Diurnal Characteristics of Rainfall over the Contiguous United States and Northern Mexico in the Dynamically Downscaled Reanalysis Dataset (US10)

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ABSTRACT

The diurnal characteristics of summer rainfall in the contiguous United States and northern Mexico were examined with the United States reanalysis for 5 years in 10-km horizontal resolution (US10), which is dynamically downscaled from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Global Reanalysis 1 using the Regional Spectral Model (RSM). The hourly precipitation outputs demonstrate a realistic structure in the temporal evolution of the observed rainfall episodes and their magnitudes across the United States without any prescriptions of the observed rainfall to the global reanalysis and the downscaled regional reanalysis. Nighttime rainfall over the Great Plains associated with eastward-propagating, mesoscale convective systems originating from the Rocky Mountains is also represented realistically in US10, while the original reanalysis and most general circulation models (GCMs) have difficulties in capturing the series of nocturnal precipitation events in summer over the Plains. The results suggest an important role of the horizontal resolution of the model in resolving small-scale, propagating convective systems to improve the diurnal cycle of summer rainfall.

1. Introduction

Most general circulation models (GCMs) exhibit substantial biases in their diurnal cycle simulations of summer rainfall. Often, deep convection develops too early over land, producing too much rainfall during the day and too little at night (e.g., Dai and Deser 1999; Zhang 2003; Collier and Bowman 2004; Dai and Trenberth 2004; Lee et al. 2007b). Reanalysis datasets have the similar problem, although they assimilate observational data over time, likely caused by deficiencies in the deep convection scheme (e.g., Lee et al. 2007b). For example, planetary boundary layer (PBL) development triggers daytime rainfall by overestimating diurnal heating in the models. Another issue is low spatial resolution in the models. Many GCMs using the Arakawa–Schubert scheme adopt the convective available potential energy (CAPE) in parameterizing deep convection (Arakawa and Schubert 1974). CAPE is the amount of energy in a parcel of air when lifted a certain vertical distance through the atmosphere; therefore, CAPE is an indicator of vertical atmospheric instability within a column. Consequently, it is sensitive to land surface conditions, including topography, albedo, and surface wetness. However, low-resolution GCMs contain insufficient conditions to determine the CAPE effectively and to capture atmospheric vertical instability to simulate diurnal rainfall patterns.

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Recently, cloud-resolving models (CRMs) have been developed (e.g., Miura et al. 2007) that implement the detailed cloud microphysics and precipitation processes associated with deep convection in an explicit manner instead of the cumulus parameterization used in GCMs. Using a two-dimensional (2D) Goddard cumulus ensemble (GCE) CRM, the mechanisms of summertime diurnal rainfall in the United States Great Plains were examined (Lee et al. 2010). The GCE model captured most of the observed rainfall events reasonably well during the intensive observation periods in 1995, 1997, and 1999, with realistic magnitudes not only for events driven by synoptic disturbances but also for diurnal convection events that developed overnight. Although cloud-resolving models tend to represent the observed characteristics of diurnal rainfall better than GCMs with parameterizations, they require substantial amount of computing time for long-term simulations over larger domains. In this paper, we present results from a dynamically downscaled reanalysis dataset [the United States reanalysis in 10-km horizontal resolution (US10)] and carefully examine the representation of diurnal rainfall in the boreal summer in the contiguous United States and northern Mexico. One of the major motivations of this study is to examine whether the broad-scale features in the rainfall are reasonably reproduced by explicitly resolving subgrid-scale convection and precipitation process.

