Regional climate model simulation of summer precipitation diurnal cycle over the United States

Xin-Zhong Liang,[1] Li Li,[1] Aiguo Dai,[2] and Kenneth E. Kunkel[1]

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[1] MM5-based regional climate model (CMM5) simulations of the diurnal cycle of U.S. summer precipitation are found to be sensitive to the choice of cumulus parameterization schemes, whose skills are highly regime selective. The Grell scheme realistically simulates the nocturnal precipitation maxima and their associated eastward propagation of convective systems over the Great Plains where the diurnal timing of convection is controlled by the large-scale tropospheric forcing; whereas the Kain-Fritsch scheme is more accurate for the late afternoon peaks in the southeast U.S. where moist convection is governed by the near-surface forcing. In radar rainfall data and the simulation with the Grell scheme, another weaker eastward propagating diurnal signal is evident from the Appalachians to the east coast. The result demonstrates the importance of cumulus schemes and provides a realistic simulation of the central U.S. nocturnal precipitation maxima. *INDEX TERMS:* 1655 Global Change: Water cycles (1836); 1854 Hydrology: Precipitation (3354). **Citation:** Liang, X.-Z., L. Li, A. Dai, and K. E. Kunkel (2004), Regional climate model simulation of summer precipitation diurnal cycle over the United States, *Geophys. Res. Lett.*, *31*, L24208, doi:10.1029/2004GL021054.

1. Introduction

[2] The diurnal cycle of precipitation is a crucial part of the earth's hydrology and climate system. It modulates surface temperature range and is closely associated with the diurnal cycles of moist convection, thunderstorm activity, cloud formation, and boundary layer development [*Dai and Trenberth*, 2004]. Collectively they control diurnal variations of air quality including photochemical production, aqueous chemistry, wet deposition, and boundary layer mixing [*Russell and Dennis*, 2000; *Crutzen and Lawrence*, 2000].

[3] Over the United States, the precipitation diurnal cycle is characterized by distinct geographic patterns of phase and amplitude variations. Summer precipitation is dominated by nocturnal maxima to the east of the Rockies and over the Great Plains and late afternoon maxima over the western and southeastern U.S. [e.g., *Wallace*, 1975; *Riley et al.*, 1987; *Dai et al.*, 1999]. The nocturnal maxima may be caused by diurnal variations in large-scale vertical motion with early morning ascending and afternoon descending [*Dai et al.*, 1999] and in the strength of moisture convergence due to the Great Plains low level jet (LLJ) acceleration at night [*Liang et al.*, 2001], while surface heating results in peak atmospheric instability and thus moist convection in late afternoon. The diurnal variations across the central U.S. have been linked to coherent propagating heavy rainfall episodes emanating from the east slope of the Continental Divide to the Midwest [e.g., *Carbone et al.*, 2002].

[4] *Dai et al.* [1999] found that three popular cumulus schemes [*Grell*, 1993; *Grell et al.*, 1994; *Kuo*, 1974; *Zhang and McFarlane*, 1995] all failed to capture the broad diurnal phase pattern in a regional model, although the Grell and Kuo schemes partially reproduced the afternoon-to-early morning phase transition from the Rockies to the central U.S. *Davis et al.* [2003] showed that two other schemes [*Kain and Fritsch*, 1993; *Betts and Miller*, 1993; *Janić*, 1994] are unable to replicate the eastward propagation of the central U.S. nocturnal maxima. *Knievel et al.* [2004] then questioned whether existing cumulus parameterizations can be tuned, new parameterization approaches are necessary, or moist convection must be explicitly resolved in order to reproduce this feature. On the other hand, *Zhang* [2003] illustrated that, when the parameterization closure is based on large-scale tropospheric (convergence/divergence and radiative heating/cooling) instead of boundary layer (surface sensible and latent heat fluxes) forcing, the Zhang-McFarlane scheme produces significantly improved rainfall diurnal patterns. *Xie et al.* [2004] also showed that the simulation of the precipitation diurnal cycle over the central U.S. can be improved substantially when the tendency of convective available potential energy (CAPE) is considered in triggering convection in the same scheme. Here we will further demonstrate that the Grell and Kain-Fritsch schemes generate drastically different and regionally dependent diurnal patterns, and the combination of the two best depicts observations.

