAS
WRF 27, W5	0.41	76.87	1.44	24.12
WRF 32, W5	0.54	69.04	1.49	14.89
WRF 27, Gd	0.24	82.99	1.42	16.75
WRF 32, Gd	0.56	53.7	1.14	-4.94
WRF 27, Th	0.36	69.94	1.25	14.39
WRF 32, Th	0.61	54.64	1.27	0.81
GPCP	1	0	1	0
TRMM	0.83	35.96	1.19	2.78
CMOPRH	0.76	41.89	1.16	10.09
MERRA	0.8	32.02	0.87	-1.69
R2	0.59	48.82	1.02	2.02
RM3	0.86	35.79	1.19	16.13

b) Time vs. Longitude Scores				
DATA	R	RMS	RATIO-SD	BIAS
WRF 27, W5	0.27	6.15	1.17	2.01
WRF 32, W5	0.32	6.05	1.27	1.24
WRF 27, Gd	0	7.11	1.22	1.4
WRF 32, Gd	0.28	5.54	1.08	-0.41
WRF 27, Th	0.1	6.1	1.02	1.2
WRF 32, Th	0.4	5.35	1.19	0.07
GPCP	1	0	1	0
TRMM	0.79	2.92	1.02	-0.57
CMOPRH	0.82	3.2	1.22	0.84
MERRA	0.44	3.98	0.53	-0.14
R2	0.09	6.85	1.28	0.17
RM3	0.52	4.24	0.84	1.34