2. Model and dynamical downscaling procedure

This study used the Regional Spectral Model (RSM; Juang and Kanamitsu 1994) that originated from a model used at the National Centers for Environmental Prediction (NCEP), with the code updated for greater flexibility and higher efficiency at the Scripps Institution of Oceanography. The dynamical downscaling method was originally tested over California using the NCEP–National Center for Atmospheric Research (NCAR) Global Reanalysis 1 (NCEP-1; Kanamitsu and Kanamaru 2007; Kanamaru and Kanamitsu 2007a), and this study expanded the domain (5.6°–53.1°N, 35.8°–145.1°W) to cover the conterminous United States with 10-km grid spacing ($\sim 0.1° \times 0.1°$) and 28 sigma (normalized pressure) vertical layers. The topography data were taken from the U.S. Geological Survey (USGS) global 30 arc-second elevation data (GTOPO30) and interpolated linearly to the 10-km model grid. Using the Earth Simulator supercomputer in Japan, the dynamical downscaling has been conducted for selected years in 1988, 1993, 1996, 1997, and 1998. These years were randomly chosen for computation, but the averaged summer-mean precipitation pattern and the characteristics of its diurnal variations are not significantly different from a longer-term analysis of the observation (cf. Lee et al. 2007a). In the RSM model, the scale-selective bias correction (SSBC) scheme was adopted by Kanamaru and Kanamitsu (2007b). This method is known to reduce large-scale errors (in this case the large-scale difference between NCEP-1 and RSM) that can be developed from systematic errors of the regional model within the domain as well as from inconsistencies between the regional model solution and the coarse-resolution global reanalysis forcing field along the lateral boundaries. The SSBC method includes the scale-selective damping for errors in zonal and meridional winds whose spatial scale is 1000 km or greater and the area-average correction of temperature, humidity, and surface pressure in the regional model. Thereby the regional model does not substantially modify the large-scale solutions represented by the global reanalysis, whereas it tends to retain small-scale features resolved by the high-resolution regional model. It is also noted that the model physics parameterizations implemented in RSM are basically similar to those of the global model used for the NCEP-1 reanalysis except the cloud-resolving moist physics (no deep convection scheme) and the modified radiation scheme (Kanamaru and Kanamitsu 2007b). Therefore, much of the simulation difference between the global reanalysis and US10 is originated from the difference in the horizontal resolution and the moist physics parameterization, particularly the treatment of deep convection.

3. Seasonal-mean rainfall simulations

First, we compared the climatological-mean summer [June–August (JJA)] rainfall in US10 with gridded rain gauge observations of the hourly precipitation dataset (HPD; Higgins et al. 1996) in $2.0° \times 2.5°$ latitude–longitude horizontal resolution, the high-resolution North American Regional Reanalysis (NARR; Mesinger et al. 2006) in $0.3° \times 0.3°$, and the NCEP-1 global reanalysis in $2.5° \times 2.5°$ (Figs. 1a–d). The rainfall climatology was based on the 5-yr average for 1988, 1993, 1996, 1997, and 1998 both in the observation and the reanalyses. The precipitation input to NARR was taken from several datasets such as HPD and the Climate Prediction Center (CPC) unified precipitation analysis (Higgins et al. 2000). HPD and NARR show similar geographical distributions in broad scale because the observed HPD rainfall was assimilated in NARR as forcing data, although NARR represents more detailed regional features than HPD. US10 represents a very fine spatial structure in the summer-mean precipitation pattern compared with the others, including the elongated rainfall maximum in the NW–SE