2. Model Simulations and Observations

[5] *Liang et al.* [2004] described the CMM5 model formulation, baseline integration, and precipitation annual cycle performance. They demonstrated that the CMM5, with a horizontal resolution of 30 km, has considerable rainfall downscaling skills, producing more realistic regional details and overall smaller biases than the driving global reanalysis [*Kanamitsu et al.*, 2002]. A branch CMM5 simulation was conducted in parallel to the baseline integration, where the Grell cumulus scheme was replaced by the Kain-Fritsch scheme with everything else being identical. The branch simulation includes each summer during 1982–2002 started from the baseline condition on April 1. The following analysis focuses only on the summer (June, July, and August) months, and refers to the CMM5 simu-

[1]Illinois State Water Survey, University of Illinois at Urbana-Champaign, Champaign, Illinois, USA.
[2]National Center for Atmospheric Research, Boulder, Colorado, USA.

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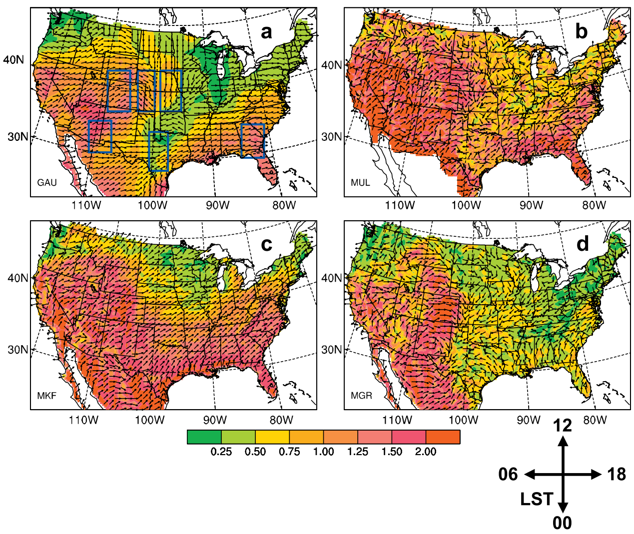

Figure 1. Spatial distributions of summer (June–August) rainfall diurnal cycles observed by (a) the rain gauge measurement (GAU) and (b) multi-sensor analysis (MUL), and simulated by the CMM5 using (c) Kain-Fritsch (MKF) and (d) Grell (MGR) cumulus schemes. Colors represent the normalized amplitude (i.e., in units of daily mean) while unit vectors denote the local solar time (LST) of the peak (phase clock).

lations using the Grell and Kain-Fritsch schemes as MGR and MKF, respectively.

[6] For comparison, we used two observational data sets of hourly precipitation, referred to as GAU and MUL. The GAU is derived from quality-controlled rain gauge records during 1982–2002 at about 2500 stations on a 2.5° longitude by 2° latitude grid [*Higgins et al.*, 1996]. The MUL is the National Centers for Environmental Prediction stage-IV multi-sensor analysis [*Fulton et al.*, 1998], which is the blend of WSR-88D radar estimates and rain gauge measurements, available during 1996–2002 on a 4-km grid. Radar data have inherent difficulties in estimating the rainfall amount while gauge data may under-represent the spatial coverage. The coarse GAU and fine MUL data are mapped onto the CMM5 30-km grid using bilinear interpolation and mass-conservative averaging, respectively.

[7] In the following, we focus on the long-term summer means, averaged over 1982–2002 (GAU), 1996–2002 (MUL), and 1982–2002 (CMM5). Each contains 24 hourly-precipitation amounts, which are normalized by a division of the daily mean at individual grids to enhance the compatibility between observations and simulations [*Wallace*, 1975; *Dai et al.*, 1999].

3. Results

[8] Figure 1 compares the spatial distributions of rainfall diurnal cycle amplitude and phase among GAU, MUL, MGR, and MKF. The amplitude represents the daily maximum of the normalized precipitation minus one, while the phase depicts the local solar time (LST) when the peak rainfall occurs. To facilitate discussions, Figure 2 shows the mean diurnal evolution of the normalized precipitation averaged over 6 regions with distinct diurnal characteristics (Figure 1a).

[9] Although the MUL exhibits greater diurnal amplitudes than the GAU, the spatial patterns closely resemble each other (Figures 1a and 1b). There are large amplitudes over and to the west of the Rockies (except Washington and Oregon), over the Southeast, and over and to the east of Appalachians. Smaller amplitudes are found across the northern U.S. (except Montana) and in a southwest-northeast oriented strip in the central U.S. The CMM5 reproduces this broad pattern except for underestimation over the southeast (western) U.S. when using the Grell (Kain-Fritsch) cumulus scheme (Figures 1c and 1d).