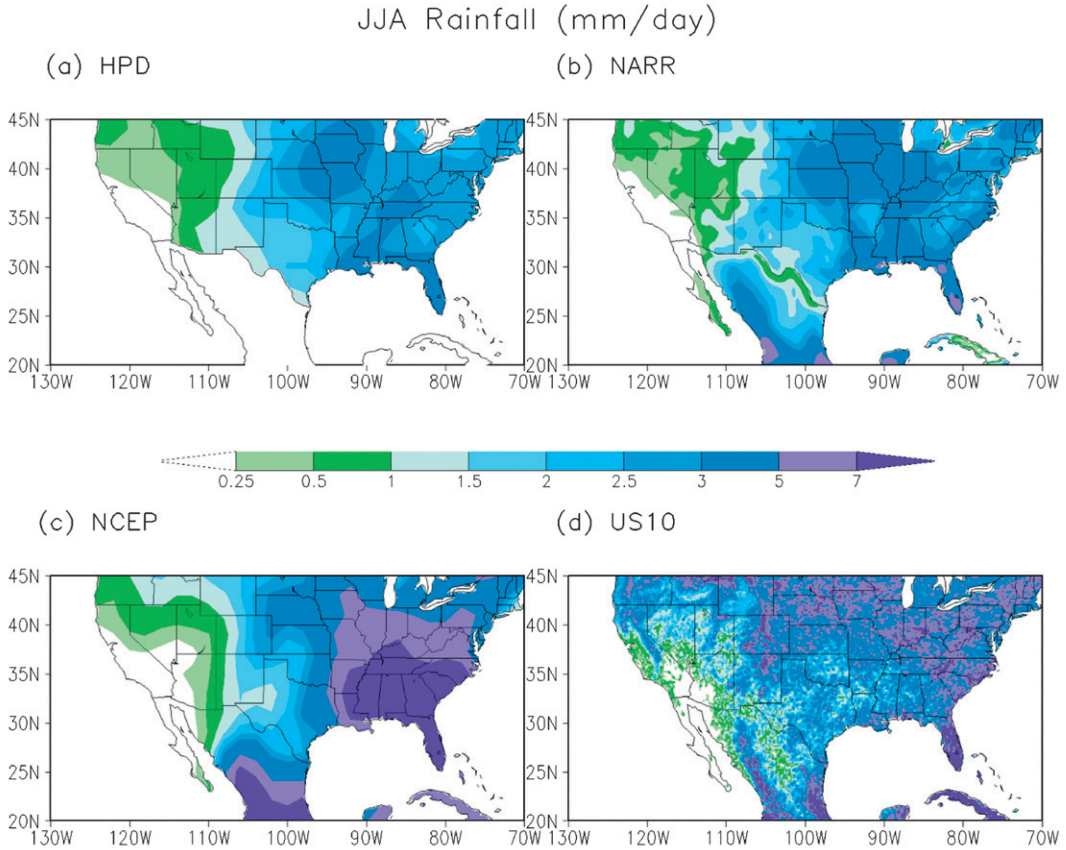

FIG. 1. The mean climatological summer (JJA) precipitation (mm day^{-1}) from (a) HPD (2.0° × 2.5° latitude–longitude), (b) NARR (0.3° × 0.3°), (c) NCEP-1 reanalysis (2.5° × 2.5°), and (d) US10 (0.1° × 0.1°). The results are the 5-yr means for 1988, 1993, 1996, 1997, and 1998.

direction over the western slope of the Sierra Madre Occidental (SMO), which is located north to south from just south of the Sonora–Arizona border southeast along the Gulf of California. Overall, the US10 reanalysis retains the broad-scale feature of the observed rainfall pattern in HPD, such as dry conditions on the western part of North America and wet conditions on the eastern part. However, some regions exhibit large anomalies in total rainfall compared with HPD, such as over the Midwest and the eastern United States (Fig. 1d). Note that NCEP-1 originally contains large rainfall anomalies over the Great Plains and East Coast, especially over the southeastern region, including the Florida peninsula. This suggests that US10 inherits the large rainfall anomaly from NCEP-1, despite a reduced wet bias in the southeastern region. We could not compare US10 with NARR over the North American summer monsoon region in northern Mexico, as the HPD rain gauge observation is limited over the United States. We speculate that another reason for larger rainfall amount in US10 than in HPD could be driven by the difference in the horizontal resolution between US10 (~10 km) and HPD (~200 km). US10 shows strong rainfall over the Rocky Mountains and the western and the eastern Sierra Madre Mountains, which might be caused by topographical effects resolved in the high-resolution reanalysis; NARR does not show such strong rainfall over the mountainous regions because the observed rainfall for assimilation was not highly resolved. HPD may not have represented rainfall patterns in mountainous regions because of its low resolution. It is interesting to note that the satellite-derived precipitation tends to show much higher precipitation amount in those complex terrains (cf. Lee et al. 2007a, their Fig. 1).

4. Diurnal cycles of rainfall

a. Amplitude and phase

Figures 2a and b compare the amplitude (mm day^{-1}) of the diurnal cycle of rainfall (24-h harmonic) between NARR and US10. The amplitude in NARR is considered observational because observed rainfall data were used in the assimilation. Both NARR and US10 exhibit

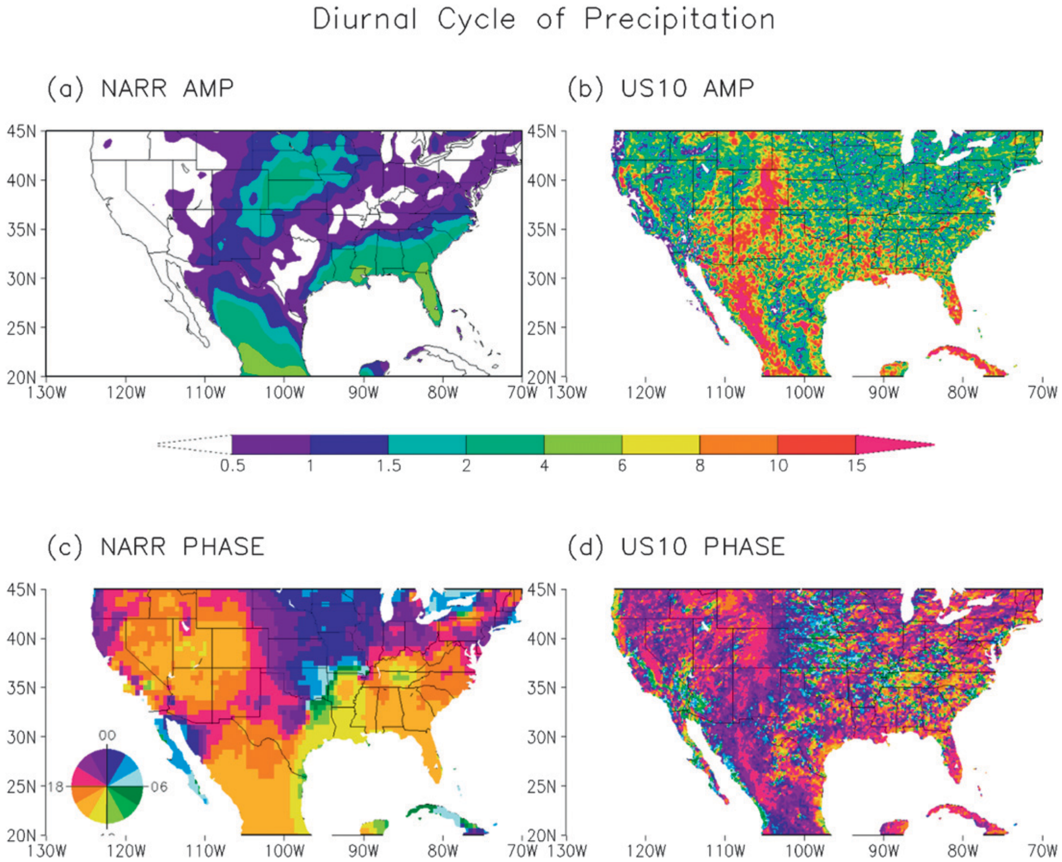

FIG. 2. The amplitude of the diurnal cycle of the mean climatological summer (JJA) precipitation (mm day^{-1}) from (a) NARR and (b) US10. The amplitude of the 24-h harmonic is given from the harmonic analysis applied to the JJA mean diurnal time series. (c),(d) LST of the maximum of the diurnal cycle of hourly precipitation for NARR and US10, respectively. The hatched areas show less than 0.25 mm day^{-1} in the target 5-yr JJA mean.

large amplitude over the Great Plains and the Florida peninsula. However, US10 shows larger anomalies in the amplitude in many regions. This feature seems to be consistent with the result of Lee et al. (2007a), whose study suggested an increase of the amplitude of the diurnal cycle with increasing model resolution in atmospheric GCMs. In addition, overall wet bias of the summer-mean rainfall in NCEP-1 (Fig. 1) may contribute to the anomalously strong amplitude of the diurnal cycle in US10. US10 also shows high amplitude in the diurnal rainfall pattern over the western side of SMO. These results suggest that the simulated diurnal rainfall is significantly influenced by improved representations of topographical effect and land–sea contrast in US10.