[10] The MUL peak rainfall occurs somewhat earlier than the GAU over most of the U.S., with less coherent phase patterns (Figures 1a and 1b); this is most evident in the

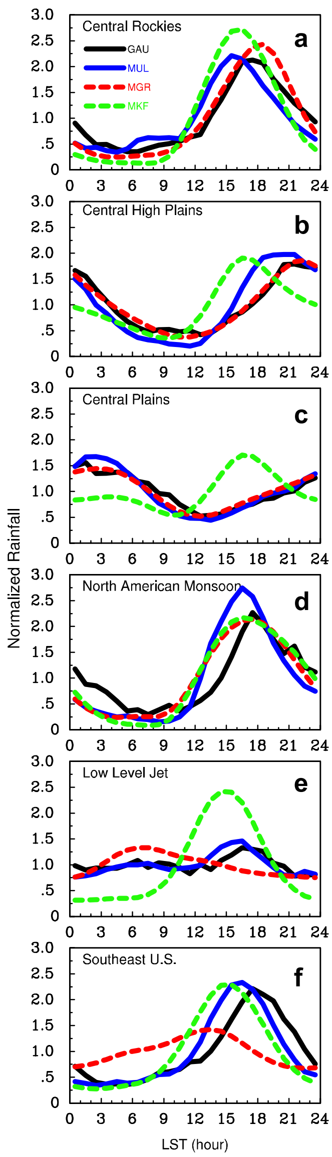

Figure 2. Mean diurnal evolution (relative to LST) of the normalized rainfall averaged over 6 key regions: (a) the central Rockies, (b) central high Plains, (c) central Plains, (d) North American monsoon, (e) low level jet, and (f) southeast U.S., corresponding to the boxes in Figure 1a from left to right and top to bottom.

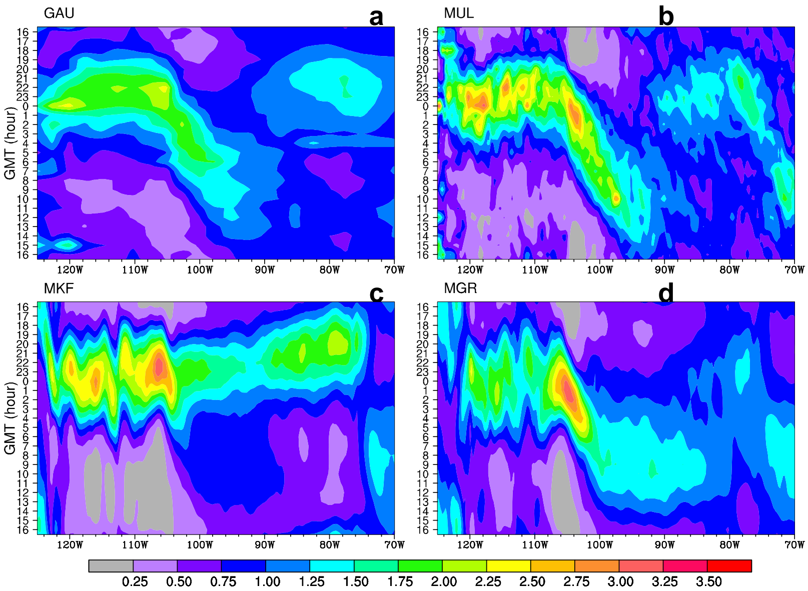

Figure 3. Hovmöller diagram (GMT hour versus 0.25° longitude bin) of normalized rainfall diurnal variations averaged between 38–42°N for (a) GAU, (b) MUL, (c) MKF, and (d) MGR.

central Rockies, North American monsoon region, and southeast U.S. (Figures 2a, 2d, and 2f). Better agreement is evident in the central High Plains, central Plains and LLJ regions (Figures 2b, 2c, and 2e). These phase differences are unlikely due to different data periods, since the summer diurnal cycle pattern is fairly stable from year to year [*Dai et al.*, 1999] and the difference between the GAU 1982–2002 and 1996–2002 averages is small. Although no definitive explanation is available, some likely causes include delays in gauge recording of rainfall (biasing GAU toward later times) and radar detection of evaporating precipitation and changing droplet size distribution during storms (both biasing MUL toward earlier times) [*Fulton et al.*, 1998; *Maddox et al.*, 2002]. The gauge and radar biases are opposite in sign and both potentially large in the western U.S. Although their resulting amount of phase shift is difficult to quantify, these biases are consistent with the fact that the GAU lags the MUL more in the central Rockies and North American monsoon region than the moist and flat central Great Plains and LLJ region. The droplet size induced errors in the radar data could be significant for the phase shift in the southeast U.S.