The local solar time (LST) of the maximum in the diurnal cycle (diurnal phase) of rainfall is compared in Figs. 2c,d. The results are based on the analysis of hourly data for June to August and for the 5 years examined. NARR exhibits a late afternoon–evening maximum over most regions in the United States, except for the Great Plains, which has a nighttime rainfall maximum (e.g., Wallace 1975; Dai and Deser 1999). The signal of nighttime rainfall over the Great Plains is also confirmed in recent studies using satellite-driven rainfall analysis such as the CPC morphing technique (CMORPH) precipitation analysis (Janowiak et al. 2007). The observations also show a clear transition of the phase from the east of the Rocky Mountains to the adjacent Great Plains and Midwest, whose features have not been accurately simulated by many GCMs (Lee et al. 2007b, 2008). US10 shows a reasonable geographic distribution of the diurnal phase over the continental United States. There is a clear east–west contrast along the Continental Divide (~100°–105°W), where the western region shows afternoon–nighttime rainfall maxima, whereas nighttime rainfall is dominant in the eastern region. On the western side of the west Sierra Madre Mountains, US10 exhibits the evolution of the phase from the afternoon rainfall on the mountain to the nighttime rainfall on the Gulf of California, whose feature corresponds well to other observational studies (e.g., Nesbitt et al. 2008). This is presumably by resolving details in land–sea contrast