[11] When compared with the GAU, the MGR realistically simulates the diurnal amplitude and phase transitions from the central Rockies (18 LST), across the central High Plains (21 LST), to the central Plains (2 LST) (Figures 1d, 2a, 2b, and 2c). In contrast, the MKF fails to capture the phase transitions across these regions, producing a diurnal phase lock with peaks at 16 LST over most of the U.S. (Figure 1c), a feature also of the Betts-Miller-Janić scheme [*Davis et al.*, 2003]. In the Southeast, the MKF produces a peak that is 3 hours earlier than the GAU, while the MGR yields an even earlier and weaker peak (Figure 2f). In the North American monsoon region, both schemes reproduce the GAU late afternoon peaks (Figure 2d). The LLJ region shows a semi-diurnal cycle in both GAU and MUL, with the primary peak in the late afternoon (~17 LST) and the secondary one just after sunrise (~7 LST) (Figure 2e). The CMM5 fails to reproduce this feature, with the Kain-Fritsch (Grell) scheme capturing the single primary (secondary) peak with greater-than-observed amplitudes.

[12] Figure 3 shows the Hovmöller diagram of normalized rainfall diurnal variations averaged between 38–42°N. The MUL and GAU results resemble Figure 12 of *Carbone et al.* [2002], which is based on radar echo frequency averaged between 30°–48°N for May–August 1997–2000. As shown previously [*Carbone et al.*, 2002; *Davis et al.*, 2003], Figures 3a and 3b suggest that summer convective systems generated over the Rockies propagate eastward to the central Plains at a speed of ~14 m/s. The MGR realistically simulates this propagating diurnal signal, although limited to west of 98°W (Figure 3d). On the other hand, the MKF completely fails to capture the eastward propagation (Figure 3c). East of 80°W, another weaker propagating diurnal signal is evident in both the MUL and MGR, but absent in the GAU and MKF. The coarse resolution may explain this absence in the GAU data. The similarity of the diurnal signals across the Rockies and Appalachians, as well as over other mountainous regions [*Dai*, 2001], suggest an important role of topography in the formation of distinct regional patterns through interaction with large-scale circulations.

4. Summary and Discussion

[13] The CMM5's capability to simulate the precipitation diurnal cycle is very sensitive to the choice of cumulus parameterizations, whose skills are dependent on climate regimes. The Grell scheme realistically simulates the diurnal patterns over the western and central U.S., including the late afternoon peaks (17–18 LST) over and to the west of the Rockies and the eastward propagating systems across the Great Plains; but it poorly depicts the late afternoon peaks in the Southeast. This result is qualitatively consistent with the Grell scheme performance of *Dai et al.* [1999]. In contrast, the Kain-Fritsch scheme fails to reproduce the propagating diurnal signal over the Great Plains, but it captures the peaks in the Southeast better. In the radar rainfall data and

the CCM5 simulation with the Grell scheme, another weaker eastward propagating diurnal signal is evident from the Appalachians to the east coast.

[14] Our results demonstrate the importance of cumulus parameterization schemes in simulating the diurnal cycle of summer continental precipitation, although the role of surface heating, the planetary boundary layer and the large-scale circulation cannot be ignored, as demonstrated by *Dai et al.* [1999]. The most common problem in current U.S. modeling studies is the eastward propagation of convective systems and the nocturnal precipitation maxima over the Great Plains [*Davis et al.*, 2003]. *Zhang* [2003] showed that the Zhang-McFarlane scheme simulates the diurnal cycle over the Great Plains with rainfall peaks predominant at 16 LST or midnight depending on whether the parameterization closure is based on large-scale tropospheric or boundary layer forcing. Our results agree with this finding, given that the Grell scheme is very responsive to large-scale tropospheric forcing whereas the Kain-Fritsch scheme is heavily influenced by boundary layer forcing (G. Grell and J. Kain, personal communication, 2004). As such, the CMM5's simulation skill is highly regime selective: the Grell scheme is more realistic over the Great Plains where the diurnal timing of convection is influenced by the large-scale vertical motion [*Dai et al.*, 1999], whereas the Kain-Fritsch scheme works better in the Southeast where convection is largely governed by the near-surface forcing. Over the central U.S., there are sufficient moisture and CAPE in the atmosphere for moist convection even during night hours [*Dai et al.*, 1999]. The determining factor for the diurnal timing of convection is not the availability of local moisture and CAPE but when and how convection is triggered and instability is modulated. These are subjects of future studies.

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A. Dai, National Center for Atmospheric Research, Boulder, CO 80301, USA.

K. E. Kunkel, L. Li, and X.-Z. Liang, Illinois State Water Survey, University of Illinois at Urbana-Champaign, 2204 Griffith Drive, Champaign, IL 61820-7495, USA. (xliang@uiuc.edu)