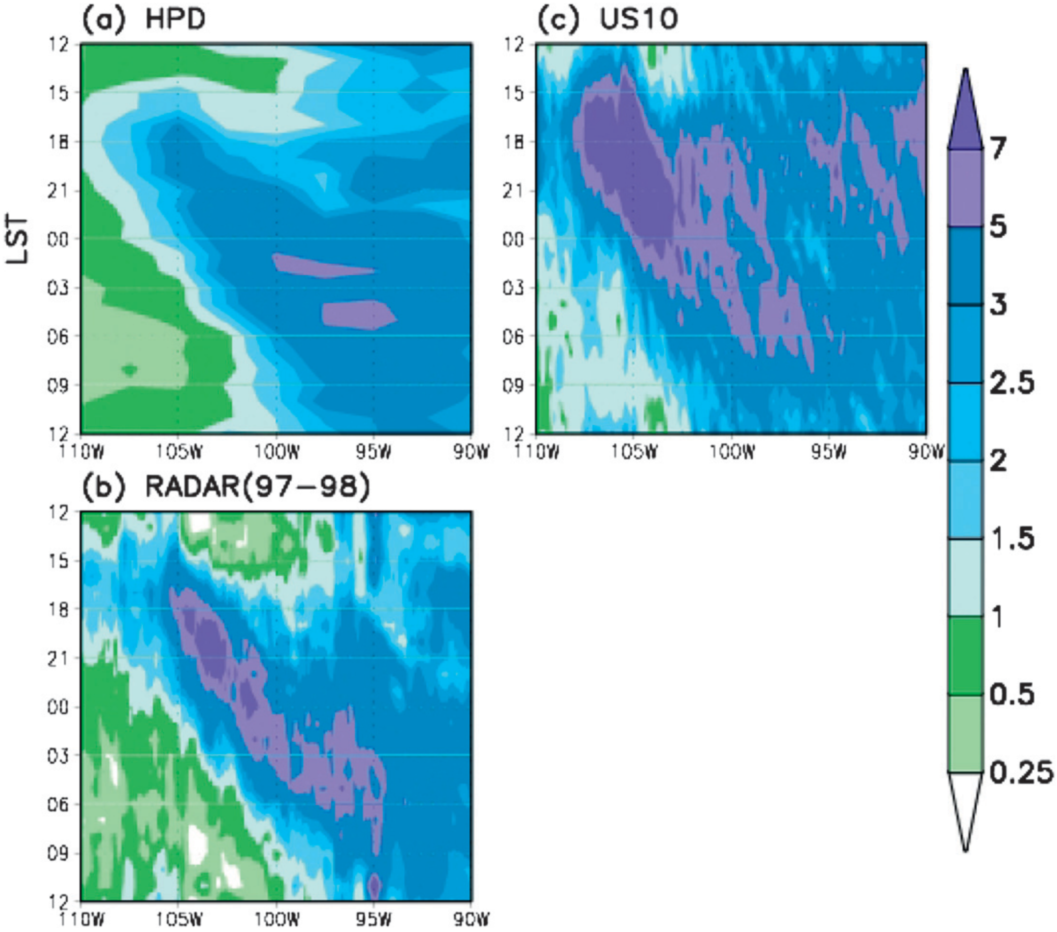

FIG. 3. The time–longitude distribution of the mean climatological summer rainfall in the 35°–45°N zone (mm day^{-1}) for (a) HPD, (b) MUL (4-km horizontal scale), and (c) US10. Panel (b) shows the 2-yr mean for 1997 and 1998.

and complex topographical effects in the high-resolution US10 analysis. NARR is not able to capture this phase transition over the western slope of SMO (Fig. 2c), although it has a fine horizontal resolution of approximately 30 km. This seems to be related with the assimilation of the observed precipitation in NARR, which is substantially limited by coarse horizontal resolution (~200 km) in gridded rain gauge observation data (Mesinger et al. 2006).

b. Great Plains

Figure 3 compares the summer-mean diurnal cycle of rainfall over the Rocky Mountains and the adjacent Great Plains (30–45°N, 112–90°W) from NARR (Fig. 3a), the Precipitation NCEP/Environmental Modeling Center (EMC) 4-km gridded data multisensor analysis (MUL; Fig. 3b), and US10 (Fig. 3c). MUL is based on gauge and radar observations. Because of data limitation, Fig. 3b is plotted using the 2-yr means of 1997 and 1998. NARR shows the eastward-propagating pattern from the Rocky Mountains to the Great Plains. Riley et al. (1987) and Carbone et al. (2002) proposed that the nighttime rainfall over the Great Plains could be linked to coherent eastward-migrating convection systems from the Rocky Mountains. Recently, Matsui et al. (2010) have examined the eastward propagation of the rainfall system using $\frac{1}{8}$° hourly assimilated rainfall datasets from the North American Land Data Assimilation System (NLDAS; Cosgrove et al. 2003) for June–August for 1998–2007. Such eastward propagation of the rainfall system is clearly shown in MUL (Fig. 3b). US10 also shows nighttime rainfall over the Great Plains, which seems to be associated with the eastward propagation of convective systems from the Rocky Mountains. According to Jiang et al. (2006), nearly half of the total mean summer rainfall over this region is associated with the propagating convection systems, whose feature is not accurately captured in many GCM simulations (e.g., Klein et al. 2006). Note that only a few GCMs are able to capture the nighttime rainfall signal over the Great Plains by some modifications in the convection trigger—for example, limiting the

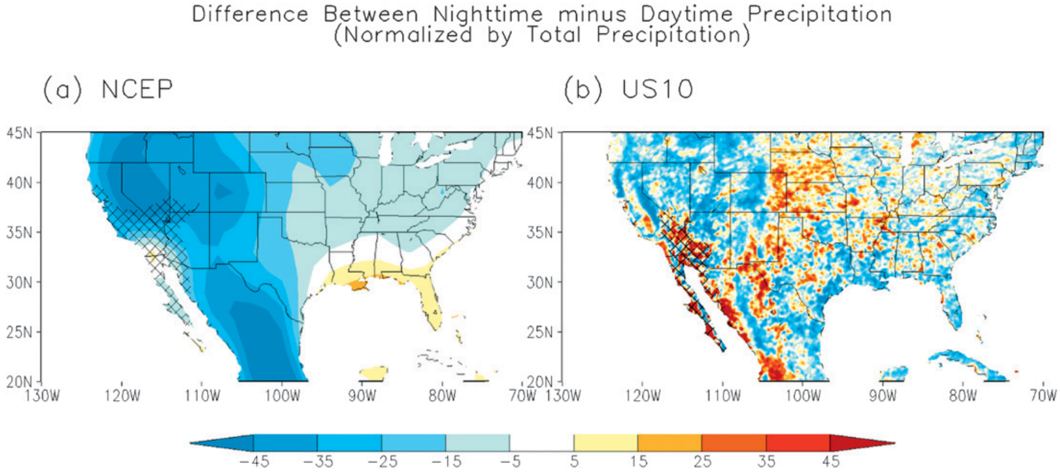

FIG. 4. The ratio of nighttime (1800–2400 LST) to daytime (0600–1200 LST) rainfall in the mean climatological summer states for (a) NCEP-1 and (b) US10. The values were normalized with the daily rainfall. The hatched areas show less than 0.25 mm day^{-1} in the target 5-yr JJA mean.

depth between the cloud base and the level of free convection in the NCEP Global Forecasting System (GFS) model (Lee et al. 2008), although this modification has been tested in coarse horizontal resolution. US10 resolves not only the nighttime precipitation over the Great Plains but also the late afternoon precipitation. This signal is a bit stronger than the observation, whose rainfall seems to be produced by local insolation and sensible heating over land.

Finally, the nighttime (1800–2400 LST) minus daytime rainfall (0600–1200 LST) was compared between US10 and the NCEP–NCAR Global Reanalysis 1—the original forcing dataset for the US10 reanalysis (Fig. 4). The rainfall difference was normalized by daily total in each dataset. NCEP-1 shows more daytime than nighttime rainfall almost everywhere in the United States except for the southeastern coastal regions. In US10, nighttime rainfall is greater in the Great Plains and North American monsoon regions, including the west side of the western Sierra Madre Mountains. This demonstrates that the dynamical downscaling is able to capture nocturnal precipitation over the complex terrain by resolving propagating mesoscale convective systems, which are fairly unresolved in the original reanalysis in coarse horizontal resolution.

5. Discussion

In this study, we examined the influences of the dynamical downscaling in a 10-km grid scale (US10) on the summertime mean precipitation and its diurnal variation characteristics. US10 reasonably captures the observed diurnal characteristics of summer rainfall, particularly over the Great Plains, without any prescriptions of the observed rainfall data during the assimilation and downscaling process. Improvements in the representation of the nighttime rainfall over the Great Plains in US10 are associated with the enhanced activity of eastward-propagating mesoscale convective systems from the Rocky Mountains, which could be attributed to the substantial increase of horizontal resolution up to 10 km in the nested CRM, and improved representation of moist convection in the model without parameterization. We anticipate a more extensive use of CRMs in future reanalysis productions with the advance of high-performance computers. Still, the use of CRMs for long-term, high-resolution weather and climate reanalysis over global or limited domain requires huge computing resources. This study demonstrates that the dynamical downscaling technique could be a practical and reasonable alternative in projecting large-scale data assimilation products to resolve meteorological phenomena both in finer temporal and spatial scales.

Soil moisture largely influences rainfall variability over the Great Plains via a strong land–atmosphere coupling (Koster et al. 2006) using a similarity index (e.g., Yamada et al. 2007). Therefore, strong interannual variability of the diurnal characteristics of summer rainfall exists over the region associated with land surface dryness. The physical mechanisms of the diurnal rainfall characteristics in US10 must be examined.

From the perspective of climate change, the fourth assessment of the Intergovernmental Panel on Climate Change (IPCC) noted that changing specific humidity and increasing air temperature would alter the diurnal characteristics of summer rainfall. The dynamical downscaling technique is a powerful tool that will help clarify future projections of the diurnal characteristics of rainfall in GCMs.

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